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# LIFE CYCLE INVENTORY ANALYSIS FOR DECISION-MAKING

## SCOPE-DEPENDENT INVENTORY SYSTEM MODELS AND CONTEXT-SPECIFIC JOINT PRODUCT ALLOCATION

A dissertation submitted to the

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ROLF FRISCHKNECHT
Dipl. Bau-Ing. ETH
born 17. August 1962
citizen of Basel-Stadt and Schwellbrunn (Appenzell Ausserrhoden)

accepted on the recommendation of
Prof. Dr. P. Suter, examiner
Prof. Dr. D. Spreng, co-examiner
Dr. G. Huppes, co-examiner

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# LIFE CYCLE INVENTORY ANALYSIS FOR DECISION-MAKING

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ROLF FRISCHKNECHT

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ESU-services Ltd.
Rolf Frischknecht
Kanzleistrasse 4
CH - 8610 Uster
Telefax: +41-44-940 61 94
e-mail: frischknecht@esu-services.ch

# Preface

This *Ph.D.*-thesis is the result of the research work carried out during my stay at the Department of Energy Technology of the Swiss Federal Institute of Technology, ETH in Zürich. From late 1990 to 1994 I cooperated in the compilation of the "Environmental Life Cycle Inventories of Energy Systems" ("Ökoinventare von Energiesystemen") which has been the basis for my further methodological research in the field of Life Cycle Assessment (LCA). Besides the coordination of and working on the revision and extension of the "Environmental Life Cycle Inventories of Energy Systems", I focused my research work on aspects of value choices encountered in Life Cycle Inventory Analysis and on the development of scope-dependent inventory system models.

During my stay at ETH, I profited by a number of persons to which I would like to express my thanks. I thank Prof. Dr. Peter Suter for enabling and promoting LCA research work at his chair and his encouragement in the realisation of my ideas, Prof. Dr. Daniel Spreng for his interest in the thesis and his supporting, experienced comments on it, and Dr. Gjalt Huppes for inspiring and stimulating discussions and challenging questions.

The case studies mainly refer to data published in the "Environmental Life Cycle Inventories of Energy Systems". I due a special thank to my colleagues of the former ESU-group and at the Paul Scherrer Institut, Villigen, and to external partners for their help in realising the present energy systems' database and for an interesting and agreeable co-operation. In particular, I thank Patrick Hofstetter, ETH Zürich, for a demanding and fruitful co-operation, challenging discussions and the review of parts of this thesis, and Roberto Dones, PSI Villigen, for his special efforts and discerning comments. I thank Wolfram Krewitt, Institute of Energy Economics and the Rational Use of Energy (IER), Stuttgart University, for his review and comments on a previous version of the chapter about environmental external costs.

I thank Prof. Dr. Wolfgang Kröger and Prof. Dr. Konrad Hungerbühler and their co-workers for the support I received in the last year to finalise the thesis.

I thank Mark Zimmermann, head of the Swiss federal co-ordination group for energy analyses and life cycle assessment, and Mr. E. Fischer, secretary of the Swiss utilities' project and research fund (Projekt- und Studienfonds der Elektrizitätswirtschaft, PSEL) for enabling the funding of my research activities as well as for their kind co-operation.

For the financial support of my research work at ETH Zürich I would like to acknowledge the Swiss National Fund of Energy Research (NEFF), the Swiss Federal Department of Energy (BFE), the Swiss utilities' project and research fund (PSEL), and the Swiss Federal Institute of Technology Zürich (ETHZ). Please note that they are in no way responsible for the content of this thesis.

Finally, I am indebted to my wife Ursula for her encouragement to continue the course I am pursuing and for blithe moments during my lucubration.

Uster, May 1998 Rolf Frischknecht

(4me)

# Contents

# Abstract

*Keywords:* *Life Cycle Assessment, Life Cycle Inventory Analysis, Systems modelling, Joint production, Allocation, Environmental external costs, Electricity model, Combined heat and power production,*

In this thesis, Life Cycle Inventory Analysis (LCI) is structured in view of its use in decision-making. Emphasis is put on often encountered inconsistencies, namely the set-up of LCI system models, the representation of decisions and value choices of actors (e.g., firms) involved in a product system, and the representation of changes within the economic system.

An LCI system model consists of numerous individual processes. Their relations are identified according to economic (such as market information or contracts) instead of mere physical information. Based on such a system model, LCA provides environmental information consistently complementary to private cost statements.

A disutility function is introduced, which is used for the default choice of (marginal) technologies or technology mixes within the product system, and for joint product allocation. The disutility function adds up economic information (i.e., private costs) and environmental information to total "social" costs. For that purpose, an environmental exchange rate is introduced. The exchange rate mirrors the variable influence of environmental aspects on decisions in different political entities such as nations. It may also express differences in uncertainty perception of the actors directly and indirectly involved in the production of the good or service under analysis.

To reflect the consequences of decisions, models capable of representing changes within the economic system shall consist of processes represented by marginal technologies, the technologies put in or out of operation next. The disutility function is used for the identification of the marginal technologies throughout the whole product system. System models are classified according to the distinction of planning tasks in firms, i.e., short-, long- and very long-term decisions. It is assumed that all firms connected within the process network of a product make their decisions based on the same time horizon (i.e., short-, long-, and very long-term). Aspects of non-linearity occur in the case of short-term optimisation. Semi-dynamic modelling in the case of very long-term planning shows its limited added value compared to static modelling.

Short-term decisions comprise the optimisation of existing production facilities. That is why capital equipment is not included in the Short Run system model. In the case of long-term decisions, capital equipment is included in the Long Run system model depending on the status of the market situation of the product under analysis. In shrinking markets, where no replacement investments are made, capital equipment is left out whereas in expanding and saturated markets it is included. Very long-term decisions require consistent scenario about the future status of society, economy and the environment. For the support of very long-term decisions with the help of LCA, emphasis is put on the accuracy of the representation of the future status, and much less on the detailed modelling of

the transition period towards that future status.

The disutility function is applied in joint product allocation assuming that environmental aspects influence decisions of a firm and its clients. Joint production situations are discriminated according to the decision context, i.e., the number of decision-makers involved, and according to the market for which joint products are manufactured.

In a single decision-maker situation within sufficiently working markets, allocation factors are chosen in view of the competitiveness of the joint products. The competitiveness of two or more joint products is determined using multiobjective optimisation.

In a single decision-maker situation within monopolistic markets, the price-output relation is determined in view of maximising profits by means of constrained optimisation.

In a multiple decision-maker situation, several parties negotiate for a voluntary coalition. The aim is to evaluate an allocation key satisfactory for all parties. A game theoretic approach is used to model such situations.

The cases "national electricity mix" and "small scale gas-fired combined heat and power generation" illustrate the new methodological approaches. The Eco-indicator 95 impact assessment method is adapted to recent knowledge about environmental damages and used for the environmental assessment of the various electricity and heat generating technologies used in the case studies.

The environmental performance of the Swiss national electricity mix represented by an economically- and a physically-based model is determined. The differences in terms of single environmental impacts are significant but minor in terms of "social" costs. The determination of marginal power plants is sensitive in respect to the underlying forecast of electricity consumption. In a system model where an increase in electricity demand is prognosticated, electricity shows a relatively good environmental performance which promotes electricity applications. But also the opposite assumption, a future decrease in electricity consumption, leads to a consistent outcome. A comparison of our results with a forecast made for the European electricity supply industry confirms the accuracy of the disutility function to a considerable extent.

Context-specific allocation in combined heat and power (CHP) production is compared with traditional allocation approaches such as the "avoided burden"-approach or allocation based on economic or arbitrary physical criteria. The competitiveness of the CHP plant highly depends on the damage cost scenario for global warming. In terms of "social" costs the CHP plant is competitive compared to combinations of existing fossil-fueled power plants and natural gas-fired boilers but also compared to nuclear power and gas-fired boilers (low $CO_2$-damage costs scenario). Gas-fired gas combined cycle power plants show a similar performance like the CHP plant if combined with natural gas-fired boilers. However, the uncertainties in the data qualify the generalization of the conclusions from both case studies.

It is concluded, that the guiding principle formulated in this thesis, namely that LCA shall complement economic information, leads to a consistent and feasible methodology capable of representing changes within the economic system.

# Zusammenfassung

*Schlagworte: Ökobilanz, Sachbilanz, Systemmodellierung, Kuppelproduktion, Allokation, Externe Kosten, Strommodell, Wärmekraftkopplung*

In der vorliegenden Arbeit werden Sachbilanz-Systemmodelle ausgearbeitet, und im Hinblick auf deren Verwendung in der Entscheidungsfindung strukturiert. Das Hauptgewicht liegt dabei auf der Reduktion von Widersprüchen im Modell. Widersprüche treten auf in Bezug auf die Art und Weise wie das Systemmodell aufgebaut wird, wie Entscheide von Akteuren (z.B. Firmen) innerhalb eines Produktlebenszyklus', und wie Änderungen innerhalb des ökonomischen Systems modelliert werden.

Das Systemmodell einer Sachbilanz besteht aus einer Vielzahl von individuellen Prozessen. Deren Verknüpfungen untereinander werden mit Hilfe ökonomischer Informationen (wie z.B. Marktinformationen, Verträge) eruiert. Daraus resultiert ein Systemmodell, welches bestmöglich traditionelle ökonomische Informationen (private Kosten) um die dazugehörigen Umweltinformationen ergänzt.

Eine Kostenfunktion wird eingeführt. Sie dient dazu, in genereller Weise eine (Grenz-)Technologie respektive einen Technologie-Mix zu bestimmen. Zudem wird sie bei Allokationsproblemen starr gekoppelter Prozesse verwendet. Die Kostenfunktion vereint ökonomische und ökologische Informationen zu sogenannten "sozialen" Kosten. Sie enthält einen Faktor ("Umwelt-Wechselkurs") mit Hilfe dessen die Bedeutung der Umweltauswirkungen im Verhältnis zu den privaten Kosten variiert werden kann. Dieser Faktor ist abhängig davon, wie Umweltaspekte die Entscheidungsfindung beeinflussen. So kann beispielsweise die Ausgestaltung der nationalen Umweltpolitik einen Einfluss ausüben. Zudem kann einer unterschiedlichen Wahrnehmung unsicherer Information über zukünftige Umweltschäden Rechnung getragen werden.

Einzelprozesse innerhalb entscheidungsunterstützender Systemmodelle werden durch Grenztechnologien, durch die als nächste in resp. ausser Betrieb genommenen Technologien, repräsentiert, um die Konsequenzen von Entscheidungen abbilden zu können. Innerhalb des gesamten Produktsystems werden die Grenztechnologien mit Hilfe der Kostenfunktion bestimmt. Es werden Sachbilanz-Systemmodelle für Entscheide mit kurz-, lang- und sehr langfristigem Planungshorizont unterschieden. Dabei wird angenommen, dass innerhalb dieser drei Modelle alle in einem Produktsystem involvierten Firmen auf der Basis desselben Planungshorizontes entscheiden.

Kurzfristige Entscheide werden bei der Optimierung bestehender Fabrikationsanlagen benötigt. Dementsprechend ist die Produktion der Investitionsgüter in diesem Systemmodell ausgeschlossen. Im Systemmodell für langfristige Entscheide wird die Produktion von Investitionsgütern lediglich in wachsenden oder reifen Märkten, in welchen (noch) Erweiterungs- respektive Ersatzinvestitionen getätigt werden, berücksichtigt. Entscheide mit einem sehr langfristigen Planungshorizont benötigen konsistente Szenarien über zukünftige gesellschaftliche, ökonomische und ökologische Entwicklungen. Um sehr langfristig ausgerichtete Entscheide mit Hilfe der Ökobilanzierung zuver-

lässig unterstützen zu können, müssen die möglichen zukünftigen Zustände möglichst genau bekannt sein. Hingegen sind Informationen über den zeitlichen Verlauf, wie diese Zustände erreicht werden, für die Genauigkeit von Ökobilanz-Ergebnissen von untergeordneter Bedeutung.

Die Kostenfunktion wird im weiteren bei Allokationsproblemen in starr gekoppelten Prozessen angewandt in der Annahme, dass Umweltaspekte bei Entscheiden der entsprechenden Firma und ihrer Kunden eine Rolle spielen. Die Allokationsprobleme starr gekoppelter Prozesse werden kontext-spezifisch, d.h. bezüglich ihres Entscheidungsumfeldes klassifiziert. Dabei werden Situationen mit einem respektive mit mehreren Entscheidern unterschieden. Zudem spielt die Beschaffenheit des Marktes eine Rolle, für den die Kuppelprodukte hergestellt werden.

In einer Situation mit einem Entscheider in einem funktionierenden Markt wird die Allokation nach Massgabe der Wettbewerbsfähigkeit (oder Tragfähigkeit) der Kuppelprodukte durchgeführt. In einer Situation mit einem Entscheider in einem monopolartigen Markt, besteht kein eigentliches Allokationsproblem. Vielmehr geht es darum, das Preis-Absatz Verhältnis im Hinblick auf eine Nutzenmaximierung zu optimieren. Bei mehreren Entscheidern müssen gerechte Aufteilungsschlüssel gefunden werden. Da Umweltbelastungen (noch) kaum auf dem Markt gehandelt werden, tritt dieser Fall in Ökobilanzen nicht nur bei freiwilligen Koalitionen, sondern generell bei der Aufteilung der Umweltbelastung eines Prozesses mit mehreren mitbeteiligten Entscheidern ein. Derartige Situationen werden mit Hilfe eines spieltheoretischen Ansatzes modelliert.

Ökobilanzen nationaler Strommodelle und von Wärmekraftkopplungsanlagen (WKK) kleiner Leistung dienen zur Veranschaulichung der erabeiteten methodischen Ansätze. Die Unterschiede der Ökobilanz des Schweizerischen Strommixes, basierend einerseits auf einem ökonomischen und anderseits auf einem physikalischen Modell, unterscheiden sich signifikant in Bezug auf einzelne Umwelteinwirkungen. Bezüglich "sozialer" Kosten hingegen sind die Unterschiede gering. Die Bestimmung der Grenzkraftwerke zeigt eine grosse Sensitivität bezüglich der zugrundeliegenden Bedarfsprognose. Wird eine Zunahme des Stromverbrauchs angenommen, so zeigt der zusätzlich zu produzierende Strom eine vorteilhafte Umweltbilanz. Dadurch können Stromanwendungen gefördert und der Strombedarf tatsächlich gesteigert werden. Aber auch ein gegenteiliges Szenario mit einem abnehmenden Stromverbrauch führt zu in sich konsistenten Resultaten. Ein Vergleich der Resultate dieser Fallstudie mit Prognosen über Investitionen in der Europäischen Elektrizitätswirtschaft bis zum Jahre 2010 zeigt eine ziemlich gute Übereinstimmung.

Der Ansatz der kontext-spezifischen Allokation wird am Beispiel der Ökobilanz einer Wärmekraftkopplungs-Anlage angewendet. Der neue Ansatz wird mit klassischen Methoden der Allokation wie Restwertmethode oder Allokation nach Massgabe ökonomischer und physikalischer Parameter verglichen. Dabei zeigt sich, dass die Wettbewerbsfähigkeit von Wärme und Strom aus WKK-Anlagen in starkem Masse vom verwendeten Szenario bezüglich Klimaschadenskosten abhängt. In Bezug auf "soziale" Kosten sind Strom und Wärme aus der WKK-Anlage wettbewerbsfähig im Vergleich zu Kombinationen von Strom aus bestehenden fossil befeuerten Kraftwerken und Wärme aus gasbefeuerten, kondensierenden Kesseln. Unter der Annahme niedriger Klimaschadenskosten ist die WKK-Anlage auch gegenüber Kernkraftwerken in Kombination mit Gasheizungen wettbewerbsfähig. Moderne Gas- und Dampfkraftwerke in Kombination mit Gasheizungen produzieren Strom und Wärme zu vergleichbaren sozialen Kosten. Infolge der Unsicherheiten in den angewendeten Modellen und Daten sind die Schlussfolgerungen dieser Fallstudien nur begrenzt verallgemeinerbar.

# Terms

The definition of terms rely to a large extent on the definitions given in the ISO documents ISO 14040-14042 (Anonymous 1997a,b&c), Heijungs et al. (1996), and Horngren et al. (1991, p. 941). However, some of them are new, defined differently or are used in a different context.

**Allocation:** Partitioning of the input and output flows of commercial and ecological commodities of a unit process to the commercial commodities produced either in fixed or variable proportions.

**Average requirements and emissions:** Requirements and emissions per functional unit caused by the production of the respective functional unit including a share of the production of capital equipment. Requirements and emissions and production are measured during a certain time period (e.g., a calendar year).

**Average technology:** The average technology (mix) is represented by a technology (mix) used to cover the demand for a certain functional unit within a specific area and a certain time period (e.g., a calendar year).

**"Avoided burden"-approach:** Procedure to enlarge system boundaries of a multi-function product system and to subtract the ecological commodities caused by the additional functional units in view of the comparability with alternative single-function product systems. See also "'System expansion'-approach".

**Basic commodity:** Commercial commodity which appears in the standard system model used for life cycle inventory analysis. It is used for the production of other commercial commodities. Examples in the energy systems database (Frischknecht et al. 1996a) are: Electricity produced in European power plants, bulk chemicals such as caustic soda, transport and waste treatment services, *et cetera*.

**By-product:** Commercial commodity which leaves a unit process and contributes little or nothing to the proceeds of the respective process. No flows of ecological commodities are allocated to it.

**Combined production:** Production process with which several valuable outputs may but need not be produced together. Separate production is possible but usually less attractive, e.g., passengers and freight transportation. Accordingly, the shares of the outputs may vary between 0 and 100%.

**Commercial commodity:** Physical or symbolic objects that flow between economic or unit processes.

**Comprehensive price:** Price of a commercial commodity comprising private costs, environmental external costs and a profit rate. See also "Social costs".

**Co-product:** Any of two or more physical or symbolic objects which leave a unit process and whose values in monetary terms are positive. A co-product is a commercial commodity.

**Cost object:** Any activity or item for which a separate measurement of flows of commercial and ecological commodities is desired.

**Cumulative intervention matrix:** Matrix containing the overall (direct and indirect) flows of ecological commodities caused by the system of all functional units comprised in the LCI database.

**Cumulative intervention vector:** Vector containing the overall (direct and indirect) flows of ecological commodities caused by the system of one single functional unit under study.

**Downstream process:** Process which occurs in the part of the process network of the functional unit under study subsequent to the process at issue.[1]

**Ecological commodity:** Objects of the natural environment and objects that are exchanged between the anthroposphere and the environment including resource extraction, emissions to air, water, or soil.

**Elementary flow:** See "Ecological commodity".

**Elementary Process:** See "Unit process".

**Enviro-economic competitiveness:** Concept to express the competitiveness of commercial commodities expressed in social costs. This concept is used in joint product allocation and in the default choice of a technique.

**Enviro-economic fairness**: Concept to evaluate a fair allocation base for jointly produced commercial commodities.

**Environmental exchange rate:** Parameter which expresses the weight given to environmental external costs compared to private costs.

**Environmental intervention:** See "Ecological commodity".

**Functional unit:** Quantified performance of a product system for use as a reference unit in an LCA study.

**Good:** A physical object which leaves a unit process and whose value in monetary terms is positive. A good is a commercial commodity.

[1] Hence, downstream is a relative term and is not restricted to waste treatment processes only.

**Intervention matrix:** Matrix containing the direct (*in situ*) flows of ecological commodities caused by all functional units comprised in the LCI database.

**Intervention vector:** Vector containing the direct (*in situ*) flows of ecological commodities caused by the unit process of the functional unit under study.

**Joint product:** Commercial commodities that are simultaneously and necessarily produced by one process. Their share is fixed. The commercial commodities need to be sufficiently distinguishable. Joint overhead activities may be interpreted as joint production processes.

**Marginal requirements and emissions:** Additional or reduced requirements and emissions caused by a process due to a marginal, short-term change in capacity load.

**Marginal technology:** A marginal technology is represented by a technology or technology mix which is put in or out of operation next due to a short-, long- or very long-term change in demand for the respective functional unit.

**Multi-function product system:** Product system with more than one positively valued flow of commercial commodities leaving the system.

**Non-basic commodity:** Commercial commodity which does not appear in the standard system model used for life cycle inventory analysis. It is not used for the production of other commercial commodities. Examples in the energy systems database (Frischknecht et al. 1996a) are: Electricity produced by means of wind power and photovoltaics, or warm water generated by means of solar heating systems.

**Product:** A physical or symbolic object (good or service, respectively) which leaves a unit process and whose value in monetary terms is positive. A product is a commercial commodity.

**Service:** A symbolic object which leaves a unit process and whose value in monetary terms is positive. A service is a commercial commodity. The treatment of wastes or the transportation of goods are services (or symbolic objects). In most cases a service is related to one or several physical objects, either waste or product.

**Single-function product system:** Product system with only one single positively valued flow of commercial commodity leaving the system.

**Social costs:** Costs of production for a commercial commodity comprising private costs and environmental external costs. In this thesis the addition of private and environmental external costs is made applying an environmental exchange rate.

**Split-off point:** Juncture in the process when products (in a joint production situation) become separately identifiable.

**Sunk flows of commercial and ecological commodities:** Flows of commodities caused in the past that are unavoidable because they cannot be changed no matter what action is taken.

**"System expansion"-approach:** Procedure to enlarge system boundaries of a mono-function product system to include additional functional units in view of the comparability with alternative multi-function product systems. See also "'Avoided burden'-approach".

**Technology matrix:** Matrix containing the direct (*in situ*) flows of commercial commodities entering and leaving the unit processes comprised in the LCI database.

**Technology vector:** Vector containing the direct (*in situ*) flows of commercial commodities entering and leaving the unit process of the functional unit under study.

**Unit process:** Smallest portion of a product system for which data are reported separately in the system model when performing a life cycle assessment.

**Upstream process:** Process which occurs in the part of the process network of the functional unit under study preceeding to the process at issue.

**Waste:** Commercial commodity which leaves a unit process and whose value in monetary terms is negative. Waste is defined in respect to its treatment service (see also service).

# Acronyms

| | |
|---|---|
| APME | Association of Plastics Manufacturers in Europe |
| BFE | Bundesamt für Energie |
| BKW | Bernische Kraftwerke AG |
| Bq | Bequerel (1 Bq = 1 decay per second) |
| BUWAL | Bundesamt für Umwelt, Wald und Landschaft |
| CFC | Chlorofluorocarbon |
| CH | Switzerland |
| CHP | Combined heat and power |
| COD | Chemical Oxygen Demand |
| D | Germany |
| DIMAG | Dieselmotoren AG, Niederdorf |
| EKZ | Elektrizitätswerke des Kantons Zürich |
| EMPA | Eidgenössische Materialprüfungs- und Forschungsanstalt |
| ESEERCO | Empire State Electric Energy Research Corporation |
| EV | Erdöl-Vereinigung |
| EWZ | Elektrizitätswerk der Stadt Zürich |
| f | (emissions into) fresh water |
| F | France |
| GCC | Gas Combined Cycle |
| GDP | Gross Domestic Product |
| GNP | Gross National Product |
| GSV | Gross sales value |
| GWP | Global warming potential |
| H-CFC | Hydrochlorofluorocarbon |
| HFO | Heavy Fuel Oil |
| I | Italy |
| IIASA | International Institute for Applied Systems Analysis |
| IPCC | Intergovernmental Panel on Climate Change |
| ISO | International Organization for Standardization |
| LCA | Life Cycle Assessment |
| LCI | Life Cycle Inventory Analysis |
| LCIA | Life Cycle Impact Assessment |
| m | (emissions from) mobile sources |
| MSW | Municipal Solid Waste |
| p | process specific emissions (e.g., fugitive emissions, emissions due to calcination) |
| PCBs | Polychlorinated biphenyls |
| PFBC | Pressurised Fluidised Bed Combustion |
| $PM_{10}$ | Particulate matter less than 10 microns in diameter |
| POM | polycyclic organic matter |
| PSI | Paul Scherrer Institut, Villigen |
| PV | Photovoltaic |
| Rp. | Rappen (1 Rp. = 0.01 SFr.) |
| s | (emissions into) sea water, (combustion emissions into air from) stationary sources |
| SETAC | Society of Environmental Toxicology and Chemistry |
| SFr. | Swiss Franc (1 SFr. = 0.71 US-$ (1990, yearly average)) |
| Sv | Sievert (dose equivalent, 1Sv = 1J/kg) |
| TSP | Total suspended particulates |
| UCPTE | Union de la Coordination du Production et du Transport de l'Electricité |
| UNIPEDE | International Union of Producers and Distributors of Electrical Energy |
| UNSCEAR | United Nations Scientific Committee on the Effects of Atomic Radiation |
| VLYL | Value of Life Years Lost |
| VSE | Verband Schweizerischer Elektrizitätswerke |
| VSL | Value of Statistical Life |
| WHO | World Health Organisation |
| YOLL | Years of Life Lost |

# Symbols

| | |
|---|---|
| $\tilde{a}_{il}$ | Flow of commercial commodity $i$ to or from process $l$ (3.4.2)[2] |
| $a_{il}$ | Cumulative flow of commercial commodity $i$ to or from process $l$ (3.4.2) |
| $\tilde{\mathbf{A}}$ | Technology matrix (3.4.2) |
| $\mathbf{A}$ | Cumulative Technology matrix (3.4.2) |
| $\tilde{b}_{jl}$ | Flow of ecological commodity $j$ to or from process $l$ (3.4.2) |
| $b_{jl}$ | Cumulative flow of ecological commodity $j$ to or from process $l$ (3.4.2) |
| $\tilde{\mathbf{B}}$ | Intervention matrix (3.4.2) |
| $\mathbf{B}$ | Cumulative intervention matrix (3.4.2) |
| $\tilde{\mathbf{P}}$ | Process matrix (3.4.2) |
| $\mathbf{P}$ | Cumulative process matrix (3.4.2) |
| $\tilde{\mathbf{e}}$ | Environmental impact or damage vector (in monetary units), (3.4.2) |
| $e^i$ | Environmental impact or damage of alternative $i$ (in monetary units) (4.2.1) |
| $r^i_s$ | Comprehensive price of alternative $i$ (7.5.2) |

[2] In brackets: Number of Section where the symbol is introduced

| | |
|---|---|
| $z_s^i$ | Social costs of alternative *i* (4.2.1) |
| $c$ | Environmental exchange rate (4.2.1) |
| $\lambda^i$ | Allocation factor of joint product *i* (7.5.1) |
| $\Pi$ | Lagrangean function (7.5.2) |
| $\xi$ | Ratio of joint product outputs (7.5.1) |

# Executive Summary

Life Cycle Assessment (LCA) is a method for the analysis and assessment of potential environmental impacts along the life cycle of a good or a service. It is applicable on products, processes or firms, to document their environmental performance, to identify potentials for environmental improvements, to compare alternative options as well as to substantiate ecolabelling criteria. In many cases, the outcome of an LCA is used in firms to order changes in the product or process design or in suppliers. However, the same static system model suitable for descriptive purposes such as environmental reporting is often used for planning purposes such as product or process development. The data taken as a basis for such analyses often represent average technology mixes (such as the annual electricity mix in a certain country), for which the emission factors and requirements are determined based on, e.g., annual averages. This may lead to a system model contradictory to the original goal of the LCA, namely to support decisions. This may in its turn result in wrong indications or in suboptimal solutions.

In this thesis, system models are developed to answer the question which *additional* economic activities are associated with which *additional* environmental impacts. For that purpose some of the inconsistencies in today's LCA are treated and proposals are made how to reduce them in view of strengthening the predictive power of LCA. The focus for improvements is put on

- the set-up of Life Cycle Inventory (LCI) system models,
- the representation of value choices and decisions made by actors (e.g., firms) involved in a product system, and on
- the representation of changes within the economic system.

## Process and System Representation

An epistemological approach is chosen to design system models, because the behaviour of the economic system in consequence of a change in demand can not be verified experimentally. Starting from the guiding principle that an LCI system model complements economic information, Hypothesis 1 is substantiated and a general procedure is formulated. It states that a process network of a product is set up according to economic information such as market information or contracts. This is in contrast to common practice which tends to set up the system model on physical flows only. Linear relationships are assumed between the intended output (the functional unit), and the demand for intermediate goods and services and pollutants released. Furthermore, three general assumptions are stated in order to reduce complexity. It is assumed that *a)* firms tend to minimise costs and maximise profits, that *b)* incremental and not average damages on the environment are considered, and that *c)* all firms connected within the process network of a product make their decisions based on the same time horizon.

## The Disutility Function

In an LCI system model capable of representing changes, the LCA analyst must model decisions made by several hundred individual actors running the processes a product system is composed of. Furthermore, value choices are required in joint product allocation. In order to be consistent with

the purpose of an LCA, namely to complement today's price system, these decisions are assumed to be based on economic *and* environmental information[3]. For that purpose, a disutility function, which aggregates private costs and environmental information to a one-dimensional figure (named "social" costs[4]), is introduced. Environmental information is added to private costs by converting arbitrary units of LCA impact assessment methods into monetary units and weighting them with an environmental exchange rate. The environmental exchange rate expresses the influence of national environmental policies on decision-making in firms, and the way firms deal with uncertainties related to environmental issues. In case environmental aspects are not considered at all in decision-making, the environmental exchange rate equals to zero.

## Scope-dependent System Models

System models capable of representing changes within the economic system are developed based on the disutility function and the representation of processes and process networks described above. In line with the classification of short-, long-, and very long-term decisions made in economics, three LCI system models are introduced, namely, the "Short Run", the "Long Run", and the "Very Long Run". They are discriminated according to the temporal structure of changes in the demand, the degree of freedom in varying the factors of production, and in the technical possibilities available. Tab. 1 shows the three system models together with the descriptive LCI system model "Status Quo".

| Name of the system model | Goal of the study | Temporal structure of a change in demand | System model properties | |
|---|---|---|---|---|
| | | | variability of the factors of production | technologies available/ technical performance |
| Status Quo | - environmental reports<br>- statements to the authorities | No change | all fixed | no choice/ fixed |
| Short Run | - short-term system optimisation<br>· changes in demand<br>· negotiations with suppliers | One time only | capital equipment fixed | no choice/ fixed |
| Long Run | - hot spot identification *and* elimination<br>- product system optimisation<br>- product development<br>- product system comparison | Long-term trend | all variable | free choice/ fixed |
| Very Long Run | - very long-term (strategic) planning<br>· technology development,<br>· technology optimisation,<br>· technology comparison. | Very long-term trend | all variable | free choice/ variable |

Tab. 1: Four different system models in LCI discerned in this thesis and its characterisation in terms of the temporal structure of a change in demand and system model properties.

The *Status Quo* system model describes the current situation, and does not predict possible changes of the economic system[5]. When either short-, long- or very long-term changes are involved, the Short, Long and Very Long Run system model are suitable. In order to accurately represent the effects of such a change, the three system models consist of the corresponding, scope-dependent marginal technologies, the technologies put in or out of operation next. They are determined by the

[3] For the sake of operability, the third dimension of sustainability, i.e., social compatibility (IDARio 1995, p. 23), is not considered here.

[4] In line with the term used for the aggregate of private and environmental external costs.

[5] It is capable of solving the attribution problem (Heijungs 1997).

LCA analyst based on the disutility function described above or based on market information. Thereby, the technology with the lowest "social" costs is assumed to be the marginal technology entering the market next, whereas the most expensive one is assumed to leave the market next.

The *Short Run* LCI is used for short-term optimisation problems. Short-term changes in demand and negotiations with suppliers, where the capital equipment available is fixed, are represented with this model. For the short-term optimisation of the product portfolio in combined production, linear programming may be applied as has been shown in previous publications[6]. In this case, allocation factors based on physical causalities of the combined production process may be determined.

The *Long Run* LCI is suited for many common LCA goals such as product comparison, product or process optimisation, product or process development, *et cetera*. It starts from a long-term forecast of future demand for the product at issue. All factors of production involved are variable and therefore theoretically included in the system model. It is suggested to separately record process data for erection/dismantling (capital equipment) and operation. It facilitates the adaptation to changes in lifetime production of the process under analysis. Furthermore, the production of capital equipment for processes is excluded in situations where no new (compensation) investments are made.

Decisions with a very long-term time horizon are modelled in a *Very Long Run* LCI. Such an LCI must rely on scenario about future political, social and environmental situations. Thereby, the accuracy with which a future status is prognosticated is much more important for the reliability of LCA results than the exact way how this future status is reached. For instance, the information that the energy required by a certain process will be halved within twenty years from now is more important than the information whether this value is reached linearly or in discrete steps in the course of the years.

### Private Consumption, Dividends and Subsidies

The allocation problems related to factors of production usually not considered in LCA, i.e., labour and related to that, private consumption, paid-out profits, taxes and subsidies are discussed. For LCA purposes like for most macro-economic models it makes no sense to entirely allocate private consumption to the labour provided by the worker, because such a system model would show no physical output. The relative relevance of private consumption of employees depends on the allocation factor, and the labour intensity and environmental impacts of the respective economic sector. Its (partial) inclusion in the LCA of products leads to reduced differences in the energy intensity of products.

No allocation problem exists between the products of a firm and its paid-out profits. One entails the other but they are situated on different levels. In contrast to paid-out profits, an allocation problem exists in respect to subsidies received. Because subsidies maintain the production of elsewise shut-down or downsized facilities, an allocation of requirements and emissions between the product and the subsidies received is necessary. It may be interpreted as an allocation between private and public consumption, between individually paid products and unpaid services to the common[7].

---

[6] See, e.g., Azapagic (1996).

[7] The preservation of recreation areas by means of cultivating forests by foresters is an example for such an unpaid service.

### Context-specific Joint Product Allocation

Allocation in joint production is required for the determination of the environmental performance of jointly produced goods and services sold to different customers, and for the valuation of a firm's inventory. In joint product allocation, no physical causalities are available to accordingly attribute requirements and emissions. That is why, other forms of causalities such as social causality are required. Under the assumption that environmental aspects are considered in the decision-making of firms, social causality shall cover environmental *and* economic information. For that purpose, the disutility function described above is used as the allocation parameter. The context within which allocation is needed is discriminated according to the number of decision-makers involved. Allocation approaches for a single and a multiple decision-maker situation are defined (see Tab. 2).

| production | Context | Market type | Method | Objective |
|---|---|---|---|---|
| Combined [1]) | | | e.g. linear programming | reflect physical causality |
| Joint [2]) | Single decision-maker | reasonably working | multiobjective optimisation | enviro-economic competitiveness |
| Joint | Single decision-maker | monopolistic | constrained optimisation | price-output optimisation |
| Joint | Multiple decision-maker | - | game theory | enviro-economic fairness |

Tab. 2: Joint product allocation approaches and their objectives depending on the decision-making and economic context (market type). They are applicable for the three system model types Short, Long, and Very Long Run.
[1]): Outputs produced in variable proportions; [2]): Outputs produced in fixed proportions.

In the *single decision-maker* situation, a further subdivision is made in relation to the market. Either the single decision-maker produces for reasonably working or for monopolistic markets. In the former situation, the allocation is made according to the "enviro-economic competitiveness" of the joint products. The allocation factor is chosen such that all products show the best possible economic *and* environmental performance (i.e., show lower "social" costs) compared to competing products. In the latter situation, the single decision-maker is able to optimise his or her production by means of the price of the joint products. This may again be done based on "social" costs, if the sales of joint products are assumed to be elastic in relation to private costs *and* environmental performance.

In the *multiple decision-maker* situation, fair allocation factors are negotiated. Fair allocation factors are required when voluntary coalitions are formed and when environmental externalities occur[8]. For such cases, a game theoretic approach is applied.

### Case Studies

*National electricity mixes:*
The environmental performance of the various electricity generating and heating systems used in the case studies, is determined based on an adapted version of the Eco-indicator 95. Knowledge from recent externality studies carried out in the European Union and the United States is used to update and extend the original valuation method. The main changes are made in consequence of the knowledge about a much higher relevance of the health effects caused by particulate matter (primary as well as sulfate and nitrate aerosols). Furthermore, three different $CO_2$-damage cost scenario are introduced and ionising radiation is included as an additional impact category. The Eco-

[8] Examples where a fair allocation is due are the erection of a dam used by different parties for electricity generation, irrigation, flood control, and drinking water supply, or the use of polymer wastes in cement production.

indicator points are converted to "environmental external" costs by assuming that the maximum annual environmental external costs in Europe amount to 10% of the European gross domestic product.

The differences between a physically- and an economically-based system model are shown based on the annual average Swiss national electricity mix. While the difference between the two models in terms of individual impact categories may reach about 25%, it is less than 10% in terms of "environmental external" costs.

Furthermore, the marginal base-load electricity generating technology is determined based on private, "environmental external" and "social" costs. Depending on the criterion applied and on the level of the environmental exchange rate, another technology proves to be the cheapest and the most expensive one. The example of small-scale electric heat pumps shows that the forecast about the development of electricity consumption and supply may influence the outcome of an LCA. When assuming an increasing electricity demand, additional electricity generation is predominantly provided by low-cost gas-fired power plants. The "social" costs of useful heat from electric heat pumps is in this case low compared to heat from competing heating systems. If however, electricity demand is assumed to decrease in the future, expensive power plants would be shut down. In that case, the "social" costs of useful heat from heat pumps would be worse compared to useful heat from natural gas-, wood- or light fuel oil-fired boilers. Both assumptions lead to consistent system models, and the question about the adequate marginal power generating technology is therefore left to political discussions about scenario on the future development of electricity demand.

Finally, a marginal electricity mix for the Long Run system model is proposed based on the forecast of investments and planning in the European electricity supply industry. According to this forecast, more than 60% of additional annual electricity production until 2010 is generated in power plants fired with natural and derived[9] gas. Fossil power plants together produce more than 75% of total additional electricity. With the dominance of natural gas in the marginal electricity mix, the forecast confirms the disutility function and the environmental impact assessment method applied to a considerable extent.

*Combined heat and power production:*
The small-scale gas-fired spark ignition engine analysed is used for district heating in combination with light fuel oil peak load boilers. An electric heat pump additionally converts a part of the losses from the engine into useful heat. The spark ignition engine is considered as a joint production process on which several allocation approaches and allocation parameters are applied.

First, it is assumed that the production of one of the joint outputs (either heat or electricity) avoids its production elsewhere by means of another technology. Hereby, negative emissions may occur which reflect the net savings achievable with the change from a single-function system (e.g., a light fuel oil boiler) to a multi-function system (the CHP plant). This so-called "avoided burden"-approach is just a special case of common allocation approaches when applying one-dimensional objective functions such as private or "social" costs. The same result may be achieved with negative allocation factors for one joint product and allocation factors above one for the other. With such allocation factors, cross-subsidies from the latter to the former occur.

[9] Such as gasworks gas, coke oven gas and blast furnace gas.

Second, economic and arbitrary physical parameters are applied for the allocation of purely joint processes. Private and "environmental external" costs for heat and electricity from the CHP plant are compared to the respective costs of several potential marginal electricity generating technologies such as an average Italian heavy fuel oil power plant or a coal-fired pressurized fluidized bed combustion (PFBC) power plant, and to different heating systems. CHP plants are economically competitive in comparison to existing fossil fueled and nuclear power plants in combination with natural gas boilers. The private costs of CHP plants are about equal to the private costs of heat from natural gas and the proceeds received from the utilities for selling the electricity (redelivery tariff). In terms of "environmental external" costs, the CHP plant is competitive compared to existing fossil-fired and nuclear power plants. Applying higher $CO_2$-damage costs, gas-fired gas combined cycle (GCC) power plants and nuclear power plants combined with natural gas- or wood-fired boilers produce at lower "environmental external costs" than CHP plants.

Third, context-specific allocation is performed for a single and a multiple decision-maker situation. "Social" costs is used as the allocation parameter. A low and a high $CO_2$-damage costs scenario with the environmental exchange rate equal to one and two, respectively are discerned. The CHP plant is enviro-economically competitive compared to existing fossil power plants combined with natural gas-fired boilers but also compared to nuclear power (low $CO_2$-scenario) and to an advanced hard coal-fired technology (PFBC). The advanced gas-fired technology (GCC) in combination with natural gas-fired boilers produce at slightly lower "social" costs compared to the CHP plant.

In these comparisons, a high level of variability and uncertainty is involved. The private costs of the different systems depend on the interest rate, on the load factor, the life time and the energy costs, *et cetera*. The environmental external costs are uncertain in relation to the damage caused by a certain emission, its monetisation (e.g., damage costs of global warming) but also in relation to the valuation of future damages (discount rate applied). The variability and uncertainty in the data qualify the generalization of the conclusions from both case studies.

## Conclusions

The thesis shows that Hypothesis 1, namely to set up the LCI system model according to economic information, leads to a consistent and feasible methodology capable of representing changes within the economic system. The disutility function introduced and applied on marginal power plants in a Long Run LCA proves to be accurate for the representation of default decisions (the choice of a technique required for all processes involved in a product system). However, refinements are needed in terms of quantifying environmental damages, in terms of its aggregation with private costs as well as in terms of including social aspects. The context within which joint product allocation is performed (single or multiple decision-maker) proves to be a suitable discriminating criterion. This approach can cope with conflicting value choices and we judge it to be superior to existing stepwise allocation procedures. The thesis provides guidance for the choice of scope-dependent system models, and of context-specific joint product allocation procedures. Different generic LCI databases are required to represent the different scopes of an LCA relevant in decision-making. Because joint product allocation is carried out in a context-specific way, only one adequate set of allocation factors per multi-function process exists. The number of datasets required for decision-making may therefore be limited to three, i.e., the Short, the Long and the Very Long Run system model.

# PART I:

# INTRODUCTION

# 1.Motivation, Objectives and Hypotheses

## 1.1Inconsistencies in Life Cycle Inventory Analysis

Some months ago, I stumbled over a paradoxical statement made by Augustin. It describes a rather strange situation:

> "From a purely statistical viewpoint", the poet said, "being a non-smoker, I could smoke for about seven years longer than a smoker".[1]

The poet starts with a boundary condition ("being a non-smoker") which he readily violates in the second part of the sentence ("I could smoke ..."). It might be true that a non-smoker may enjoy a longer life of about seven years compared to the life of a smoker. But it is impossible by definition that the *non*-smoker would enjoy *smoking* during his longer life. With his inconsistent train of thought, the poet describes a - maybe - desirable but unreal situation.

Violations of initial boundary conditions is a problem also encountered in Life Cycle Assessment (LCA). Models of economic activities are usually established based on today's situation in relation to technology, society, law and economy. Static models are used to compute emissions and resource consumption of the life cycle of alternative goods or services, and to determine the environmental impacts. Based on this, the most ecologically efficient good or service is evaluated. However, as soon as the outcome of such an LCA is translated into action, the underlying system conditions may change substantially if not entirely. Decisions may therefore be inappropriate as long as the effects of such decisions are not (or not sufficiently) represented in the LCA system model. While many LCA textbooks and theses cover the field of descriptive or *ceteris paribus*[2] LCAs, emphasis is put here on how to represent changes in Life Cycle Inventory Analysis (LCI).

In this thesis, improvements of the LCI system model are developed to make it more consistent with decision-making. We particularely focus on

- the set-up of LCI system models,
- the representation of decisions and value choices made by actors (e.g., firms) involved in a product system, and on
- the system representation of changes within the economic system.

Inconsistencies in these fields may lead to wrong indications or to suboptimal solutions. By removing or at least diminishing them, the predictive power of LCA is strengthened.

## 1.2Towards Consistent LCI System Models

### 1.2.1Introduction

The methodological improvements are made within the structure of the Life Cycle Assessment framework as described in the ISO standard 14040 (Anonymous 1997a). The thesis deals in particular with methodological aspects within the second phase of Life Cycle Assessment, the

[1] Augustin (1997), (originally in German: *"'Rein statistisch betrachtet', sagte der Dichter, 'könnte ich als Nichtraucher etwa sieben Jahre länger rauchen als ein Raucher.'"*)

[2] *Ceteris paribus* means "other things being equal".

Inventory Analysis (see Fig. 1.1). Inventory Analysis is related to and influenced by the other phases of the LCA and by the economic system under analysis.

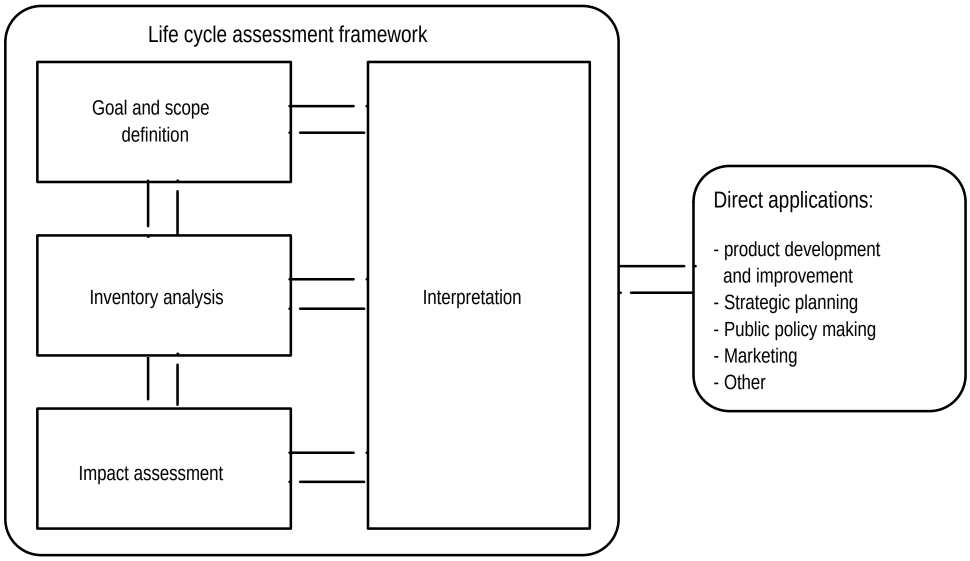


Fig. 1.1: Phases of a Life Cycle Assessment according to ISO 14040 (Anonymous 1997a, p. 10).

Because the behaviour of the economic system can not be verified by means of experiments, an epistemological approach is chosen and three hypotheses are formulated which cover some of the main influences.

First, the need for congruence between the structure of the part of the economic system under analysis and the inventory model is postulated (Hypothesis 1). Second, environmental issues are assumed to exercise an influence on the way how actors within the economic system under analysis decide (Hypothesis 2). This influence may, for instance, be caused by direct applications of LCA or by environmental policy and legislation. Third, emphasis is put on the interrelations of the Inventory Analysis and the preceeding Goal and Scope Definition phase. Hereby, the need for scope-dependent inventory models is postulated (Hypothesis 3).

LCI system models for decision-making will be designed based on these hypotheses. The accuracy of the models will be reasoned on a theoretical level and partly tested on case studies.

### 1.2.2How to Set up an LCI System Model

As a reaction to physically incomplete system models designed and used by economists, natural scientists have seeked after alternative ways to represent economic activities in relation to their natural environment. One of the first I am aware of was Patrick Geddes, a Scottish biologist and economist, whose exposé "On the Classification of Statistics and its Results" published in 1882 contains a description of the

> developmental history of any given product (which is in many respects analogous to that of an organism),[3]

a description of the life cycle of products. He tried to combine economics with natural sciences such as physics, geology, botany, and zoology. He emphasized the close relationship between economy and the natural sciences and proposed to name them physical, geological, botanical, and zoological

[3] Geddes (1882, p. 312)

economics because of the sociological properties within these scientific disciplines. Geddes states that

> the change is no mere verbal one, but involves a radical alteration of the point of view and the mode of treatment, and indeed demands the handing over of these subjects to other cultivators.[4]

Unfortunately, he did not specify what kind of "other cultivators" he meant. I anticipate that he thought about interdisciplinary scientists and, maybe, about LCA, if such an instrument did already exist at that time. Geddes suggests in "An Analysis of the Principles of Economics", presented during a subsequent session of the Royal Society of Edinburgh, to describe the economic activities in physical terms:

> The apparatus and the processes of social activity have to be observed and classified with an equal eye towards minuteness of detail and extent of generalisation; they must, moreover, be expressed in terms of physical science.[5]

He deplores that economic theories remained unaffected by modern knowlegde gained in physics and biology, and pleads to look at

> (...) society as a machine, in which all phenomena are interpreted as integration or disintegration of matter, with transformation or dissipation of energy, (...).[6]

Nearly one century after Geddes, the same principle is considered appropriate to represent economic processes by Georgescu-Roegen. He writes:

> The question before us is whether there is some other mode of describing analytically a process, a mode that is both manageable and adequate in the sense that it does not leave out any essential factor. And the wear and tear, this work of the Entropy Law, is such a factor.[7]

But to exclusively focus on the physical aspects of economic processes as, for instance, the International Standard on Life Cycle Assessment ISO 14040 does, stating that the product system is a

> collection of materially or energetically connected unit-processes which performs one or more defined functions,[8]

bears some pitfalls. Such a system model may deviate from a system model based on economic information[9]. But which model represents reality in a more adequate way? Shall we stick to physical information because we know that economic information failed to accurately consider environmental impacts? Or shall we rely on economic information because money is the medium which causes actions ("money is power")? We postulate that LCA should complement economic information which implies a system model set-up that follows as far as possible the structure of the "real" economic system.

*Hypothesis 1:*

[4] *Op. cit.* (p. 312)
[5] Geddes (1884, p. 950)
[6] *Op. cit.* (p. 955)
[7] Georgescu-Roegen (1971, p. 219)
[8] Anonymous (1997a, p. 7)
[9] In such a model, single economic processes are still described in physical units such as kg, kWh, kBq, et cetera. However, the links between single processes is established according to the way of coordination between them (i.e., markets, contracts, hierarchies).

The set-up of the system model used in Life Cycle Inventory Analysis follows economic information, in order to more adequately and more completely represent the "real" economic system, and its causalities.

### 1.2.3 How to Model Decisions in Life Cycle Inventory Analysis

In the Life Cycle Inventory Analysis of changes, the analyst has to model decisions with regard to the choice of a technique and to joint product allocation[10]. In both decision situations mere economic information may be applied assuming that firms tend to maximise profits[11]. However, we take the view that an LCA is carried out in order to get *additional* insights into the performance of a firm's products or services, i.e., concerning their environmental performance. That is why, we judge the use of mere economic parameters to choose a technique or to allocate requirements and environmental impacts to joint products to be too limited. Our aim is therefore to include environmental information besides of economic information for the representation of decisions required in modelling the changing economic system.

A process network of a good or service comprises hundreds of economic processes. Each of these processes is embedded in particular legal, political and social environments. That is why the decision criteria with which a technology will be chosen varies from one economic process to the other. Furthermore, one particular firm knows in advance only the outcome of decisions they exercise influence on. This makes it practically impossible for the LCA analyst to anticipate, for instance, the marginal technologies of all economic processes involved in the process network that are put in or out of operation because of a change in demand. Therefore simplifications are indispensible.

When requirements and emissions of production processes are allocated to their joint products, a kind of valuation scheme, an objective function is needed. In many LCA textbooks as well as in the Draft International Standard ISO 14041 (Anonymous 1997b), economic value is proposed as one alternative. However useful such economic parameters are in the context of mere economic considerations such as inventory costing or transfer pricing, we question their justification in the context of LCA. With an LCA, the firm's objective function is enlarged compared to mere economic considerations by adding environmental to monetary information. Hence, if a firm includes environmental aspects into their decision-making, we plead to consider the same aspects within allocation procedures in the inventory analysis too. Summing up, Hypothesis 2 may be formulated as follows:

*Hypothesis 2:*

Objective or disutility functions of firms including private costs *and* environmental information are applied in Inventory Analysis in order to more adequately represent changes within the economic system.

### 1.2.4 How to Represent Changes within the Economic System

In reasonably working markets, firms are able to choose the cheapest techniques or suppliers[12] for additional requirements, and to quit contracts with the most expensive ones when they reduce their requirements. Such a behaviour relies on the assumption that firms seek to maximise profits and therefore try to minimise their costs of production. If changes in the production or sales volumes occur, the actors in the economic system will adjust by either changing the capacity load of existing

[10] Joint products are produced in fixed proportions (cf. Section 7.1.2).
[11] As, for instance, the gross sales value method, which is frequently used in joint product allocation (see Appendix 1).
[12] Among equal offers, and in terms of private costs.

facilities, or by commissioning new or decommissioning old ones. The adaptations take place "at the margin"; the major part of existing production facilities are hardly influenced by such changes, at least as long as the changes remain moderate compared to the installed capacities. Therefore, an LCA which analyses a change shall reflect these adaptations "at the margin". We judge it more adequate to leave the strict *ceteris paribus* assumption and to assume a system model with the necessary changes having been made (*mutatis mutandis*). This allows for the modelling of the relevant changes within the economic system, i.e., the change in capacity loads or in installed capacity. Hence, either marginal behaviour of running facilities (the variable part of requirements and emissions), or marginal technologies or technology mixes (the ones commissioned or decommissioned, respectively) shall be considered when analysing changes. We therefore formulate the third, twofold hypothesis as follows:

> *Hypothesis 3:*
>
> In an LCI that represents the effects of a change within the economic system, processes are represented by their variable material, energy and service flows (marginal behaviour), and/ or by technologies or technology mixes put in or out of operation (marginal technology mixes).
>
> The time perspective of the decision at hand is the characteristic to discriminate between different system models.

### 1.2.5 The Scope of the Hypotheses

LCA is used for several purposes. It is applied for environmental reporting and environmental management systems in firms, for product or process development, for eco-labelling, and even for long-term (energy) policy. Hence, the aim to develop consistent LCI system models shall rely on a classification of the purposes of an LCA for which the hypotheses are formulated.

- *Hypothesis 1* describes a fundamental procedure of how to set up an LCI system model. Therefore it shall be generally valid for all LCA purposes from documentation to comparative assertion and product and process development.
- *Hypothesis 2* deals with the disutility or objective function for the choice of a technique and joint product allocation used within an LCI system model. In principle, the disutility function proposed is applicable independent of the LCA's purpose. However, the choice of a technique to be represented within LCI is only relevant for LCAs of changes.
- *Hypothesis 3* postulates a procedure how to represent an economic system which undergoes a change (either due to a change in consumption pattern or volume, or in production technology). It therefore shall only concern LCAs of changes, i.e., comparative assertion, product and process development, long-term (energy) policy, and the like.

## 1.3 The Way Towards Consistency

The derivation of consistent LCI system models relies on knowledge from several scientific disciplines. For the following reasons, the main emphasis is put on knowledge from political economy and management sciences: First, LCA information is assumed to complement economic information. Second, the quantification of damages to nature and humans as performed in this thesis partly relies on data from studies about environmental externalities. Third, LCA aggregates information of entire life cycles, is effective on the micro-level and delivers comparative information on products, processes and the like, similar to the price system of market economies, and forth, methodological aspects in LCA are identical with aspects dealt with in economics.

*Political economy:* The valuation of ecological services and damages to humans arising therefrom, as described in Chapter 8, is influenced by the quantification of environmental external effects. While the theory of externalities originates from political economy, the quantification of environmental external effects requires extensive knowledge in natural sciences, such as atmospheric, aquatic and environmental chemistry, biology, epidemiology, *et cetera*. Political economy is further used for considerations about the inclusion of private consumption in LCA system models (Chapter 6) which is based on knowledge gained with macro-economic models.

*Management sciences:* Predominantly, the objects analysed in an LCA are goods or services, processes or firms. Hence, one main domain of LCA provides information for decisions to be made by firms. That is why methodological concepts are borrowed from management sciences and micro-economics. First, the representation of a process, be it "refining oil in western European refineries", "refining light fuel oil in refinery X", or "atmospheric destillation of crude oil in refinery X", takes pattern from the classification made in cost accounting (Chapter 3). Second, a firm's decisions are classified according to the degree of freedom in adjusting the factors of production (short-, long-, and very long-term) and LCA system models are discriminated accordingly (Chapter 5). Third, the assumption that firms seek to maximise their profits is applied to the problem of the choice of a technique (Chapter 5) and of joint product allocation (Chapter 7) under altered economic conditions (where environmental external effects are included).

Due to this variety of cradles this thesis emerged from, it has been unavoidable that the terminology used cannot always meet all requirements of the scientific disciplines involved. It inevitably leads to a mixture of terms which makes it difficult to classify this thesis into one particular discipline. However, I have tried to minimise misinterpretations by explaining ambiguous terms. The main contribution of this thesis lies in the combination and operationalisation of disciplinary knowledge rather than in the further development of such knowledge.

# 2.Synopsis

## 2.1System Model Design

In Chapter 3, Hypothesis 1 about how to represent processes in the system model is discussed and verified. Hereby, emphasis is put on the complementary feature of LCI by taking pattern from economic information of the "real" economic system. In Chapter 4, an environmental exchange rate is introduced according to Hypothesis 2. The exchange rate allows for a variable weighting of environmental information in relation to private costs. The valuation concept developed quantifies the "enviro-economic competitiveness" of comparable goods and services. It is used, on the one hand, in the set-up of the system model which is capable of representing changes in the economic system induced by changes in consumption patterns, consumption level or technological changes. On the other hand, joint product allocation is performed based on this parameter. By explicitely introducing aspects of valuation into the Inventory Analysis, further aspects of inter-subjectivity enter this phase. In Chapter 5, Hypothesis 3 is evaluated. The disutility function is applied on the choice a technique and the features of different system models which are able to represent changes are derived. These system models are discriminated according to the time scope of the decisions to be made (i.e., short-, long-, and very long-term). Among others, questions about the inclusion of capital equipment (short-term) as well as about the need of quasi-dynamic analyses (very long-term) are treated. In Chapter 6, selected general system boundary and allocation problems such as the inclusion of the environmental impacts induced by salaries and paid-out profits are treated. It follows Hypothesis 1 and the general procedure derived therefrom. Chapter 7 is dedicated to one particular case in allocation, namely joint production. The disutility function is applied here as the allocation parameter. A context-specific distinction is made in view of the number of decision-makers involved. The concepts of "enviro-economic competitiveness" and "enviro-economic fairness" are introduced.

## 2.2Case Studies

In Part III, the feasibility of the system models designed is tested with case studies on the electricity supply industry. In Chapter 8 the valuation concept which allows to aggregate environmental impacts and private costs to one-dimensional indicators is introduced. It is achieved by merging knowledge from studies about environmental external costs with information from a fully aggregating valuation method used in LCA (Eco-indicator 95). National electricity mixes are discussed depending on the scope of the decision at stake (Chapter 9). It is further evaluated whether a complete change in the system's behaviour (due to the change in the disutility function for all processes involved in the process network) leads to substantially different results compared to a system modelled according to the status quo situation of today's economy (Subchapter 9.4). In Chapter 10, the example of combined production of heat and power in small-scale gas-fired spark ignition engines is used to illustrate the context-specific allocation approaches for joint production introduced in Part II (Subchapters 10.3 and 10.4).

## 2.3 Conclusions

In Chapter 11, the hypotheses introduced in Chapter 1 are revisited, and conclusions are drawn. It also contains a critical review of the methodologies developed in this thesis. A guide for system model design, i.e., for the choice of an adequate, scope-dependent system model for the analysis of changes and for the choice of an adequate, context-specific joint product allocation method is given in Chapter 12. Chapter 13 contains an outlook with suggested future LCA research topics.

## 2.4 Appendices

Appendix 1 contains a description of several allocation approaches used in cost accounting. In Appendix 2, recent studies about damage costs are described and the details of the impact assessment method Eco-indicator $95^{RF}$ applied on the case studies are documented. In Appendix 3, the detailed private cost data used in the case studies are shown.

# PART II:

# SYSTEM MODEL DESIGN

# 3. The Production Function and Process Networks

## 3.1 Motivation and the Guiding Principle

### 3.1.1 Introduction

In this chapter, the principle how to model a single, individual process and how to connect them to process networks is described. The system model for individual processes takes pattern from cost accounting, and the flows from and to the process are classified according to the direction of the monetary flows. In line with this approach, process networks are set up according to the monetary flows between individual processes. This contradicts to the approach described in the ISO Standard 14040 (Anonymous 1997a) where systems are interpreted as a collection of materially and energetically linked processes. It also implies the investigation whether to include activities not (yet) considered in LCA such as the authorities' activities or the activities induced by the distribution of dividends. This aspect will further be treated in Chapter 6. In the last Subchapter, the matrix approach used in the Life Cycle Inventories of Energy Systems ("…koinventare von Energiesystemen", Frischknecht et al. 1994/1996a) and also used in this thesis is described and illustrated.

### 3.1.2 From the Motivation to a Guiding Principle

It is a common knowledge that the production or delivery of goods and services causes damages to the natural environment which may diminish the ecological services provided by nature. But the price of goods and services does not reflect the use of ecological services, like energy resources, fresh air to breathe, fresh water to drink, or the absorption and purification of waste streams, because ecological services are free goods. However, free goods will be wasted or used inefficiently. Even worse, free use of vital common goods - and ecological services *are* bare necessaries of life - will sooner or later lead to the ruin of a society as a whole, a fact which was impressively brought to a broader public by Garrett Hardin in his article "The Tragedy of the Commons" (Hardin 1968).

Standard economics uses to represent the economy as a circular system. Producers (enterprises) deliver goods and services at certain prices to the consumers (households), which buy and consume these commodities and sell their work, or more generally spoken, their factors of production to the producers. This perception implies "a circular flow between production and consumption with no outlets and no inlets", "an isolated, self-contained and ahistorical process", as Georgescu-Roegen (1971, p.2) formulated it. There is only reversible motion and a circular flow, and no recognition of irreversible (entropic) change. But where do material and energy needed for the production of goods and services come from, where do wastes and waste heat go to? From physics we know that the entropy of any isolated structure or system increases constantly and irrevocably.

Hence, to maintain the functioning of a system, a source of low entropy and a sink of high entropy are needed. This fact may be observed in any living organism. It needs two kinds, two levels of supply systems:

*a)* a circular transportation system (e.g., blood circulation) which supplies the cells (consumers) with oxygen and nutrients and carries off carbon dioxide and slags.

*b)* a unidirectional supply system which relies on low entropy food and converts it to high entropy excreta while extracting valuable matter. It supplies the circular transportation system with substances of low entropy, i.e., oxygen and nutrients.

The same holds true for all manmade organisms, from a central heating system to entire societies or nations. Our world economy relies on sources of low entropy exclusively received from the sun, and extracted from nature (ecosystem), which are converted to wastes of high entropy, released to nature and dissipated to the universe (see Fig. 3.1).

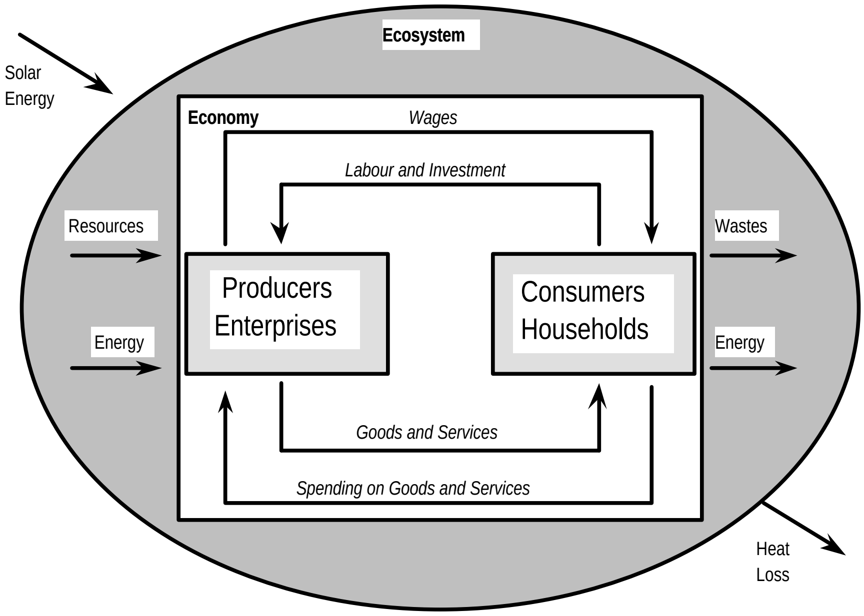


Fig. 3.1: The perspective of ecological economists: the ecosystem provides the economy with low entropy resources (material and energy) and absorbs high entropy waste streams.

Instruments such as energy accounting or Life Cycle Assessment are developed in order to overcome the deficiency of the price system of market economies. Spreng (1988), for instance, interpretes energy accounting as a complement to monetary accounts. He writes:

> Energy accounting can be a useful complement to economic analysis at the boundaries of the economic system, where energy flows enter and leave the system. Two kinds of energy account are particularly useful - energy resource account and waste-heat account. Both types measure something that can only be dealt with inadequately by economic accounts, if it can be dealt with at all.[1]

LCA as described, e.g., in Heijungs et al. (1992a&b), Braunschweig et al. (1993), Consoli et al. (1993), Huppes (1993), Lindfors et al. (1995c), or Anonymous (1997a) is a methodology used for the environmental assessment of goods (products and services), and companies. LCA is used to determine their emissions and resource requirements, and subsequently their potential environmental impact or damage. On the basis of this information, life cycle taxes for intermediate and final products may be settled. LCA is situated on the microeconomic level[2]. Hence, it is mainly suited for decision support on the level of management sciences and helps to optimise the allocation of scarce factors of production.

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[1] Spreng (1988, p. 130)

[2] See, e.g., Baumgartner (1987, p. 154), Rubik (1991, p. 103), and Beck et al. (1995) for a detailed classification of LCA and other tools for environmental management.

The fact that ecological services are free goods, and that prices therefore do not allow an efficient and optimal allocation of natural production factors, leads us to the guiding principle underlying the set up of a system model used in LCI in this thesis.

> *Guiding Principle:* LCA complements economic information, expressed in prices for goods and services, and provides information about the damage on the natural environment ("ecological costs") due to activities induced by the consumption of goods and services. In analogy to standard price calculation, "ecological costs" are determined on a life cycle basis.

Because of its complementary character to the existing economic information system, the system model of a Life Cycle Inventory is set up in parallel to the "real" economic system. All money flows to and from an activity, either induced by a firm or an individual, which are connected to the activity analysed are mirrored by relations within a Life Cycle Inventory system model.

Accordingly, the check whether all environmentally relevant activities in relation to the activity, product, or service at issue are considered - considered at all, *and* considered adequately - will be based on the cost accounting of the corresponding firms, business units or individuals[3]. The firm's book-keeping and budget supplies information about business-relations, customers and clients as well as sub-suppliers which helps to *a)* establish the system model relevant for the corresponding firm, business unit or a particular product or service, and *b)* to determine the amounts of intermediate goods, services, etc. needed from sub-suppliers and supplied to customers, respectively.

Based on discussions about a standard cost accounting scheme which shows the relations between physical and financial flows in a firm, an accounting system is developed for LCI system models.

## 3.2 From Definitions to Modes of Process Representation

### 3.2.1 Cost Accounting and Production Functions

For the purpose of modelling unit processes[4] on the level of industrial management, a classification scheme is applied, which takes pattern from cost accounting systems. For a characterisation of (economic) processes in this thesis, the aspects of the means (production factors), and the ends (purpose(s) of the process) are placed into the foreground. However, the ends or purposes of a process should not be limited to the mere output of commodities, but should also comprehend the fulfilment of other objectives of the individual, or of the firm's business plan. These may comprise, e.g., the satisfaction of the demands of shareholders by the achievement of sufficient profit rates, an increase in sales and production, etc., but also aspects of common interest, like the reduction of permanently unemployed persons in the surroundings of an enterprise (MŸller-Wenk 1978, p. 9).

This aspect becomes clear when we look at a standard cost accounting scheme as described, e.g., in Mšllers (1974, p.15ff), shown in Tab. 3.1. The upper part shows the acquisition market on the left

[3] For both the documenting and predicting purposes of an LCA.

[4] A unit process may be a single process within a production facility (e.g., an atmospheric destillation unit in a refinery), a production site or a firm (e.g., a refinery or all activities of a petroleum company). The definition of a unit process is related to the system model used in an LCI. According to ISO 14040 a unit process is the "*smallest portion of a product system for which data are collected when performing a life cycle assessment*" (Anonymous 1997a, p.8).

and the selling market on the right hand side, where the means of production are purchased, and the produced commodities are sold respectively. The lower part, the capital market, shows a similar "give-and-take" structure, in that money as a means of production has to be purchased, and money in the form of, e.g., dividends is paid to the shareholders. The government is a third kind of business partner of the firm, providing subsidies, and collecting taxes.

| **acquisition market** | | **firm** | | **market** |
|---|---|---|---|---|
| | | *combination process*<br>*objective: profitability* | | |
| employees | -> | labour 1) | product 1 | -> client 1 |
| | | | product 2 | -> client 2 |
| plots | -> | working funds | ..... | -> ..... |
| buildings | -> | | ..... | -> ..... |
| machinery | -> | | product i | -> client j |
| equipments | -> | | ..... | -> ..... |
| materials | -> | materials | ..... | -> ..... |
| goods | -> | | ..... | -> ..... |
| services | -> | additional factors of production | product n | -> client n |
| | | *process of payment*<br>*objective: financial equilibrium* | | |
| remunerations | <- | | | <- returns |
| **government** | | | | **government** |
| taxes | <- | | | <- subsidies |
| **capital market** | | cash and readily available money of transfer | | **capital market** |
| interests and discharge of outside capital | <- | | | <- raising of credit (outside capital) |
| dividends and other kinds of distribution of profits (repayment of own capital) | <- | | | <- raising of own capital |

Tab. 3.1: The firm and its flows of goods and money; translated and adapted from Mšllers (1974, p. 17);
1): management, planning, organisation, and object related labour

Let us look closer at the single items listed in this cost accounting scheme. Labour as one main production factor, is further divided in management, planning, organisation, control, and object related labour, the latter belonging to the elementary production factors ("Elementarfaktoren")[5], together with working funds and materials. Management, planning, organisation, and control are so called planning factors ("dispositive Faktoren"). Plots figure under the header "working funds", together with machines, equipments, and buildings, *et cetera*, the latter specifying one part of the capital involved. The third major category of production factors is called "materials", and subsumes raw, working, and auxiliary materials, and semifinished products. Tools are sometimes classified as working funds, sometimes as materials.

In addition and besides the payments for the production factors mentioned above, payments are needed for taxes, interest rates, dividends, *et cetera*. On the other hand, the shareholders may make a payment for an increase of capital, the firm may receive subsidies from the government, or new

5 "Elementary factors" ("*Elementarfaktoren*") are production factors with a direct link to the object of production. The opposite term "planning factors" ("*dispositive Faktoren*"), subsumes production factors, which are needed to combine the elementary production factors to reach the aims of the company (Bloech et al. 1992, p.7ff.)

credits from the credit grantor. These special kinds of services provided by the government, societies, insurances, credit institutes, consulting and testing laboratories, *et cetera*, may be subsumed under "additional production factors". The acquisition of knowledge, legal rights, transportation or the treatment of wastes by a third party also belong to this group.

Consequently, the objective of a process embedded in a firm as shown in Tab. 3.1 is threefold: The first, and in most cases central one is the production or provision of goods and services. Secondly, and thirdly, shareholders have to be satisfied (by paying them dividends), and taxes are paid to the government for common services provided (education, transportation, national security, etc.). The second and third objective are achieved by means of the first one, but the second one steers the first and third one.

### 3.2.2 Existing Models for Production Processes

The structure of cost accounting systems gives a sound foundation for the analytic representation of economic processes, underlying the guiding principle, that LCA information shall complement economic information. I now will try to extend and transform this structure into a comprehensive production function. But first, let us look how existing models analytically represent processes and whether the approaches are suited for my purpose.

In the early seventies, Nicolas Georgescu-Roegen (1971, p. 211ff) developed a procedure for the analytical, physical representation of processes, which starts from the classical production factors (land, labour, and capital), and of which the results relevant for this thesis will be discussed. The main characteristics of his derivation of the production function are documented and summarised in Heijungs (1997, p. 41f).

The production function presented by Georgescu-Roegen (1971, p. 236) differentiates between the direction of flows, namely inputs and outputs, and between their physical characteristic (flow or fund element, between the agents of the process and the elements which are used or acted upon by the agents), as well as between their nature. The purpose of the represented process is indicated with the output flow of products being the only item on the left hand side of the equation. In the final form, his production function looks as follows:

$$\overset{T}{\underset{0}{Q}}(t) = F\left[\overset{T}{\underset{0}{R}}(t), \overset{T}{\underset{0}{I}}(t), \overset{T}{\underset{0}{M}}(t), \overset{T}{\underset{0}{W}}(t); \overset{T}{\underset{0}{L}}(t), \overset{T}{\underset{0}{K}}(t), \overset{T}{\underset{0}{H}}(t)\right] \tag{3.1}$$

In (3.1) $Q$ is the output flow of products, $R$ is the input flow of so-called natural resources, like solar energy and the rainfall but also the 'natural' chemicals in the air and the soil as well as the coal-in-the ground, *et cetera*. $I$ is the input-flow of the materials which are normally transformed into products (intermediate goods), $M$ is the input-flow needed to maintain the capital equipment intact (e.g., lubricating oil, paint, parts, etc.) and $W$ is the output flow of waste, or, with its topical term, pollution (Georgescu-Roegen 1971, p. 281). All these objects (i.e., $R$, $I$, $M$, and $W$) are used up in the process (materials, see Tab. 3.1). Among the funds (or working funds), $L$ is the Ricardian land (an inert element), $K$ represents the capital proper and $H$ the labour power. Furthermore, Georgescu-Roegen stresses the point that a production function should be represented by a functional, considering the time-dependency of each coordinate in the analytical representation of the corresponding process. It highlights that the process has a finite duration, which, in his notation, lasts from $t = 0$ until $t = T$.

We recognise some differences between the items mentioned in the cost accounting scheme (Tab. 3.1) and in the production function (3.1):

*a)* the treatment of resources and emissions,

*b)* the classification of funds and flows, and

*c)* the classification of capital.

*Ad a)* Opposite to Georgescu-Roegen's production function, standard cost accounting scheme neither include emissions nor resources, because they are free of charge. This means, that non-commercial flows have to be added to the items of the cost accounting scheme.

*Ad b)* The distinction of flows and funds made by Georgescu-Roegen depends on the duration of the process at issue. In cost accounting a similar distinction is made, whether a factor of production is used up in one or several production periods, which allows a classification on the basis of relative durations. From the point of view of a research institute for instance, computers may be regarded as a factor of consumption due to their relatively short period of use compared to, e.g., the university building, or even compared to its furnitures. Compared to distinct research projects carried out ("production periods") with the aid of one particular computer it may well be classified as a working fund.

The distinction between material inputs converted to a product and material inputs needed to maintain the capital equipment (the working funds) is less important in cost accounting, because both result in variable costs. One reason for a distinction in Georgescu-Roegen (1971) might be however, that a production process may be sustained on the short-term without maintaining capital equipment. Then, only indispensible variable costs would incur. However, such a production situation cannot be maintained forever due to the entropy law, and a precipitated depreciation of the capital equipment used. Such a situation, which may be rather common in free market competition, is of minor importance in LCA.

*Ad c)* Georgescu-Roegen makes no distinction between capital in the sense of capital goods and monetary capital. Here, the cost accounting scheme is more detailed and differentiates between several categories of capital equipment on the one hand, and several input and output flows of monetary capital from and to the capital market[6].

Heijungs (1997) takes the production function (3.1) as a starting point and reformulates it in view of its use in his methodology of inventory analysis, which deals with the attribution problem[7]:

> Still, it [Georgescu-Roegen's production function] is designed within the context of fairly traditional economics, not of ecological economics. A number of alterations is required to safeguard clarity in the environmental context. These concern:
> *a)* What is comprised by waste?
> *b)* Can materials be an output?
> *c)* Are there waste inputs?

[6] The question, whether the flows induced by financial transaction on the capital market shall be included in LCA will be treated in Chapter 6.

[7] The attribution problem is defined as follows (Heijungs 1997, p.4): "The attribution problem is the question which environmental problems are to be attributed to which economic activities." It is concerned with the problem to find relations between all economic activities happening and all environmental impacts occurring.

*d)* Are there product inputs and maintenance outputs?[8]

His answers to these questions are determined by the physical reception of elements in the production function of Georgescu-Roegen, i.e., their material flows to and from elementary (or unit) processes. Heijungs finally arrives at an analytical representation of a process in the following form:

$$0 = F\left[ G_0^T(t), W_0^T(t); R_0^T(t), E_0^T(t) \right] \tag{3.2}$$

where he discerns the following categories:

*a)* economic commodities: goods (G), wastes (W);

*b)* environmental commodities: natural resources (R), emissions (E).

The left hand side equals to zero because the output flow of product(s), i.e., of functional unit(s)[9], is included in the category "goods". In detail, Heijungs (1997) classifies the following as economic commodities:

> Goods comprise materials, products, services, energy, *et cetera*. They also comprise labour: labour is a flow (or a service) flowing from man, woman, or animal, to a process. (...). Wastes basically comprise goods with a negative value, although this will most often be discarded materials and products. (...). And in this context, economic commodities comprise goods, services, bads and disservices.[10]

On the one hand, Heijungs defines 'goods' indirectly by listing some representatives, including labour, of this category. To consider labour as an economic good like any other output of a process is not undisputed. Even Sraffa (1960) uses different points of view concerning the representation of human labour in his economic models.[11] On the other hand, Heijungs uses a rather stringent economic definition to describe the category "wastes" or "bads". But is this special position of wastes justifiable? Heijungs thinks about treating waste treatment as a service but uses the argument of the completeness of the mass balance to categorise all tangibles (including wastes to be processed) as "goods" or "bads":

> One might introduce waste treatment as a service, but that complicates a consistent representation in the sense that the "bad" waste should be left out, to prevent any double counting. When priority is given to the service over the tangible "bad", we are faced with the problem of incomplete mass balance. It is therefore proposed to express every flow of tangible commodity as a good or a "bad", and to only introduce (dis)services for commodities that are intangible like electricity, light, and music.[12]

However, the distinction between goods and services, between tangibles and intangibles should not be exaggerated, because

> any good is valued because of the services it yields to its owner. In the case of an automobile, for example, the service consists of such things as transportation, mobility, and possibly, status. (...)
> Goods and services are the means by which people seek to satisfy some of their needs and wants. (...) In most societies and for most men, goods (...) are not regarded as desirable in themselves, and no great utility is attached to piling them up endlessly in warehouses, never to be consumed.[13]

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[8] Heijungs (1997, p. 43)

[9] In the ISO standard 14040, the term "functional unit" is described as the "*quantified performance of a product system for use as a reference unit in an LCA study*" (Anonymous 1997a, p. 6).

[10] Heijungs (1997, p. 45)

[11] In open economic input-output models, labour is not included (labour is treated as a non-basic good in such models, see Section 5.4.1 for a definition of basic and non-basic goods), i.e., consumer goods are interpreted as the final end of industrial acitivies. For further considerations of the representation of labour, see Chapter 6.

[12] Heijungs (1997, p. 38, footnote 3)

[13] Lipsey et al. (1972, p. 5)

Furthermore, not only the *mass* balance should be fulfilled in an elementary process. In addition, the energy balance, and the balance of each chemical element should prove right. If we consider electricity as a service, we would, following the argumentation used by Heijungs, face the problem of an incomplete energy balance. Another problem occurs in connection with services linked to a tangible good like transportation services. What is the difference between a product that leaves the production site of a firm to be transported to a further processing step on the one hand, or to an incineration plant on the other? Assume that in both cases the firm has to pay to "get rid of" the product. In both cases money and physical flows (of the intermediate good and the waste, respectively) go in the same direction. Hence, the intermediate good might as well be judged as a negatively priced good! In the terminology used by Heijungs (1997), however, the first would be classified as "service" (transport activity), and therefore as a "good", the second as a "waste".

Moreover, and maybe more relevant in this context, the aim of a complete mass and energy balance may be achieved despite any kind of classification of input and output flows. The balance of energy and mass flows is, at least for tangible energy carriers and their chemical elements, not evident from the representation of a process. If a process needs a certain amount of light fuel oil, the amount is reported either in MJ or kg. Hence, either the mass or energy balance, and, imperatively, the balance of sulphur, nitrogen, nickel, copper, etc. has to be controlled separately. I therefore prefer to look at "waste treatment" as an "additional production factor" (Mšllers 1974, Bloech et al. 1992) and to classify it as a service. This means that discarded materials and products (which are the goods with a negative economic value) are defined in relation to the service needed for their treatment and hence they are classified under the header "service".

This distinction is relevant for co-production. As defined here, a waste incinerator is a multi-output process which delivers the service "treating various kinds of wastes", and the goods "electricity", "district heat", maybe even "building materials". This distinction seems to be more a matter of semantics. But it helps to perceive the co-production aspect of waste treatment and recycling processes similar to "common" co-production processes such as combined heat and power generation.

## 3.3 Commercial and Ecological Commodities and the Purpose of Production

### 3.3.1 General Procedure to Build up a System

For the purpose of system representation in this thesis, a distinction is needed between inputs and outputs, and between interactions with other economic activities and interactions with nature.

The separation of inputs and outputs from and to nature is straightforward, because in inventory analysis, the physical flows and not the ecological services sacrificed by means of these physical flows are reported. There may, however, be identified some special cases, like the extraction of $CO_2$ in biomass growing processes, where "negative emissions" may occur. These will be discussed in Section 3.3.2.

We discriminate between inputs and outputs from and to other economic activities based on the guiding principle (see Section 3.1.2). It is operationalised with the following general procedure, which corresponds to Hypothesis 1:

*General procedure:* The system model is set up according to the financial flows connecting economic processes, disregarding the fact where the commercial commodities *physically* come from and go to. Furthermore, the commercial commodities are discerned according to the direction of the corresponding financial flows disregarding whether they physically enter or leave an elementary process.

The environmental commodities, however, are distinguished according to the direction of their physical flows relative to the process at issue.

This way of analytical representation of a process takes pattern from the structure of the cost accounting system of business units (which may be interpreted as a single process, although it often consists of a cluster of processes). The similarity to economic cost accounting is derived from the guiding principle, that LCA information complements economic information on goods and services.

As a consequence, all (physical and symbolic) objects connected with a financial flow, be it to or from the firm (or a single process), are classified as commercial commodities. All other flows which have no economic value, i.e., they have no price, are ecological commodities[14]. The financial flows of a firm are structured according to their nature as well as to the fact whether they belong to the proceeds or to the spendings (see Fig. 3.2). The main distinction lies in the direction of the money flows, i.e.:

- to the firm (proceeds), and
- from the firm (expenses or spendings).

The aspect of changing assets is taken into account by the fact that the process is represented by a functional (see equation (3.2)).

The expense items are grouped into

- "employees", which covers all kinds of labour needed (from management, planning, organisation, and control, to object related labour);
- "intermediate goods" comprising raw, and ancillary materials;
- "third party services" comprising, among others, insurance rates, transportation, and waste treatment services;
- "depreciation of plant equipment" comprising the amortisation of machinery, and equipments;
- "taxes" comprising emission taxes, etc.;
- "interests on credits, and mortgage"; and
- "distribution of dividend".

The first as well as the last three items, i.e., employees, taxes, interest rates, and dividends are hardly ever considered in today's LCA.

The proceed items are grouped into returns from sales of products and services (including joint, co-, and by-products), raising of credits and own capital, and subsidies. Only the part of the activities

[14] The problem of how to classify pollutants that are charged with a tax (e.g., control tax on VOC emissions) is treated in the next section.

connected to the sale of products and services are usually considered in a standard LCA. Subsidies, and the raising of credits and own capital are omitted in most cases.

This systematic representation of a process guarantees a complete picture of its economic inputs and outputs. It forms the basis for the set-up of the economic part of the system model representing the product system to be analysed. Using actual financial flows of a firm or parts of it, the actually related upstream and downstream processes (with its corresponding firms, its business units or firm mixes), and by that the system model is automatically set up.

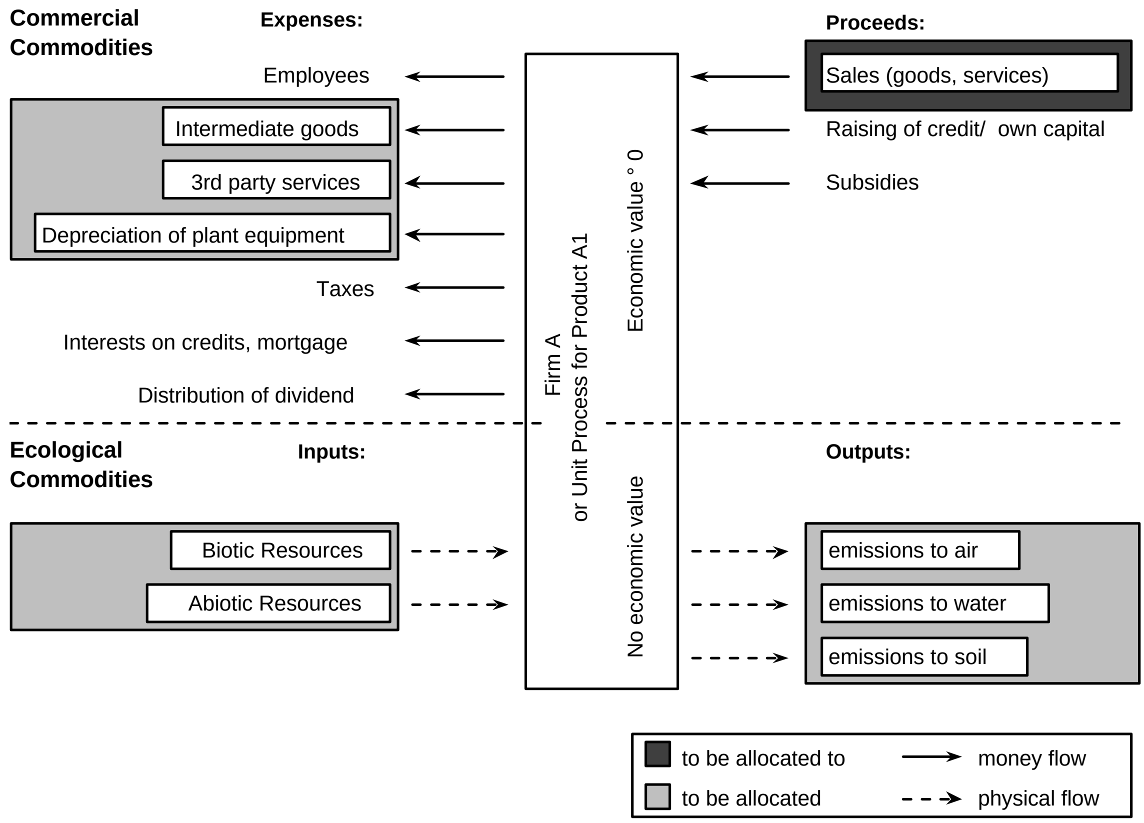


Fig. 3.2: Expenses and proceeds (commercial commodities) and resource consumption and emissions (ecological commodities) of an elementary process which constitutes the economic and the environmental part of a unit process in a system model for Life Cycle Inventory Analysis[15]. The elements generally considered in today's LCA are shaded.

It also makes us think about the environmental relevance of activities induced by financial flows usually not considered until now (see Fig. 3.2). Among these, the reproduction of labour is the most discussed one. Duties of the government (taxes and subsidies), raised credits and own capital as well as interests on credits may also be of some importance. The relevance of these items is discussed in Chapter 6.

Within the category "ecological commodities", a distinction between inputs from and outputs to nature is made. On the input side, a first distinction is made between biotic and abiotic resources and land use, according to Finnveden (1996, p. 40). On the output side, emissions to air, water, and soil are separate categories. Further considerations about this categorisation are made in Section 3.3.2.

[15] For the sake of clarity, no distinction is made between common and separate costs. Plant equipment, for instance, may be used by more than just the unit process at issue.

The analytic representation of an elementary (or unit) process based on a distinction in proceeds and expenses differs from the one developed by Heijungs (1997), given in equation (3.2). In addition, the scaling factor of our production function is represented by the functional unit, whereas Heijungs, and Georgescu-Roegen use the duration of a process (e.g., the calendar year). The independent variable *t*, which in Heijungs (1997, p. 51, and footnote 30) is interpreted as the duration of the process, is replaced by the proceeds of the functional unit $P_{FU}$ of a single process:

$$0 = F\left[ P(P_{FU}), S(P_{FU}); R(P_{FU}), E(P_{FU}) \right] \tag{3.3}$$

where we distinguish the following categories:

*a)* commercial commodities: proceeds (P), spendings (S);

*b)* ecological commodities: natural resources (R), emissions (E).

The production function presented in equation (3.3), is valid for unit processes with one or more than one output that yield proceeds. In other words, it is the production function of the unallocated system. The purpose of the process should be specified, to enable an adequate allocation of spendings, natural resource requirements and emissions to the items of proceeds. Spatial and temporal information about the process, and its technological characterisation are in addition needed to judge the data quality and its applicability for specific purposes. Singhofen et al. (1996), for example, provide a detailed specification of requirements to describe processes.

*Ad a)* Commercial commodities comprise all physical and symbolic objects with a monetary value that flow from and to the process[16]. All kinds of flows connected with proceeds may as well occur in connection with spendings. A kWh electricity purchased by a firm for a certain process has been (or, more adequate, is) produced in a power plant and transported by a utility. Hence, the money flow connects the particular firm with the utility and the utility with the power plant owner. The waste treatment of a certain waste in an incineration plant has been paid for by the firm which "produced" the waste, linking these two companies together (one providing the service, the other one purchasing it). This shows, that, in principle, the only difference between flows of proceeds and spendings lies in their sign. In most of the recent publications about system representation, inputs (proceeds) are noted with a negative, outputs (spendings) with a positive sign[17]. In Frischknecht et al. (1996a, Appendix D), the sign convention is not that stringent. Inputs from nature in the form of resources and from technosphere, and outputs to nature in the form of emissions are positive, the corresponding opposite flows have a negative sign (see also examples in Section 3.3.2).

*Ad b)* A flow of an ecological commodity is a synonym to "elementary flow", defined in Anonymous (1997a), and "environmental intervention", as used, e.g., in Heijungs et al. (1992b, p. iii)[18]. It comprises, on the output side, the release of air- and waterborne pollutants like $SO_X$, $NO_X$, PAH, phenols, radioactive isotopes, *et cetera*, and of pollutants directly emitted to soil (e.g., oil spills of continental pipelines, waste heat from subsoil district heating systems), and of used land.

[16] Either positive or negative from the point of view of the firm (or unit process).

[17] Concerning a short overview of sign conventions in the literature, see Heijungs (1997, p. 42, footnote 5)

[18] An overview of synonyms for "ecological commodity" is given in Heijungs et al. (1996, p. 33). Heijungs (1997, p. 45) uses the term "environmental commodity", Georgescu-Roegen (1971, p. 232) talks about "natural factor of production" in addition to the standard list of factors of production. Daly (1991, p. 78) concentrates on the stock aspect of nature and uses the terms "ecosystem stock" for what is available in nature and "throughput" for that part used by men.

On the input side, stocks or deposits (mineral resources) like iron, nickel, crude oil, hard coal, lignite, and uranium, funds (renewable resources) like wood, rush, and cultivated plants, and flows (e.g., wind, water and sunlight) are included[19]. Land use is mostly perceived as a natural resource (see, e.g., Heijungs (1997, p.45), and represented by a resource inflow (Finnveden 1996, p. 40). If classified in that way, it may also be called "land to be used" in opposite to the output related commodity "used land" (see next section).

The production function may therefore be simplified and written as vectors:

$$0 = F\left[\mathbf{a}(a_{FU}), \mathbf{b}(a_{FU})\right] \tag{3.4}$$

where **a** and **b** are the vectors of cumulative flows of commercial and of ecological commodities, respectively, and $a_{FU}$ is the scaling factor (amount of the functional unit for which the cumulative flows of ecological commodities shall be determined).

### 3.3.2 Resources or Emissions, Commercial or Ecological Commodities, and Market Imperfections

Although the concept and the criteria are rather simple, complications cannot be avoided, and conventions are needed how to consistently treat these particularities. In detail, difficulties occur due to:

*a)* the treatment of land use and transformation,

*b)* input of potential (air) pollutants, and output of potential resources,

*c)* internalised environmental externalities (i.e., pollution taxes on substances), and

*d)* market imperfections.

*Ad a)* The production function in standard economics considers land, sometimes even its qualities and properties (Ricardo, Malthus). If we want to adequately represent land-use in environmental terms, at least six aspects are relevant:

- the amount of surface (the area) affected by human activities,
- the time during which human activities directly affect the area,
- the ecological state of the area before a particular human activity starts,
- the ecological state of the area when it is affected by that particular human activity,
- the ecological state of the area after the human interference, and
- the recovery or restoration period of the area affected to reach a "natural", uninfluenced state again.

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[19] Finnveden (1996, p. 40) defines the terms used for the classification of resources as follows: "The *deposits* (e.g., mineral ores) are resources that have no, or only very limited regrowth possibility within a relevant time horizon (human lifetime(s)), and are therefore depleted when extracted. The *funds* are resources that may, or may not be depleted. When the funds are harvested (either biotic of abiotic funds), they will decrease temporarily, but since they are intrinsically renewable, they will regrow if they are not irreversibly damaged, i.e., harvested in a sustainable way. The *natural flow resources* are continuously flowing resources from which a society can deflect a flow and use the resource. Although the flow resources can be affected by human activities, they are essentially non-depletable by humans." These definitions deviate from the ones of Georgescu-Roegen (1971, p. 220f), who uses the terms "funds" and "flows" in connection with the representation of an economic (unit) process.

Therefore, land use may partly be interpreted as a resource (input, occupation of a certain area) and partly as an emission (output, when this area is left by the activity at issue). Additionally, the temporal aspect of land use is important. In Frischknecht et al. (1992, 1994/1996a), land use (or land transformation) has been quantified adapting a classification introduced in IUCN et al. (1991, p. 34) and classified rather incidentally into the category "resources" (and not, e.g., "emissions to soil", or another, additional output related category). The extent to and the time during which a certain area is disturbed or degraded is recorded on an ordinal scale using several categories of land transformation (see Tab. 3.2), expressed in square meters times occupation or interference time (incl. natural or manmade recovery)[20]. In the mean time, similar methods have been developed by Heijungs et al. (1997a), Knoepfel (1995) and others[21].

| Ecosystem category | Criteria | Land use category |
|---|---|---|
| natural | Ecosystems where human impact (a) has been no greater than that of any other native species, and (b) has not affected the ecosystems structure. | I |
| modified | Ecosystems where human impact is greater than that of any other species, but whose structural components are not cultivated (e.g., naturally regenerating forests). | II |
| cultivated | Ecosystems where human impact is greater than that of any other species, and most of whose structural components are cultivated (e.g., farmland, sown pasture, plantations, aqua culture ponds). | III |
| built | Ecosystems dominated by buildings, roads, railways, docks, dams, mines, and other human structures. | IV |

Tab. 3.2: Land use categories as implemented in the database ECOINVENT (Frischknecht et al. 1992, 1994/1996a), based on IUCN (1991, p. 34).

*Ad b)* From the point of view of human activities, biomass is the natural resource extracted from the ecosystem, although carbon, nitrogen, phosphorus, and other elements as well as sunlight, and water are its ultimate resources. It is questioned therefore, whether "*growing* wood" or "*cutting* wood" should be considered as the resource extraction process. In other words, whether "wood" or its ultimate resources $CO_2$, nitrogen, trace elements, sunlight, water, land, *et cetera*, should be registered as the relevant ecological commodities in the system model. If the latter concept is applied, $CO_2$, for instance, occurs as an emission and as a resource. Heijungs (1997, p. 45) gives further examples and classifies "dumping cadmium in an old cadmium mine" as a "negative resource extraction". Both examples show, that several commodities may occur as a resource and as an emission. The consequences for the inventory model are minor, in that either for certain elementary flows two accounts have to be opened (one for the resource extraction and one for the emission), or that the same account is used for inputs and outputs (hence, negative emissions or resource extractions will occur in the inventory system model). With the former approach, a balance of emissions and resource consumptions and their environmental impacts respectively may be postponed to the impact assessment phase, whereas following the latter concept, the balancing is already performed in the inventory analysis[22].

[20] The very initial state of the ecosystem in a historical or even geological perspective is not relevant for decisions to be taken. The actual state just before the beginning of a (new) human activity is more decisive.

[21] An overview is given in Finnveden (1996, p. 44).

[22] If an a priori balancing (e.g., with negative $CO_2$-emissions) is favoured, care should be taken, that no information needed in the impact assessment phase gets lost. For instance, it should be warranted, that the time dependence of the

In Frischknecht et al. (1994/1996a) the natural process of biomass growing with negative $CO_2$ and waste heat emissions is introduced. This leads to a closed carbon cycle and to balanced energy flows in the inventory table. This concept has not been applied to nitrogen, phosphorus and trace metals, due to the fact that these elements may be released in compounds harmful to human health (besides its nutritive value for biomass). Furthermore, sunlight and water needed in growing biomass have neither been considered.

*Ad c)* In his distinction of economic and environmental commodities, Heijungs emphasizes that:

> The word economic here only denotes the fact that the commodities flow from economic process to economic process. There is no principle relation with monetary criteria. The fact that (flows of) environmental commodities may be charged by the government does not make them economic commodities. For similar reasons, a release to the sewage system is an economic commodity flow because the flow is towards a sewage treatment plant, even if there is no price per litre effluent.[23]

However, following the guiding principle formulated in this thesis, of LCA being a complementary instrument to standard economics, commercial commodities *are* the ones with a monetary value. The release of a pollutant (or environmental commodity) for which a tax is charged by the government (e.g., $CO_2$-emissions in Norway, or VOC-emissions in Switzerland) causes activities within the country's administration. Hence, the emission of a pollutant *per se* is still an ecological commodity but accompanied by an additional process "taxation of 1 kg pollutant emitted", which will include requirements of electricity, heat, printing paper, and other commodities typical for government activities (or, in particular, the taxing authority). Hence, a sharp distinction between the release of a pollutant and the "service" paid with the pollutant's tax should be made. The emission of 1 kg pollutant shall still be recorded within the representation of the process releasing it. A similar analytic procedure is applied with the commercial commodity of land acquisition and renting. If firm A buys or rents a plot from firm B, the ecological commodity of land use is registered within firm A, but an additional process covering a share of the administrative activities of firm B is added to the product system.

*Ad d)* Free discharge of wastes towards treatment facilities (e.g., free discharge of waste water into a sewage system) means, that this treatment is financed with the tax yields of the government and not on the basis of a causality principle. The (general) taxes are paid, among others, by the firm producing and getting rid of the waste. If we therefore would follow mere monetary information, not the *actually* caused environmental damages due to the waste water stream were attributed to the firm, but a (small) share of a mixture of ecological commodities caused by the manifold activities paid or subsidised with tax yields (i.e., infrastructure build-up, waste treatment, health care, military, etc.).

In such cases, where the classical economic system does not follow the causality principle, i.e., where the market fails, the system model described here will imperatively show the same shortcoming. In such cases, the general procedure must be abandonned and physical flows become relevant to determine the relation between processes.

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damage function of pollutants, and the differences in physical properties of potential resources may adequately be considered. In the $CO_2$-example, a time lag of several decades to centuries between the growing of a tree and the burning of its wood may be important in view of the effects of $CO_2$ on global climate change. In the cadmium example, the concentration of the cadmium dumped may differ from the average cadmium concentration of ores actually exploited, an aspect which may be relevant in the characterisation of resource consumption.

[23] Heijungs (1997, p. 44ff., footnote 13)

However, one has to keep in mind that a mere correction on the level of *environmental* externalities by modelling the physical flows according to the causality principle only removes one part of externalities. Some enterprises may still profit from *financial* externalities (e.g., free discharge services).

### 3.3.3 The Role of Monetary Information

The proposal to distinguish between commercial and ecological commodities and to use monetary flows as a key information, when setting up a system model, rises the question about the relation between physical and economic information. It may seem rather strange, that a physically oriented tool like LCA, which should complement economic information, seems to rely substantially on just this economic information. Therefore, some clarifying words concerning the role of monetary flows within the inventory system model are needed.

The first, and most important information monetary flows are able to provide is the information about economic relations[24]. From the cost accounting of a firm we know, where it buys its commodities and services to which government taxes are paid, *et cetera*. We know from contracts, that firm A buys its electricity from utility X, polymers from firm Y, and waste treatment services for production wastes from firm Z. Whether the *amount* purchased expressed in physical units may also be derived from these contracts, or whether physical units are more feasible mainly depends on the kind of good.

The bill paid or fashioned for electricity, gasoline, natural gas, lubricants, or boilers purchased may easily be converted from Swiss francs or any other currency into kWh, kg, $Nm^3$, or units respectively, whereas the conversion of money paid for a waste treatment service, an insurance rate or a consultancy into a physical "currency" is less straightforward. Because in some cases - especially in the tertiary sector - it is difficult to quantitatively and qualitatively measure services, the scale of charges of the corresponding institution is applied as the measuring unit (Dellmann 1980, p.33). These units of course mirror the measure used for the commercial outputs, the functional units. In most cases, additional information is needed to correctly model the relation between two economic entities whatever "currency" is used. For an adequate system representation of electricity use, the voltage, the frequency, and the course of demand (daily, weekly, or yearly) of electricity is needed in addition to the mere kWh. Gasoline, for instance, should be further specified in terms of its chemical composition (e.g., hydrocarbons, trace elements) and its physical properties (e.g., heating value) for an adequate description of its emission behaviour.

Similar to this, additional information is needed in the case of services. The extent to which a waste is eliminated or rendered harmless in a waste treatment process not only depends on the technology applied but also on the physical and chemical properties of the waste to be processed. The measure of the service itself, however, may be chosen rather arbitrarily. The facts that wastes are nearly always tangibles, that their relevant properties are related to mass, and that prices for waste treatment services fluctuate very much, mass terms may be the most suitable measure for this kind of service. Finally, consultant's services are specified in terms of knowledge successfully transferred, or the accomplishment of a planning task, *et cetera*. A civil engineer may minimise the requirement of reinforcement steel by some additional expenditure on planning. Because the volume of such

[24] Markets, contracts and hierarchies establish these relations.

tasks is independent of any tangible measuring unit like mass, or volume, working hours are preferable.

To summarise, the main purpose of economic information lies in establishing links between economic entities dealing with commercial commodities, and not in indicating how much of such a commodity is transferred between them. In special cases however, like services delivered by the tertiary sector (consultants, banking institutes, insurances), money may be an adequate and suitable measure.

### 3.3.4 The Linearity Assumption of the Production Function

The system model of the LCI database on energy systems developed by Frischknecht et al. (1994, 1996a), is based on linear relationships. And also Heijungs (1997) bases his methodology for the solution of the attribution problem on linear relationships between the analytical rate of production and the analytical rate of emission, and between the analytical rate of emission and the analytical environmental impact. This linear attribution principle satisfies the following three requirements:

- The results of the analysis should be insensitive to the order in which economic activities are analysed.
- The results of the analysis should be insensitive to the amount of economic activity that is analysed.
- The results of a separate analysis of all economic activities should add up to the result of an analysis of the total economic activity.[25]

According to Heijungs, these requirements are suited for the question to attribute all current environmental problems to all current economic activities. However, they also apply for the question to attribute all *additional* environmental problems to all *additional* economic activities (the planning problem, see Chapter 5). The first requirement implies that there is no ranking order within additional economic activities or classes of activities. All additional economic activities are equally important or useful for humans on the one hand, and in terms of responsibility for certain additional environmental problems on the other. According to this requirement, the decision about an installation of any additional source of $NO_X$, be it a wood chips boiler, or an additional traffic lane, would be taken similarly, especially in areas with a critical $NO_X$ immission level. The environmental impacts of an additional kg $NO_X$ would be the same, presumed the same location and time of emission.

The second requirement implies that all units of production of an economic activity are equally responsible for the environmental problems caused by the total amount of that economic activity. This requirement may also be assumed for the planning problem. These assumptions are questionable, as on the one hand, larger production volumes show the effect of scale which results in a higher productivity (in terms of money, but also in terms of labour and the other production factors). On the other hand, higher emissions due to higher production volumes may result in an over proportional increase of environmental problems caused. To simplify matters, scale independence is assumed also for the planning problem.

The third requirement, also called 100%-additivity, implies that all economic activities related to final consumption and all environmental problems, or damage caused by these activities happen within the period of observation (e.g., one year). This requirement strongly abstracts from the time lag between final consumption and its related production processes, and between economic activities and environmental problems caused by these activities.

Heijungs justifies this neglect with the argument, that

> [...] the economy-environment system can be considered to be in a more or less stationary state: a quasi-stationary state so to say. A similar assumption is very often made in economic modelling, where equilibrium models are successfully used while growth and innovation to some extent violate the basic assumptions of suchlike models.[26]

[25] *Op. cit.* (p. 17)
[26] *Op. cit.* (p. 15, footnote 7)

For *economic* equilibrium models this assumption may hold true. But for an economy-environment model, this is a rather crude assumption in two respects. For instance, the time-lag between consumption and production, and the dramatic improvement of the environmental performance of industrial facilities such as fossil power plants, or coke plants in Germany within a few years do not fit into such a quasi-stationary state assumption. Furthermore, and Heijungs admits this, there is a time-lag between economic activity and environmental problem. Some environmental problems increased dramatically within the last decade, and some of them will further increase, although the economic activities that caused and cause the problem are reduced to a small size (i.e., production and use of ozone depleting substances). Some environmental problems may up to now only be anticipated. Within the relevant time period, no "real world" experimental verification is and will be available for decisions about the economic activities which may cause these anticipated environmental problems (e.g., final depository of highly active nuclear waste). This time-lag may be overcome by attributing the *anticipated* instead of today's environmental problems caused by today's economic activities. The quantification of environmental impacts by means of external costs as described in Chapter 8 is one attempt in this direction.

In both the attribution and the planning problem case, the 100%-additivity escapes experimental verification. While it is possible to get a picture of all emission sources in a region at a certain time and to combine these data with data about, for instance, critical loads of acidifying and nutrifying pollutants[27], such a procedure is not practicable when emission sources are tied to process networks on the basis of responsibilities like in LCA. The structure and the sum of all ongoing economic activities during, let us say, 1996, do not coincide with the structure and sum of economic activities induced due to, e.g., the total of final consumption in 1996. To overcome the time-lag between final consumption and its related production processes, a time stamp for each economic process would be needed. The system model would then comprise several economic processes producing the same good or delivering the same service but at different time periods (e.g., railway transport in Europe in 1998, 1999, ..., 2009, *et cetera*). However, the set up of such a system model would require a very large amount of additional information about the technical development of all these processes and of the time period when these processes would be required.

We may conclude, that the three requirements stated for the analysis of a current situation, which is used to attribute economic activities to environmental problems, may also be applied for an analysis of a change in the current situation (where additional economic activities are attributed to additional environmental problems). In line with Heijungs (1997), I will therefore also assume linear relationships in the production function developed for unit processes in Section 3.3.1.

All process data are referred to one unit of the functional unit (see equation (3.4)). Other processes will then require a fraction or a multiple of that functional unit. This approach deviates from the concept of the duration of a process introduced by Heijungs (1997, p.50), because the latter may lead to unreal or misleading figures. The artificial, analytical "duration of a process" of Heijungs should not be confounded with the real duration of a process. The real duration of a process may remain the same for every whatever tiny fraction of a batch of production. For instance, the transportation of a wagon-load of product X from firm A to firm B takes the same amount of time like any small fraction of that wagon-load. It does not last half as long just because only half of the wagon-load is required within the system to be analysed (cf. Hofstetter 1996a, p. 101). Hence, the

[27] This has been achieved, e.g., in the six-year IIASA study on acid rain in Europe (cf. Alcamo et al. 1990).

full duration of the process (the time needed to reach firm B starting from firm A) is still needed but only half the amount of ton-kilometres. The functional unit, in this case ton-kilometres, will generally be a sensible reference variable.

This alteration is a minor one, because both approaches rely on the same data, although they deviate by a constant factor with a time dimension. The production function of equation (3.4) may therefore be written as being proportional with the functional unit[28]:

$$\mathbf{a}(a_{FU}) = \tilde{\mathbf{a}}\frac{a_{FU}}{\tilde{a}_{FU}}; \quad \mathbf{b}(a_{FU}) = \tilde{\mathbf{b}}\frac{a_{FU}}{\tilde{a}_{FU}} \tag{3.5}$$

The vectors $\tilde{\mathbf{a}}$ and $\tilde{\mathbf{b}}$ contain technical coefficients (the amounts of commercial and ecological commodities needed and released respectively) normalised per unit output of the functional unit. Equation (3.5) already shows the dependence of ecological commodities on the amount of wanted output, or functional unit produced. The notation given in equation (3.5) are brought together in a process vector $\mathbf{p}$:

$$\mathbf{p}(a_{FU}) = \begin{pmatrix} \mathbf{a}(a_{FU}) \\ \mathbf{b}(a_{FU}) \end{pmatrix} = \tilde{\mathbf{p}}\frac{a_{FU}}{\tilde{a}_{FU}} = \begin{pmatrix} \tilde{\mathbf{a}} \\ \tilde{\mathbf{b}} \end{pmatrix}\frac{a_{FU}}{\tilde{a}_{FU}} \tag{3.6}$$

The vector $\mathbf{p}$ comprises the flows of commodities needed and released to produce a fraction or a multiple of the functional unit. Single entities of commercial commodities are indexed with the subscript i, of ecological commodities with subscript j. The total number of commercial commodities is denoted with m, of ecological commodities with n.

$$\mathbf{p} = \begin{pmatrix} a_1 \\ \cdots \\ a_i \\ \cdots \\ a_m \\ b_1 \\ \cdots \\ b_j \\ \cdots \\ b_n \end{pmatrix} = \begin{pmatrix} \tilde{a}_1 \\ \cdots \\ \tilde{a}_i \\ \cdots \\ \tilde{a}_m \\ \tilde{b}_1 \\ \cdots \\ \tilde{b}_j \\ \cdots \\ \tilde{b}_n \end{pmatrix}\frac{a_{FU}}{\tilde{a}_{FU}} \tag{3.7}$$

The subscript FU denotes the functional unit or intended output among all commercial commodities from 1 to m. All commodities flowing to and from the process are normalised by $\tilde{a}_{FU}$, the amount of the intended output of the process. Hence, with $a_{FU}$ being the variable external demand of the intended output, $a_{FU}/\tilde{a}_{FU}$ is the dimensionless scaling factor of the process vector[29].

To illustrate the process vector, the example of lime production as represented in Frischknecht et al. (1996a, Appendix A, p.55) is used (see Tab. 3.3). Process data of the unit process "calcination of limestone" is presented. Commercial commodities (ten in total) are the functional unit "lime

[28] The duration t introduced by Heijungs (1997, p.50ff.) is also given by $t = a/\tilde{a}$, because Heijungs registers data as flows (per unit of time).

[29] In cases of combined or joint production, the scaling factor $a_{FU}/\tilde{a}_{FU}$ may be applied on the allocated process vector. In these cases, several production vectors exist.

(CaO)", energy carriers (i.e., coal, natural gas, electricity, heavy and light fuel oil), water, limestone, and services (i.e., transportation by lorry, waste treatment in a landfill for inert materials). Ecological commodities (three in total) are waste heat, particulates and $CO_2$, all released to air. All commodities are linearly dependent on "lime (CaO)". They will double, if 2 kg of lime are required instead of one.

This form of linear and fixed ratios between the output of the functional unit and all other commercial and ecological commodities implies that no commercial input may be replaced by any other one. The production factors are fully non-substitutable and any de- or increase in output of the functional unit implies a proportional de- or increase in output or input of every single ecological and commercial commodity.

| **per kg** | **Unit** | Lime (CaO) |
|---|---|---|
| *Commercial commodities:* | | |
| Industrial coal boiler 1-10 MW | TJ | -2.8á10$^{-6}$ |
| Natural gas in industrial boiler >100kW Euro | TJ | -2.2á10$^{-6}$ |
| Electricity medium voltage - supply in UCPTE | TJ | -1.3á10$^{-7}$ |
| Heavy fuel oil, Euro in boiler 1 MW | TJ | -7.6á10$^{-8}$ |
| Light fuel oil in boiler 1 MW | TJ | -1.5á10$^{-7}$ |
| Water | kg | -1.1 |
| Lime (CaO) | kg | 1 |
| Limestone | kg | -2.0 |
| Transport lorry 40 t | tkm | -4.0á10$^{-2}$ |
| Wastes in landfill for inert materials | kg | -0.182 |
| *Ecological commodities:* | | |
| Waste heat in air | TJ | 1.3á10$^{-7}$ |
| Particulates | kg | 0.018 |
| $CO_2$ carbon dioxide | kg | 0.88 |

Tab. 3.3: Commercial and ecological commodities needed and released when 1 kg limestone is calcined. Signs have been adapted according to the conventions introduced in Section 3.3.1. Data are commented in Frischknecht et al. (1996a, Appendix A, p.54ff.)

The example shows the representation of a unit process with its *in situ* emissions. To reach a complete LCI of a commercial commodity like lime, process networks have to be established. In the next subchapter, the representation of such process networks and its properties will be described. Differences between *in situ* and life cycle considerations are explained based on the responsibility principle.

## 3.4 Commercial Commodities and Their Process Networks

### 3.4.1 Causality Ties Process Networks

In the last subchapter the production function for single (elementary or unit) processes is deduced, taking pattern from cost accounting schemes and physically based system representations developed by Georgescu-Roegen (1971) and Heijungs (1997). Linear relationships between the output of the functional unit of a unit process and all other ecological and commercial commodities are assumed. These single processes will be combined to process networks in order to determine caused flows of ecological commodities. For that purpose, the representation of process networks and its arithmetic procedure will be introduced.

The intention behind the description of LCA is to identify the environmental impacts which are caused by a certain product and its product system. Heijungs uses the term "attribution" to emphasise the epistemological foundation of his theory of attributing environmental problems to economic activities. His basic idea is the revelation of causalities of and responsibilities for environmental problems, or, in other words, the search for the instigators of environmental impacts (Heijungs 1997, p. 3).

Due to the fact that in most cases two perspectives have to be distinguished, namely the perspectives of the

- causing social entity, and of the
- affected social entity,

the aspect of causality will imperatively be discussed controversially. Linneweber (1997), for instance, points out that

> actors generally are interested in presenting themselves in the position of being affected by activities of other social entities - in other words presenting themselves as victims.[30]

Causing social entities tend to deny the causality between an environmental damage and their activities, and their responsibility for certain activities or environmental problems. LCA has to take two hurdles in view of its application in negotiations:

*a)* negociating parties have to agree on the responsibility concept[31], and

*b)* negociating parties have to agree on an analytical, epistemologically founded approach to represent causalities.

*Ad a)* This is a condition which lies outside of further methodological developments in LCA. Either one agrees on the responsibility concept, and then a life cycle approach and LCA is one possible technique, or not. This hurdle will not be discussed further.

*Ad b)* To represent causality, different approaches exist and are applied. Because none of these approaches is experimentally verifiable, it is impossible to judge between good and bad, but it is possible to judge between adequate and inadequate solutions. As expected, discussions about diverging conclusions due to different system models underlying the LCA of the same products are rather frequent. There are two central questions in this respect, namely:

- Should the system network which represents the product system be built up according to monetary or physical flows? Considerations about and answers to this question as well as an operationalisation in terms of a general procedure are given in Subchapter 3.2.
- Should the analysis of a change in the economic system (which may be assumed in the case of a comparative assertion) only consider additional activities and environmental impacts (marginal approach), or use the average of all (present and additional) activities and environmental impacts (average approach)? This aspect is elaborated in Subchapter 5.1.

I leave for the moment the question how to adequately choose process relations, and will turn to the deduction of the mathematical model to represent process networks.

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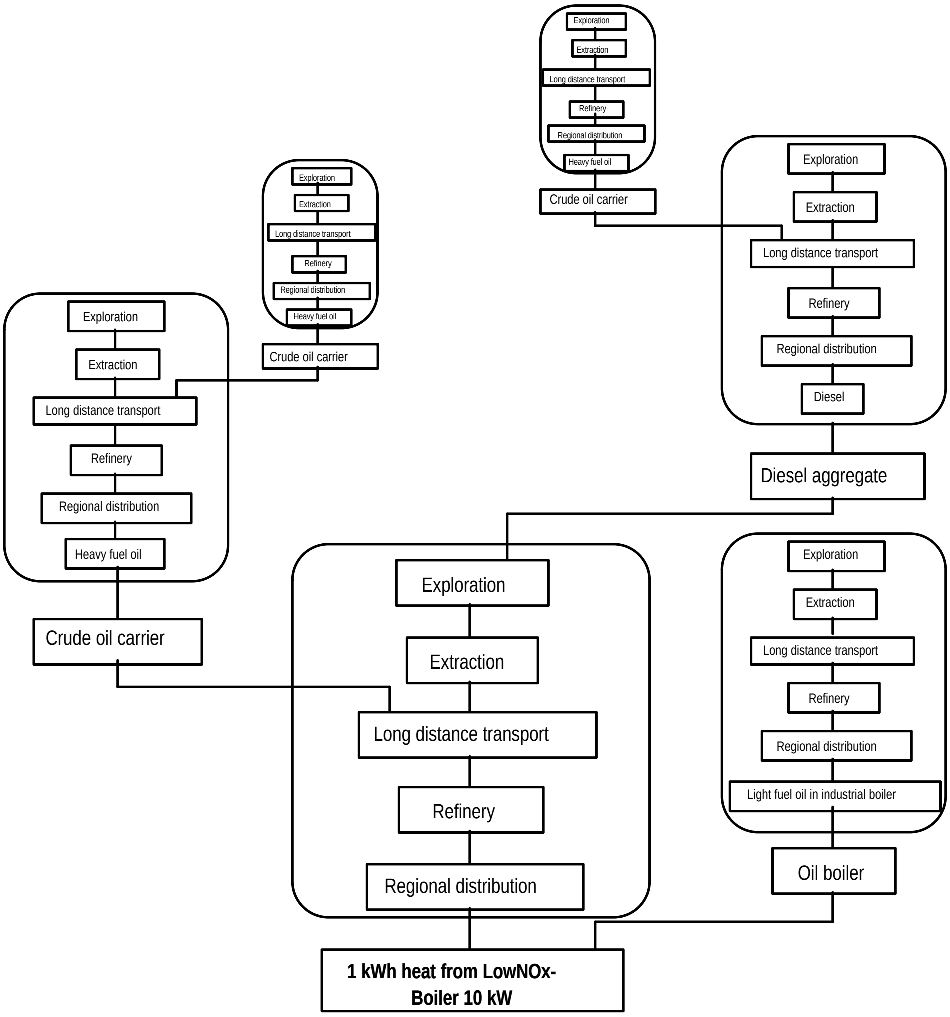
[30] Linneweber (1997, p.4)

[31] In this thesis, the responsibility concept is operationalised by setting up the LCI system model according to the economic relations between actors (e.g., firms).

### 3.4.2 From Trees to Networks: The Matrix Approach

An individual economic process is embedded in a vast number of preceding, simultaneous, and following economic processes. To a few of them, it is related directly by business relations (contracts or purchase/sale). To all the others, it is related only via other processes and actors. The intensity of these indirect relations varies between practically inexistant to even stronger than a direct relation. For basic commodities[32] one of these rather weak relations is the one of the product system to itself (feedback loop). For instance, a power plant which needs concrete for additional flue gas treatment equipment may provide the electricity for the production of the cement needed in concrete production. Such kinds of feedback-loops are widespread in economy. They should therefore be considered in LCA system models which represent parts of the economic system. However, the figure in the recently published draft of ISO 14041 (Anonymous 1997b, p. 5) suggests, that energy and transportation activities do not depend on commodities produced in other economic sectors, like agriculture, basic chemistry, building industry, *et cetera*. But every power plant relies on transport and waste treatment services, building and working materials, and other commodities, which on their turn partly rely on the energy supplied by - among others - exactly this power plant. The interrelations lead to infinite process trees in which identical sequences occur in several parts of several branches (see Fig. 3.3).




32 See Section 5.4.1 for the definition of basic and non-basic commodities.

Fig. 3.3: Excerpt of the process network of the delivery of 1kWh useful heat from a LowNOx light fuel oil boiler, shown as a process tree; adapted from Frischknecht et al. (1995a, p. 80).

For instance the crude oil carrier is needed to transport crude oil from the oil well to the refinery. It uses heavy fuel oil which is co-produced in the refinery. In Fig. 3.4, these two processes are shown in a simplified version with selected flows of commercial and ecological commodities. Each process needs a certain amount of the other one as an input. This means that a tiny share of the heavy fuel oil refined is used up by the crude oil carrier which transports the crude oil, the feedstock to produce that heavy fuel oil in a refinery.

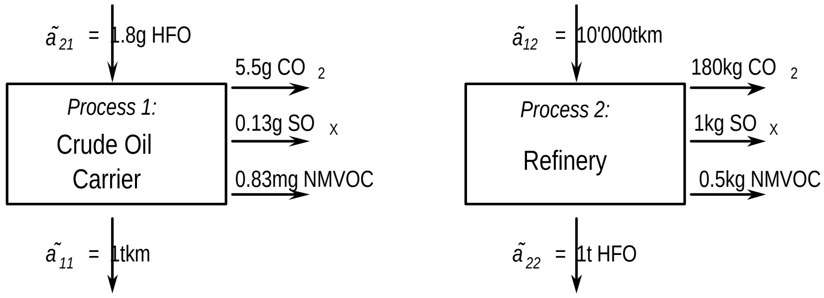



Fig. 3.4: Simplified unit processes "1tkm transport service with a crude oil carrier" and "1t heavy fuel oil (HFO) produced in a refinery".

For $\tilde{a}_{22}$ or 1 ton of heavy fuel oil (HFO), a transportation service of $\tilde{a}_{12}$ or about 10'000tkm with a crude oil carrier is assumed to be needed. On the other hand, a crude oil carrier needs about $\tilde{a}_{21}$ or 1.8g heavy fuel oil per $\tilde{a}_{11}$ or 1tkm (Frischknecht et al. 1996a, Part IV "Erdšl", p. 125). A feedback loop occurs which makes the system theoretically infinite (see Fig. 3.5). Equation (3.8) shows the formula for the total amount of heavy fuel oil needed ($a_{22}$) when 1 ton of heavy fuel oil is produced. Due to the feedback loop, it has the structure of a geometric series.

$$a_{22} = \tilde{a}_{22} + \tilde{a}_{21}\tilde{a}_{12}\tilde{a}_{22} + \tilde{a}_{21}\tilde{a}_{12}\tilde{a}_{21}\tilde{a}_{12}\tilde{a}_{22} + \tilde{a}_{21}\tilde{a}_{12}\tilde{a}_{21}\tilde{a}_{12}\tilde{a}_{21}\tilde{a}_{12}\tilde{a}_{22} + \ldots \tag{3.8}$$

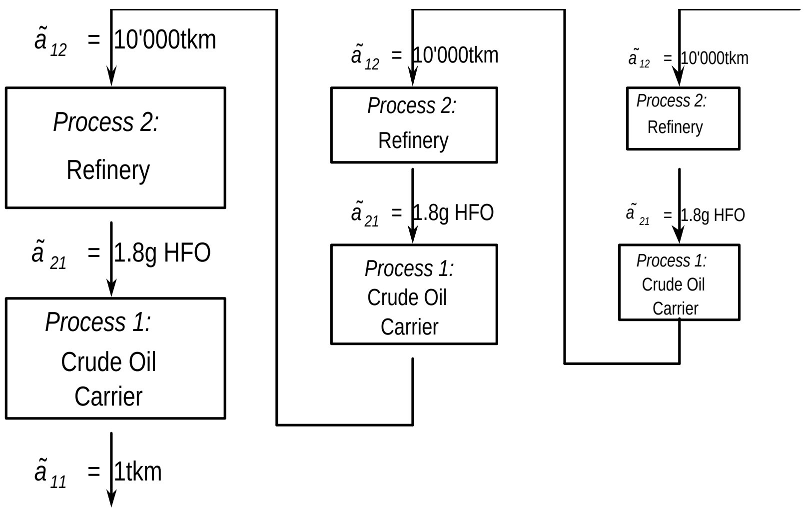



Fig. 3.5: The (simplified) product system or process network for "1tkm transport service with a crude oil carrier".

The geometric series may be rearranged and written in its closed form:

$$a_{22} = \frac{\tilde{a}_{22}}{1 - \tilde{a}_{21}\tilde{a}_{12}} \tag{3.9}$$

The commercial flows between these two processes as well as selected ecological flows are listed using the same structure as in Tab. 3.4. We recognise the matrix structure introduced by Leontief and used for the analysis of the relations within economic sectors (e.g., Leontief (1985)). In LCA, this approach has first been presented by Heijungs et al. (1992b, p. 52ff.), and used in Frischknecht et al. (1994) for large LCA databases, i.e., the energy systems' database "…koinventare von Energiesystemen" ("Life Cycle Inventories of Energy Systems").

| | | Transport by Crude Oil Carrier | Heavy Fuel Oil from Refinery |
|---|---|---|---|
| | unit | tkm | t |
| *Commercial Commodities:* | | | |
| Transport by Crude Oil Carrier | tkm | 1 | -10'000 |
| Heavy Fuel Oil from Refinery | t | -1.8á10-6 | 1 |
| *Ecological Commodities:* | | | |
| $CO_2$, Carbon dioxide | kg | 5.5á10-3 | 180 |
| $SO_X$, Sulphur oxides | kg | 1.3á10-4 | 1 |
| NMVOC | kg | 8.3á10-7 | 0.5 |

Tab. 3.4: Commercial and ecological commodities needed and released for "1 tkm transport services with a crude oil carrier", and for "1t of heavy fuel oil produced in a refinery". Data are not complete and are not intended to represent real cases.

All process vectors of a product system are combined to a production matrix $\tilde{\mathbf{P}}$, composed of the technology matrix $\tilde{\mathbf{A}}$ representing the flows of commercial commodities between processes $\tilde{a}_{il}$, and the intervention matrix[33] $\tilde{\mathbf{B}}$ representing the flows of ecological commodities to and from the environment $\tilde{b}_{jl}$.

$$\tilde{\mathbf{P}} = \begin{pmatrix} \tilde{\mathbf{A}} \\ \tilde{\mathbf{B}} \end{pmatrix} = \begin{pmatrix} \tilde{a}_{11} & \dots & \tilde{a}_{1l} & \dots \\ \dots & \dots & \dots & \dots \\ \tilde{a}_{i1} & \dots & \tilde{a}_{il} & \dots \\ \dots & \dots & \dots & \dots \\ \tilde{a}_{m1} & \dots & \tilde{a}_{ml} & \dots \\ \tilde{b}_{11} & \dots & \tilde{b}_{1l} & \dots \\ \dots & \dots & \dots & \dots \\ \tilde{b}_{j1} & \dots & \tilde{b}_{jl} & \dots \\ \dots & \dots & \dots & \dots \\ \tilde{b}_{n1} & \dots & \tilde{b}_{nl} & \dots \end{pmatrix} \tag{3.10}$$

Here and in the system model used for the energy systems' database it is assumed, that there are as many sets of equations as commercial commodities (m) and that for each commercial commodity, the external demand equals one for the functional unit (the respective commercial commodity) and zero for all the others. This results in a set of m sets of equations within the technology matrix. It is an extension of the first fundamental equation introduced by Heijungs (1997, p.59),where only *one*

[33] The terms "technology matrix" and "intervention matrix" are used in line with Heijungs (1997). The first term has been defined in the early fifties, the latter has been created by Heijungs (1994).

set of external demand, and therefore one set of equations is used. For illustrative purposes, the set of equations for the economic process (functional unit) "2" is presented here:

$$\begin{aligned}
\tilde{a}_{11}\frac{a_{12}}{\tilde{a}_{11}}+\tilde{a}_{12}\frac{a_{22}}{\tilde{a}_{22}}+\ldots+\tilde{a}_{1l}\frac{a_{l2}}{\tilde{a}_{ll}}+\ldots&=0\\
\tilde{a}_{21}\frac{a_{12}}{\tilde{a}_{11}}+\tilde{a}_{22}\frac{a_{22}}{\tilde{a}_{22}}+\ldots+\tilde{a}_{2l}\frac{a_{l2}}{\tilde{a}_{ll}}+\ldots&=1\\
\ldots&=0\\
\tilde{a}_{i1}\frac{a_{12}}{\tilde{a}_{11}}+\tilde{a}_{i2}\frac{a_{22}}{\tilde{a}_{22}}+\ldots+\tilde{a}_{il}\frac{a_{l2}}{\tilde{a}_{ll}}+\ldots&=0\\
\ldots&=0
\end{aligned}\tag{3.11}$$

Furthermore, the output of the functional unit of every process $\tilde{a}_{ii}$ equals 1, which simplifies the set of equations shown above:

$$\begin{aligned}
a_{12}+\tilde{a}_{12}a_{22}+\ldots+\tilde{a}_{1l}a_{l2}+\ldots&=0\\
\tilde{a}_{21}a_{12}+a_{22}+\ldots+\tilde{a}_{2l}a_{l2}+\ldots&=1\\
\ldots&=0\\
\tilde{a}_{i1}a_{12}+\tilde{a}_{i2}a_{22}+\ldots+\tilde{a}_{il}a_{l2}+\ldots&=0\\
\ldots&=0
\end{aligned}\tag{3.12}$$

This set of equations is combined with all other sets of equations (for all economic processes of the technology matrix) and written in matrix notation:

$$\begin{pmatrix} 1 & \tilde{a}_{12} & \ldots & \tilde{a}_{1l} & \ldots\\ \tilde{a}_{21} & 1 & \ldots & \tilde{a}_{2l} & \ldots\\ \ldots & \ldots & \ldots & \ldots & \ldots\\ \tilde{a}_{i1} & \tilde{a}_{i2} & \ldots & \tilde{a}_{il} & \ldots\\ \ldots & \ldots & \ldots & \ldots & \ldots \end{pmatrix}\cdot\begin{pmatrix} a_{11} & a_{12} & \ldots & a_{1l} & \ldots\\ a_{21} & a_{22} & \ldots & a_{2l} & \ldots\\ \ldots & \ldots & \ldots & \ldots & \ldots\\ a_{i1} & a_{i2} & \ldots & a_{ll} & \ldots\\ \ldots & \ldots & \ldots & \ldots & \ldots \end{pmatrix}=\begin{pmatrix} 1 & 0 & \ldots & 0 & \ldots\\ 0 & 1 & \ldots & 0 & \ldots\\ \ldots & \ldots & \ldots & \ldots & \ldots\\ 0 & 0 & \ldots & 0 & \ldots\\ \ldots & \ldots & \ldots & \ldots & \ldots \end{pmatrix},\tag{3.13}$$

or using matrix symbols where $\mathbf{A}$ is the scaling matrix:

$$\tilde{\mathbf{A}}\cdot\mathbf{A}=\mathbf{I}\tag{3.14}$$

This equation can be solved for $\mathbf{A}$ by inverting the technology matrix $\tilde{\mathbf{A}}$ and postmultiplying it with the matrix of external demand $\mathbf{I}$, the unit matrix:

$$\mathbf{A}=\tilde{\mathbf{A}}^{-1}\cdot\mathbf{I}\,.\tag{3.15}$$

$\mathbf{A}$ represents the life cycle amounts of commercial commodities used directly and indirectly by the commercial processes constituting the technology matrix. The two fundamental requirements on a matrix to be invertible, namely its squareness and non-singularity, and the possible approaches, how the technology matrix can be made square, are discussed *in extenso* in Heijungs (1997, p.63ff.). One of the main reasons, why a technology matrix may be rectangular, is due to the fact that certain processes deliver more than one output (multi-function processes). The allocation procedure for joint production, which helps to make a square technology matrix, and the choices needed for it, is treated in Chapter 7. For a profound description of how to mathematically represent allocation, I refer to Heijungs (1997, p. 80ff.) and Heijungs et al. (1997b).

The intervention matrix $\tilde{\mathbf{B}}$ and the cumulative technology matrix are needed to compute the cumulative intervention matrix, the cumulative resource extractions and emissions of all commercial processes *1* to *m* comprised in the technology matrix. This is achieved by multiplying the intervention matrix with the cumulative technology matrix:

$$\mathbf{B} = \tilde{\mathbf{B}} \cdot \mathbf{A} = \tilde{\mathbf{B}} \cdot \tilde{\mathbf{A}}^{-1} \cdot \mathbf{I} \,. \tag{3.16}$$

The size of cumulative emissions and resource consumptions is dependent not only on the environmental performance of unit processes but also on their technological efficiency. We now have both the cumulative commercial commodities and the cumulative ecological commodities for all unit (or elementary) processes delivering the corresponding commercial commodities:

$$\mathbf{P} = \begin{pmatrix} \mathbf{A} \\ \mathbf{B} \end{pmatrix} = \begin{pmatrix} \tilde{\mathbf{A}}^{-1} \cdot \mathbf{I} \\ \tilde{\mathbf{B}} \cdot \tilde{\mathbf{A}}^{-1} \cdot \mathbf{I} \end{pmatrix} \tag{3.17}$$

While it is not possible to represent actual demand patterns of consumers (the "demand pattern" is represented by the unit matrix, representing a demand of one unit of each commercial commodity) and compute the overall emissions and resource requirements with equation (3.17), it is perfectly suited to efficiently deliver LCA data of a large number of basic commodities, like energy carriers, transport or waste treatment services. After the determination of the cumulative production matrix $\mathbf{P}$, the relation between a certain demand pattern and its associated emissions and resource extractions is easily computed by multiplying a demand vector $\mathbf{d}$ or a demand matrix $\mathbf{D}$ with the cumulative intervention matrix $\mathbf{B}$:

$$\mathbf{b_d} = \mathbf{B} \cdot \mathbf{d} \,, \tag{3.18}$$

and

$$\mathbf{B_D} = \mathbf{B} \cdot \mathbf{D} = \tilde{\mathbf{B}} \cdot \tilde{\mathbf{A}}^{-1} \cdot \mathbf{D} \tag{3.19}$$

respectively. The matrix $\mathbf{B_D}$ is influenced by the demand pattern $\mathbf{D}$, the technological efficiency $\tilde{\mathbf{A}}^{-1}$, and the environmental performance of unit processes $\tilde{\mathbf{B}}$. Improvements in terms of reducing environmental impacts may therefore be achieved on these three levels, a fact that has been recognised by several authors in the past, like Basler (1971, p. 86), or Daly (1991, p. 78). Based on these approaches, ecological efficiency may be defined as a measure for the amount of ecosystem services sacrificed per person. It may be further broken up into five component ratios:

$$\text{ecological efficiency} = \underbrace{\frac{\text{service gained}}{\text{person}}}_{(1)} \cdot \underbrace{\frac{\text{consumption}}{\text{service gained}}}_{(2)} \cdot \underbrace{\frac{\text{throughput}}{\text{consumption}}}_{(3)} \cdot \underbrace{\frac{\text{environmental impact}}{\text{throughput}}}_{(4)} \cdot \underbrace{\frac{\text{ecosystem service sacrificed}}{\text{environmental impact}}}_{(5)} \,, \tag{3.20}$$

In equation (3.20), we may recognise Matrix $\mathbf{D}$ in ratios (1) and (2) together (consumption per person), Matrix $\tilde{\mathbf{A}}^{-1}$ in ratio (3) and Matrix $\tilde{\mathbf{B}}$ in ratio (4). Ratio (5), expresses the damage vector $\tilde{\mathbf{e}}$ which quantifies damages on the ecosystem due to emissions and resource requirements in terms of monetary or physical units (see Chapter 4 and 8).

### 3.4.3 An Example to Elucidate the Matrix Approach

The previous example of a refinery producing and a crude oil carrier using heavy fuel oil will be used to illustrate the use of the formalism deduced. See Fig. 3.4 and Tab. 3.4 for a description of the system. The technology matrix is

$$\tilde{\mathbf{A}} = \begin{pmatrix} 1 & -1.0 \cdot 10^{4} \\ -1.8 \cdot 10^{-6} & 1 \end{pmatrix}, \tag{3.21}$$

the intervention matrix is

$$\tilde{\mathbf{B}} = \begin{pmatrix} 5.5 \cdot 10^{-3} & 180 \\ 1.3 \cdot 10^{-4} & 1 \\ 8.3 \cdot 10^{-7} & 0.5 \end{pmatrix}, \tag{3.22}$$

and the "external demand" matrix is the unit matrix **I**. The inverse of the technology matrix, the cumulative technology matrix is

$$\mathbf{A} = \begin{pmatrix} 1.018 & -1.018 \cdot 10^{4} \\ -1.83 \cdot 10^{-6} & 1.018 \end{pmatrix}, \tag{3.23}$$

and the cumulative intervention matrix is (just showing two significant digits)

$$\mathbf{B} = \begin{pmatrix} 5.9 \cdot 10^{-3} & 240 \\ 1.3 \cdot 10^{-4} & 2.3 \\ 1.8 \cdot 10^{-6} & 0.52 \end{pmatrix}. \tag{3.24}$$

The life cycle emissions of 1 tkm transport service increases by 7%, Å0%, and 116% for $CO_2$, $SO_X$, and NMVOC respectively compared to the *in situ* emissions of the crude oil carrier (see Tab. 3.4). The life cycle emissions of 1t heavy fuel oil produced in a refinery increase by 33%, 130%, and 4% for the same pollutants compared to the corresponding *in situ* emissions. Some additional 1.83% or 18.3kg of HFO are needed for the production of 1t of HFO due to the requirement within its own "product system".

| | | Transport by Crude Oil Carrier | Heavy Fuel Oil from Refinery |
|---|---|---|---|
| | unit | tkm | t |
| *Commercial Commodities:* | | | |
| Transport by Crude Oil Carrier | tkm | 1.018 | -10'180 |
| Heavy Fuel Oil from Refinery | t | $-1.83 \cdot 10^{-6}$ | 1.018 |
| *Ecological Commodities:* | | | |
| $CO_2$, Carbon dioxide | kg | $5.9 \cdot 10^{-3}$ | 240 |
| $SO_X$, Sulphur oxides | kg | $1.3 \cdot 10^{-4}$ | 2.3 |
| NMVOC | kg | $1.8 \cdot 10^{-7}$ | 0.52 |

Tab. 3.5: Cumulative commercial and ecological commodities needed and released for "1 tkm transport services with a crude oil carrier", and for "1t of heavy fuel oil produced in a refinery". Data are not complete and are not intended to represent real cases.

With the matrix notation and an implementation in an environment for numerical mathematics, we are equipped with an efficient tool to calculate life cycle inventories of a large number of processes within a short time (see, e.g., Frischknecht et al. (1995a, p. 88ff.)).

### 3.4.4 Consequences for LCI models

In this chapter the way how to represent unit processes and process networks in Life Cycle Inventory has been described. The major difference between the procedure developed here and the ISO Standard (Anonymous 1997a) lies in the strict application of economic information for the set-up of the system model in the former. This methodology has been applied to a large extent while compiling the Life Cycle Inventories of Energy Systems (Frischknecht et al. 1994/1996a). The set-up of process networks according to economic information has been applied in the inventories for national average electricity mixes in the updated version. How the system models for electricity supply may differ between physically and economically based approaches will further be elaborated in Chapter 9. Paid-out profits, private consumption, subsidies and taxes have been left out in the Life Cycle Inventories of Energy Systems. Their importance in the highly industrialised energy sector is assumed to be minor as will be shown in Chapter 6.

Up to now, we have concentrated on the phase of inventory analysis and the representation of (commercial) processes in terms of energy and material flows. We will now turn to the representation of decisions and value choices in Inventory Analysis used to model changes within the economic system. An approach is developed which allows for a combination of economic and environmental information. The representation of default decisions and joint product allocation are the two applications in the Inventory Analysis where we judge environmental information to be necessary in addition to mere economic data.

# 4.The Disutility Function

## 4.1Introduction

### 4.1.1Decision-Making in LCI System Models

When a firm decides to change its supplier of a particular commodity or to change some of its manufacturing processes, many other related activities are affected by such changes. An LCI system model used for decision making must be able to cope with and represent decisions not only concerning the functional unit at issue but also concerning all processes directly or indirectly linked to it. For that purpose, a simplifying disutility function is introduced which combines economic and environmental information[1]. On the one hand, it helps to model the (in most cases anticipated) behaviour of several hundred decision units comprised in a process network that produces a certain functional unit (a good or a service, i.e., a commercial commodity). Economic and environmental information are in this case used in view of chosing the respective empirical marginal suppliers (see Chapter 5). On the other hand, the disutility function is applied as a parameter for allocation in joint production (see Chapter 7).

Decision problems of firms are mostly multiobjective. And also Life Cycle Assessment usually provides multidimensional information on the environmental performance of a product, be it on the level of environmental impacts such as global warming or acidification, or on the level of safeguard subjects (i.e., human health, ecological health and resources). A number of techniques and tools have been developed to provide answers or to help in multiobjective decision-making processes. A classification of such methods is given in Azapagic (1996, p. 61ff.).

In the (background[2]) process network of a particular product, decisions are made in several hundred firms running the corresponding unit processes. Their representation by the LCA analyst requires a simplifying approach. To enable an easy and automatic modelling of these decisions and allocation procedures, an environmental valuation method is required that aggregates flows of ecological commodities (i.e., emissions and resource consumption) to a single, one-dimensional figure, that is suitable for a further aggregation with economic information. The objective of the disutility function may be characterised with the terms "enviro-economic competitiveness", and "enviro-economic fairness", respectively. The latter is used in joint product allocation where just allocation factors are negotiated between several decision-makers[3].

The decision function is developed on grounds of the requirements to model default decisions needed in the LCI phase. It is by no means intended to take the place of the decision-making process a commissioner of an LCA or its audience is confronted with and for which the outcome of an LCA is used.

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[1] Legal aspects, aspects of social security, or of infrastructure (communication, transport, *et cetera*) influencing, e.g., investment decisions remain disregarded in order to maintain the operability of the approach. By that, the approaches developed here exclude one important dimension of sustainability, i.e., social compatibility (IDARio 1995, p. 23).

[2] See Section 5.3.2 for a description of the terms "foreground" and "background system".

[3] See Section 7.5.2 for a description of this approach.

### 4.1.2 Overview

In Subchapter 4.2 the disutility function used in allocation and system modelling is described and discussed. In Subchapter 4.3, the mathematical model used to compute environmental impacts is described.

## 4.2 Enviro-Economic Competitiveness

### 4.2.1 The Disutility Function

The disutility function used in this thesis is mechanistic and abstracts from a number of important but complicating aspects, in order to be operational. The disutility function is a one-dimensional objective function $z_s$. It is used to determine the option with the lowest private costs and environmental impacts possible among the set $A$ of possible alternatives. The possible alternatives provide the same service (the same functional unit), they are technically feasible and comply with the relevant legislation.

$$z_s^i(z, e, c) = z^i + c \cdot e^i \text{; for } i \in A \text{ with } e^i = k \cdot f^i, \qquad (4.1)$$

In the disutility function $z^i$ are the private or internal costs, and $e^i$ quantifies the environmental damage in monetary units, here called environmental external costs. They are determined by multiplying the environmental damage $f^i$ expressed in arbitrary units of LCA valuation methods such as Eco-indicator 95 with a conversion factor $k$. For the addition of private costs and environmental external costs, the environmental exchange rate $c$ is applied (see Section 4.2.2).

The conversion factor $k$ may be defined with a bottom-up approach on the level of individual pollutants (as is implicitely done by externality studies such as the ExternE projects (European Commission 1995a-f)) or with a top-down approach on a national or international level. In the latter case, the share of costs caused by observed environmental damages on the total gross domestic product of a nation or an economic area (e.g., the European Union) may be anticipated and related to the total flows of ecological commodities in the same area. The latter approach will be followed in the case studies (see Chapter 8).

### 4.2.2 The Properties and Use of the Environmental Exchange Rate

The environmental exchange rate shall express the following aspects:

*a)* uncertainty perception, and

*b)* national environmental policy.

*Ad a)* Massive differences exist in the degree and in the nature of uncertainty between private and external costs. The dispersion models, with which the increase in ambient air concentration of a pollutant is determined, and the impact models where, e.g., the change in crop yield is assessed, still show rather high uncertainties. The weighting factor $c_w$ allows to consider, for instance, different cultural perspectives with which environmental problems and uncertainties related to them are perceived[4]. The uncertainty related to environmental effects and costs give rise to an individualist, a

[4] Cultural perspectives are introduced and used in LCA by Hofstetter (1996b, p. 180) where a summarising description of the three main perspectives, egalitarian, individualist, and hierarchist, is given.

risk-seeking person, to choose a weighting factor between zero and one, whereas an egalitarian, risk-aversive person may tend to add a safety margin.

*Ad b)* In today's economy, environmental damages are hardly monetised and included in the prices of goods and services. Until now, laws and regulations on environmentally relevant aspects of a firm's activities such as emission standards for furnaces, and environmental policies are the only official environmental guidelines for firms to make their decisions[5]. The degree to which environmental external effects are internalised varies from country to country. The influence of different environmental issues and of environmental issues in general on legislation and policy may vary. While for the latter aspect a scalar quantity is applicable, the former would need a vector or the application of country-specific weighting schemes. The vector and specific weighting schemes would allow for a differentiated consideration of a nation's implementation of emission reduction and resource consumption targets. The scalar quantity as well as the individual elements of the vector may be varied between zero (about status quo of today's economy) and one (environmental policy in accordance with the scientific knowlegde about the extent of environmental damages)[6]. For the sake of simplicity we consider here only a *scalar* political factor $c_p$.

That is why, the environmental exchange rate $c$ consists of the two factors, $c_w$ and $c_p$:

$$c = c_w \cdot c_p, \tag{4.2}$$

Special care has to be taken if environmental external costs are already internalised in the form of, e.g., pollution taxes. In such cases, the environmental effects of a pollutant charged with a tax would be considered twice if included in the Impact Assessment. Its environmental impacts are reflected in the price of products that directly and indirectly caused its release, on the one hand, and by the LCA on the other. The release of such pollutants in countries with a comprehensive pollution tax[7] on that pollutant shall therefore not be recorded in an LCA to avoid double counting. The VOC-tax introduced in Switzerland, for instance, is a means for reducing the level of tropospheric ozone immission concentrations. Health aspects of certain hydrocarbons like cancerogenity have not been considered in fixing the level of the tax. Therefore, the policy factor of VOCs for tropospheric ozone formation in Switzerland may equal one.

A firm which uses LCA information in its decision-making processes knows the disutility functions of only a few actors (e.g., firms) related to the production of its goods or services. In most cases just its own objectives are known explicitely. That is why the firm (or, in general, the commissioner of an LCA) must rely on assumptions about the decision functions (objectives) of most other firms. These assumptions will allow the LCA analyst to model how related industries will decide about techniques to be put in or out of operation in the case of a change.

Because environmental legislation and awareness vary among the countries, several different environmental exchange rates may be required in one single LCI system model. But the number of different LCI system models would not increase by that. Per type of LCA (cf. Chapter 5) only one single environmental exchange rate may suffice for a country's processes. If people agree on the level of the environmental policy factor $c_p$ and the weighting factor $c_w$, only one LCI would exist for an additional demand for a certain product in Switzerland. While the environmental policy

[5] In addition to these instruments, voluntary committments get growing attention.
[6] This implies that from the point of view of policy maker, science knows the "whole truth" about environmental impacts. Unavoidable uncertainties shall be covered by the weighting factor $c_w$.
[7] The pollution tax is comprehensive if it covers all environmental impacts a pollutant contributes to.

factor[8] might be determined by political bodies such as the Swiss Parliament, the weighting factor may be chosen based, e.g., on experiences in relation to the behaviour patterns of firms (from risk aversive to risk seeking).

For joint product allocation, the assumption that *all* firms behave according to the principle of enviro-economic competitiveness is not essential. The disutility function is in this case restricted to the individual (firm) which decides on its allocation approach in order to maximise profits (Sections 7.5.2 and 7.5.3).

In the case studies in Part III, no differentiation between these two factors is made. It is varied in its total from zero to more than one.

## 4.3From Ecological Commodities to Damages The Mathematical Model

In Chapter 3, the representation of a single process and of process networks has been introduced. Processes are described by the flows of commercial and ecological commodities in relation to the production of commercial commodities summarised in the process vector **p** (see equation (3.6))

$$\boxed{\phantom{xxxxxx}}, \qquad (4.3)$$

and the process matrix **P** (see equation (3.17)):

$$\mathbf{P} = \begin{pmatrix} \mathbf{A} \\ \mathbf{B} \end{pmatrix} = \begin{pmatrix} \tilde{\mathbf{A}}^{-1} \cdot \mathbf{I} \\ \tilde{\mathbf{B}} \cdot \tilde{\mathbf{A}}^{-1} \cdot \mathbf{I} \end{pmatrix}. \qquad (4.4)$$

The flows of ecological commodities to and from nature have an influence on commercial and ecological commodities. For that reason, Heijungs (1997, p. 122) introduces two additional matrices, the damage and the fate matrix, with which these processes are modelled. While the former is used to model, e.g., damages on buildings due to air pollution, the latter models the effects of the emission of pollutants on nature itself (e.g., impacts on other species). For the case studies no such separation is required because only the aggregated results (in monetary terms) of environmental modelling performed, e.g., in the ExternE studies is used. According to their experience, linear behaviour of incremental changes may be assumed for several pollutants considered in their studies. The authors state:

> (...) the physical damages assessed are a linear function of the concentrations. This applies for radionuclides, particulates and several other air pollutants. Concentrations are linearly related to emissions for most dispersion processes. The exceptions are complex phenomena that involve non-linear effects, in particular [tropospheric] ozone formation.[9]

Non-linear effects are encountered where background concentrations play an important role in chemical reactions[10]. Nevertheless, linear models are used here to represent marginal damages caused by the flows of ecological commodities to and from nature. Furthermore, the methodology of externalities merges effects on commercial and on ecological commodities by adding up damages on

[8] Or the environmental policy vector, or the assessment method itself.

[9] European Commission (1995b, p. 414)

[10] In addition to non-linearities in ozone formation, non-linear effects are encountered in the formation of secondary particulates (sulfates), where the availability of $NH_3$ exerts a strong influence on the level of damage costs (IER et al. 1997, p. 71)

buildings, on humans, and on plants and animals. The outcome of such environmental models like EXMOD (Rowe et al. 1995a&b) or EcoSense (e.g., European Commission 1997) show the integral relative damage caused by the flows of ecological commodities.

For the purpose of this thesis, it is sufficient to create a damage vector where the environmental impact expressed in units compatible with private costs (e.g., environmental external costs) is given for each single ecological commodity. The corresponding equation is therefore

, (4.5)

where $€_j$ are the specific environmental impacts converted to monetary units (i.e., environmental external costs) per unit flow of ecological commodity $j$, and $e_l$ the cumulative environmental external costs of process $l$. In matrix notation, equation (4.5) is reduced to

$$\mathbf{e} = \mathbf{€} \cdot (\mathbf{B}) . \tag{4.6}$$

We are now prepared to turn to the question about how to represent changes in the economic system. But before, let us summarise the conclusions drawn from this chapter:

- The disutility function represents decision making processes in a simplified way by merging economic and environmental information. The environmental exchange rate allows to consider differences in environmental policies of nations and uncertainty perceptions.
- The disutility function is used in the Inventory Analysis, namely, as a parameter for joint product allocation, and for the representation of default choices of a technique needed for the numerous economic processes of the process network of a particular product.

# 5. LCA for Decision-Making: The Advantage of Marginal Considerations

## 5.1 Introduction

### 5.1.1 Overview

In this chapter, different system models suitable to represent changes of the economic system are developed. Based on a discussion about the benefit and the limitations of descriptive LCAs, the use of marginal technologies[1] in LCAs capable of supporting decisions is substantiated. In Subchapter 5.2 decisions are classified according to their time horizon, and three LCI system models are proposed, covering short-, long- and very long-term planning. Subchapter 5.3 contains a description of the models in terms of how to represent unit processes, and the relation between unit processes. Thereby, emphasis is put on different kinds of dynamic and non-linear aspects. Three general assumptions help to facilitate the set-up of the system models. The procedure how to determine marginal technologies is described in Subchapter 5.4 based on two fictional examples. In Subchapter 5.5, an overview over the system models developed in this Chapter is given and their relation to the descriptive model is discussed.

### 5.1.2 The Benefit of Descriptive Methods and Databases

In the last years, a comprehensive LCA database for energy systems has been established and extended (Frischknecht et al. 1994/1996a). Simultaneously, Heijungs (1997) developed a consistent method about how to attribute environmental impacts to economic activities, how to treat the "attribution problem". Both approaches perfectly fit together. But the fields of application of the method and of the database are limited. A descriptive LCA is valid under the *ceteris paribus* assumption, which means that

> the choice of the functional unit of the product alternative investigated should not influence other activities on this planet.[2]

The definition implies that the functional unit does not cover an additional necessity nor a change in the means to satisfy an existing necessity. The functional unit is a part of the existing economic activities and a part of existing environmental impacts is attributed to it.

But we think that LCA should not be limited to a mere description of what happens now (or, more accurate, what happened in the last years). If we consider LCA as

> (...) important for identifying when the selection of one product over another or when modifications made to any part of the system have the desired end result of decreasing environmental impacts from all the life-cycle stages, from cradle to grave,[3]

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[1] See Section 5.1.4 for a description of the term "marginal technology".

[2] Heijungs et al. (1992b, p. 12). The choice will of course influence the activities within the product system under analysis.

[3] Curran (1996, p.1.5)

and if we want to

> (...) evaluate and implement opportunities to effect environmental improvements[4]

with LCA, comparisons and the analysis of changes becoming effective based on the outcome of such comparisons are indispensible. However, we have to keep in mind that the consequences of LCA are rather limited, as Hofstetter points out:

> Some countries started recently to set freight targets for substances or impact categories. All these policy measures aim at a reduction of actual towards target loads. (...) Environmental policy will have to operate with regulations if these target loads are to be reached within a pre-defined time period. But it is desirable that the impact reductions are realised in an efficient manner and with least costs. (...) LCA is one of the instruments that helps to optimise the effort along the path from actual to target loads.[5]

But again, if this optimisation of reducing environmental impacts should be effective, comparisons of different alternatives on the micro level (goods and services) are needed and changes towards options that are more "environmentally friendly" have to be expected. These changes in consumption patterns (of households and firms) will, to a variable and sometimes even hardly detectable extent, influence other activities within the economic system.

Because the attribution approach is made for an *analysis* of the current or past situation of an excerpt of economic activities, and attributes environmental interventions and environmental impacts to these economic activities, the benefit of such kind of analysis is questioned. If the findings would be transferred to real life, changes are to be expected which cannot be represented by the system model underlying the attribution analysis, independent from the size of the expected changes.

If an LCA is meant for supporting choices, its functional unit would be defined as an additional unit of product or service, additional to the actual overall consumption volume, or compensating a decrease in purchase of a competing product or service. In this case, a large number of economic activities would be influenced, because more would have to be produced to satisfy the additional demand for the functional unit and - in the case of a product switch - less for competing products because of a decrease in purchase. Heijungs admits that choices and changes (even if sometimes almost neglegible) are the relevant topic in LCA:

> One can only make choices which affect the way the world is running in a neglegible or almost neglegible way. One might therefore propose that the only relevant question in decision-making is the marginal question, that starts from the *ceteris paribus* assumption and then leads to questions such as: what are the additional environmental problems if one extra product is made? This would disqualify the use of tools for the attribution problem as these were interpreted throughout this study as achieving a static aportioning for use in environmental analysis and decision support.[6]

Where lies the benefit of such kinds of system models and databases? Heijungs (1997) and Frischknecht (1997) propose to use the attribution analysis for hot spot identification, and other types of approaches for the analysis of changes.

But we have to take into account that the change may be as little as 1 additional litre of milk delivered to a customer in a certain region, and as far-reaching as the substitution of electric for gasoline cars for all cars bought in Switzerland within one year. Therefore, the tools for

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[4] Fava et al. (1991, p. 1)
[5] Hofstetter (1996b, p. 153ff.)
[6] Heijungs (1997, p. 178)

the analysis of changes will have to be further subdivided according to the extent of change expected or assumed:

> Goals in LCA may range from short term process engineering, design and optimisation in a life cycle (type 1) through product comparison including product design, product improvement, ecolabelling in the medium and long term (type 2) to long term strategic planning (type 3). Each goal requires its own types of analysis and modelling. Data requirements then can be specified more precisely, both for case applications and for generic databases.
>
> The results and conclusions of a type 0 analysis (using average data of average technology mixes) - although widely used - are only of limited use. It may be used to show the effects attributed to a certain service or product (i.e., functional unit) purchased last week or last year. If however the effects of a choice or an improvement of a product system should be highlighted, a type 1, 2 or 3 analysis and model should be chosen.[7]

The same proposition of a two step procedure is made by Heijungs:

> So, a combination of tools might be envisaged:
> - First, tools for attribution analysis are used to identify key issues (dominant aspects, hot spots).
> - Next, tools for marginal analysis are used to investigate the change that is introduced by switching to an alternative.[8]

The use of an attribution analysis does however not guarantee to recognise the important issues. The outcome of an analysis of "what *is*" (attribution analysis) and an analysis of "what *will be*" due to (small or large) changes may differ substantially. Processes and activities that have been identified to be relevant in an attribution analysis, may show only little effect in environmental improvements when performing an analysis of the corresponding change. For instance, the fact that electric heat pumps presently in operation in Switzerland cause only little amounts of greenhouse gases compared to oil boilers[9] does not automatically imply, that this is also true for every additional heat pump installed in the future. Care has therefore to be taken not to take conclusions with farreaching consequences based on inadequate system representations. This leads us to the conclusion that marginal technology should be applied in LCIs for decision-making.

### 5.1.3 Marginal Technologies to Represent Changes

The aspect of marginal and average technologies is not often treated in LCA source books. Müller-Wenk (1978) founds the choice of marginal technologies instead of average ones as follows:

> One could establish an equivalence coefficient for electric energy, which corresponds to the equivalency factor of the average of the primary energy sources used weighted by their shares. This seems not to be the right solution, bearing in mind, that changes around the actual demand are generally not covered by the same mix of primary energy sources than the actual demand itself. Because the equivalency factor steers the rate of exchange in between individual resources within the ecological bookkeeping, the

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[7] Frischknecht (1997, p. 3ff.)

[8] Heijungs (1997, p. 178)

[9] This is due to the fact that the share of fossil power plants producing the electricity consumed in Switzerland is not more than about 11% (considering domestic electricity generation and trade, Frischknecht et al. (1996a, Part XVI Strommix, p. 8)).

> marginal scarcity of a resource is required; i.e., the ecological scarcity of the last unit of resource used up, in contrast to the integral scarcity of that resource.[10]

According to Müller-Wenk, the environmental impacts caused by marginal techniques have to be compared to adequately reflect the environmental impacts of commodities produced by these techniques. With this opinion, Müller-Wenk implicitly assumes that additional consumption has to be treated differently compared to current total consumption. Wenzel et al. (1997, p.65ff.) are in opposition to this view by defining a trend analysis within which the projection of the most important key figures are determined. Among other aspects, they predict the changes in the electricity mixes of each country and the development of performance of each electricity producing technology, which results in country-specific, future average electricity mixes. Hence, they use future average technology (mixes) to cover the demand induced by the consumption of goods and services.

Lindfors et al. (1995a) establish a correlation between the goal of the LCA and the type of technology to be used:

> The choice between marginal or average energy depends on the actual situation. While using LCA in a decision process in relation to future production it is relevant to [consider] marginal energy sources because marginal energy sources will be used to fulfil small changes in the energy demand. In order to study the influence of different life cycles on the existing energy supply system it is more relevant to consider the average energy supply system (...).[11]

Hence, for a descriptive LCA, they plead to apply average technologies in the system model, whereas for an analysis of changes, marginal technologies are more important. But we suggest that not only small changes in the energy demand shall be modelled using marginal technologies as Lindfors et al. state. Any change in demand, either short- or long-term, will be compensated for by marginal technologies. The technologies may however be different depending on the time horizon.

The view of Lindfors et al. and Müller-Wenk is shared by Pedersen Weidema (1993), who touches upon another problem:

> It can be argued that the use of environmental data on the marginal production [technology] reflects most correctly the actual environmental impact of implementing the result of the life cycle assessment. However, identification of the marginal production may be time-consuming and will often demand information from industrial experts or market researchers. On the other hand, once identified, the data collection effort is limited and the marginal production will often be more stable over time than the average production.[12]

Although one might doubt his statement that marginal production is more stable and that data collection effort is reduced, we agree with Pederson Weidema that the identification of the marginal technique is a central, time-consuming issue. For us, the main question concerning

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[10] Müller-Wenk (1978, p. 46ff.), (originally in German: *"Man könnte nun für elektrische Energie einen AeK [Äquivalenzkoeffizienten] bilden, der dem nach Anteilen gewichteten Mittel der AeK der verwendeten Primärenergien entspricht. Dies erscheint aber nicht als die richtige Lösung, wenn man sich vor Augen hält, dass im allgemeinen Bedarfsschwankungen um den gegenwärtigen Bedarf an Elektrizität herum nicht mit der gleichen Mischung von Primärenergien abgedeckt werden, wie der gegenwärtige Bedarf selbst. Da der AeK das Austauschverhältnis zwischen einzelnen Ressourcen im Rahmen der ökologischen Buchhaltung steuert, muss gewissermassen die "Grenzknappheit" einer Ressource bestimmt werden; das ist eben die ökologische Knappheit der letzten verbrauchten Einheit der Ressource, im Gegensatz zur 'integralen' Knappheit der Ressource."*)

[11] Lindfors et al. (1995a, p. 2)

[12] Pedersen Weidema (1993, p. 163)

the identification is, whether the financial flows between firms and between households and firms show us the way to the relevant marginal technique, or whether it needs to be identified independently from the economic actors actually involved in the production of a certain commodity. We guess, Pederson Weidema suggests the latter when he defines the marginal production as

> (...) the production facility that would be taken into use or out of use when the demand respectively increases or decreases as the result of implementation of the life cycle assessment (...).[13]

In the same direction goes a statement by Boguski et al. (1996), who argue that no environmental benefit is achieved by using an "incremental system approach" when systems or markets are involved that are not expandable.

> If a company seeks to improve its environmental profile by increasing the use of scrap, it will reduce its own energy and emissions by using the incremental approach. However, the planet, and society in general, will not benefit. The increase of industrial scrap or trim by one company simply takes the scrap or trim away from another company because the supply of scrap or trim is not expandable. From a narrow, individual company's point of view, recycling of industrial scrap is good and may reduce the energy and wastes allocated to its operations, but from the larger point of view, no environmental value accrues to society. One possible exception is that increased demand for industrial scrap may force marginal users to replace industrial scrap with postconsumer scrap. (...)[14]

The statement that "(extra) recycling is good for an individual company" is valid for market situations where invariable capacity constraints on the supply side exist (i.e., if supply is inelastic) *and* demand exceeds supply. In a market where the supply of one factor of production is limited by capacity constraints, a change from one commodity requiring this factor to another, identical commodity which does not need this factor, does not necessarily lead to a corresponding overall, "global" decrease in environmental loads. But as already stated, LCA is not suitable for stearing such macro-level goals.

The "real" changes in the "global" environmental situation may be established on a macro-economic level based on information about marginal technologies and/ or firms entering and leaving the market, and their environmental performance. The link, however, from these technologies to atomised decisions and strategy plans is hardly possible because the development of demand is only one out of many parameters influencing the trend of affairs of firms.

It is much easier to consider marginal technologies that are actually purchased than to establish technologies on the margin on a world-wide level and for all economic sectors. If the actual financial flows are used to identify the marginal suppliers for each and every derived demand of a firm, firms are encouraged to strive for environmentally efficient technologies. It enhances competition about scarce resources and by that may give incentives towards environmentally benign technologies and commodities. This shows another property of LCA that is similar and complementary to the price system. LCA helps to optimally allocate scarce environmental resources such as clean air and water[15].

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[13] *Op. cit.* (p. 163)

[14] Boguski et al. (1996, p. 2.20ff.)

[15] Thereby, the scarcity of environmental resources is in most cases determined indirectly by the environmental policy and legislation of a country.

The objectives and the consequences of the approaches discussed in this chapter are summarised in Tab. 5.1. Hereby we find two technological levels which comply with Heijungs' attribution problem, namely, today's and future average. Whereas the former represents today's economic system, the latter is mainly useful for the description of an economic system in the future which requires scenario about the technological and economic development. However, both approaches only describe a status quo (either now or in the future) and do not represent changes that will be encountered due to decisions made in today's or in a future context. In this thesis, only the third level, "marginal", is relevant. It helps to support short-, long-, and very long-term decisions.

| Technology Level | **Objective** | **Consequences** |
|---|---|---|
| Today's Average | Structural analysis of today's product system | - All consumption is treated equally,<br>- The environmental consequences of a change in demand are averaged.<br>- Little incentives are given on a firm's level to individually optimise the environmental impacts of derived demand because suppliers of homogeneous commodities are averaged. |
| Future Average | Structural analysis of the product system in the future | - All consumption in the future is treated equally,<br>- The environmental consequences of a change in demand in the future are averaged.<br>- Little incentives are given on a firm's level to individually optimise the environmental impacts of derived demand because suppliers of homogeneous commodities are averaged. |
| Marginal [1]) | Analysis of changes in the product system | - All *additional* consumption is treated equally<br>- The environmental consequences of a change in demand represent environmental impacts directly induced by a firm. They are established on the basis of the marginal technology(ies) a supplier uses to satisfy the demand of a firm.<br>- Incentives are given for firms to choose a certain supplier to cover an additional derived demand of homogeneous commodities.<br>- Incentives are given to individually optimise the environmental impacts of derived demand by changing suppliers of intermediate goods, changing intermediate goods (i.e., from oil to gas or *vice versa*), and by changing the level of demand. |

Tab. 5.1: Consequences of the use of average, future average and marginal technology(ies) to cover additional, derived demand.
[1]): Here, the term "marginal" is used in respect to "marginal technology or technology mixes". Depending on the system model (Short, Long, and Very Long Run) the marginal technology is either represented by its average or its marginal performance (see Sections 5.1.4 and 5.2.2).

[...]

After specifying decisions to be supported with LCA, three system models used to represent changes are introduced and characterised. These models are deduced from a set of assumptions. Its main consequences for the inventory analysis are described. For that purpose, the two different meanings of the term "marginal" are explained.

### 5.1.4 Marginal - a Multi-function Adjective

**Marginal technology or technology mixes (change in production capacity):**

A marginal production capacity is represented by a technology or a technology mix which is put in or out of operation if *total production* is increased or reduced, respectively. The change is caused by a (usually long-term) increase or decrease in demand for the output of that process. The determination of the marginal technology is difficult because an LCA covers only a small share of the total economy, and it is difficult to link an increase in production capacity of an installation to the functional unit analysed.

Production capacities (capital goods) are usually built up in discrete steps. If such expansions are considered, and it is decided not to entirely allocate them to the one functional unit under analysis, the corresponding emissions and requirements have to be allocated to the total expected lifetime production of the technology under study. Hence, the marginal technology will then be analysed on an average basis assuming or applying a certain lifetime capacity load factor. Marginal technologies will be applied in inventory system models to support long-term and very long-term decisions.

**Marginal requirements and emissions (change in capacity load):**

Marginal requirements and emissions are the *additional* or *reduced* effects caused by a process due to an incremental change in capacity load. The change is caused by a (usually short-term) increase or decrease in demand for the output of that particular process. This implies that the production takes place with the same installation hence without additional requirements for capital goods. The marginal requirements and emissions apply in the case the installations do not work at full capacity[16].

## 5.2 Decision Support in LCA

### 5.2.1 Goals of a Firm and Strategic Planning

In a firm, goals are set specifying its time horizon, its scope and its dimension. For the purpose of LCA a distinction according to the variability of the factors of production is the most feasible one. Lipsey et al. distinguish between short, long, and very long run planning:

> In order to reduce the decisions firms are constantly making to manageable proportions, economists organise them into the three theoretical groups: (a) how best to employ the existing plant and equipment (the *short run*); (b) what new plant and equipment and production processes to select, given the framework of known technical possibilities (the *long run*); (c) what to do about encouraging the invention of new techniques (the *very long run*).[17]

In the *short run*, at least one factor of production cannot be varied (fixed factors). Money payments that are associated with these factors have to be made (fixed costs). The time period of the short run may correspond to several years, months or even weeks. It corresponds to situations when a firm is confronted with a one-time-only special order, with the question whether to make or buy a product, or with the problem of adjusting production mix and volume to changes in demand.

In the *long run*, all factors of production may be varied, but the basic technology of production is unchanged. Again the long run does not correspond to a specific period of time. It corresponds to situations when a firm is planning to go into business, to expand substantially the scale of its operations, to branch out into new products or new areas, or to modernise, replace or reorganise its methods of production.

In the *very long run*, all factors of production may be varied, and the technological possibilities open to the firm are subject to change. The firm may affect changes in technology by what it does itself, particularly in its program of research and development.

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[16] A similar situation is encountered when an incremental augmentation of demand of a process-output leads to a marginal change of the chemical composition of inputs (e.g., waste incineration). Due to this marginal change, emissions and requirements may change in composition.
[17] Lipsey et al. (1972, p. 186)

These three classes match very well with the requirements for a representation of unit processes in LCA. Fixed factors of production, like the capital equipment in short-term considerations, need not to be included in an inventory analysis. However, as is stated above, the time horizon in terms of calendar time of the three categories strongly depends on the type of technology and varies substantially[18]. Hence, all three kinds of time horizons (i.e., short-, long-, and very long-term) may usually be encountered within the process network of a particular functional unit and a particular question (decision to be made). How this problem may be treated in LCI is discussed in Subchapter 5.3.

One might as well rely on a discrimination according to the size of a change in demand in relation to the capacity available. But this relation does not express the time scope of the change nor does it determine the production factors that are variable. The variability of production factors, in its turn, is an important discrimination criterion for different inventory system models.

### 5.2.2 A Classification Scheme for Decisions to be Supported with LCA

The process network of a good or a service consists of hundreds of individual decision units. This complicates the issue of model building for representing changes within the economic system. The process which increases its output in order to cover additional demand needs additional factors of production, namely of materials and energy, and information. But the signal to be recognised by a related economic actor about additional needs of one single process (or one single plant) competes with similar or opposite signals of other activities which simultaneously start, take place or stop. The detectability of the signal will be better, when the change in demand is large in relation to the capacity of the actor receiving the signal and/or when the processes are economically "close" to each other. The more "distant" a process is from the functional unit, the more will the signal of a change in demand of a certain functional unit be drowned out by the noise caused by all other economic activities.

Confronted with this rather complex situation of interactions, and with the realisation that the problem escapes experimental verification, because

> one cannot do an experiment in which only one isolated economic activity takes place with the other economic activities switched off.[19]

We shall follow Heijungs and also take the way of epistemology to found the basis of system models which can cope with changes.

We shall classify possible LCA applications, i.e., decision situations of firms into the following categories: "Status Quo", the "Short Run", the "Long Run", and the "Very Long Run". The system model underlying a "Status Quo" of a product system, describes current, or even, due to the inherent timelag between an activity and its documentation, past situations[20].

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[18] For Bea et al. (1991), for instance, the reference period is about one year and less for short term planning, between one and five years for medium, and more than about five years for long term planning.

[19] Heijungs (1997, p. 13)

[20] Annual reports usually publish data from the period previous to the year of publication. The most recent data in OECD energy statistics, for instance, are usually two years old.

Heijungs (1997) extensively treats the "attribution problem", and so we will not further discuss it here. The other three categories will be discussed in view of typical questions asked in firms and its underlying system model properties.

| Type of system model | temporal structure of changes in demand | Degree of freedom [1]) factors of production | technologies | technical performance |
|---|---|---|---|---|
| Status Quo [2]) | - | all fixed | no choice | fixed |
| Short Run | one time only | at least one fixed [3]) | no choice | fixed |
| Long Run | long-term trend | all variable | free choice | fixed |
| Very Long Run | very long-term trend | all variable | free choice | variable |

Tab. 5.2: The four different system models in LCI discerned in this thesis and its characterisation in terms of the temporal structure of the functional unit (change in demand) and the degree of freedom of possible solutions;
[1]): see Section 5.2.1
[2]): equals the model of the attribution problem developed by Heijungs (1997); no change in demand, everything as it is (was), no decisions to be made, only reporting purposes.
[3]): relevant only: capital (equipment) fixed

*Short-term* decisions are made, when a decision unit (be it a firm or a household) is confronted with a one-time-only problem like an unexpected increase in demand or an unexpected change in demand pattern of products from a multiproduct firm. For such one-time-only problems, the Short Run model will be applied. If changes in demand are forecasted on the *long term*, firms will mobilise unused or shut down excess production capacities, or will invest in new production facilities. The technical possibilities that may be applied in case of new investments are restricted to the currently available ones. But the firm may choose among all feasable alternatives. For such small and large, long-term trend related problems the Long Run model is intended. Finally, the Very Long Run model is thought to be used for the representation of changes in demand on the *very long term*. Here, all factors of production, and the technical possibilities are free variables and therefore subjected to scenario of different forecasts.

The two central questions for the representation of the situations outlined are, how to represent

*a)* the unit process itself,

*b)* the relation between unit processes[21].

To illustrate this, let us take the example of an increase in electricity consumption and formulate corresponding questions:

*Ad a)* How should a power plant be represented in the case of an increase in electricity demand from that power plant? Should the kind of representation be dependent on the time scale relevant for the problem? How shall we deal with "environmental undercosting"[22]?

*Ad b)* How should the production of electricity be represented within a utility in the case of an increase in demand? Should an average or marginal production situation be underlied? If

[21] This corresponds to the representation of the *derived demand*, which is the demand for the factors of production (Lipsey et al. 1972, p. 330).
[22] Environmental undercosting occurs if not all flows of commercial and ecological commodities are considered that are induced by a certain action.

choosing a marginal production situation, how should marginal technologies be established in a consistent way? Should the kind of representation used also be dependent on the time scale relevant for the problem?

In mathematical terms, question *a)* deals with the determination of the amount of each single item in the process vector $\tilde{\mathbf{p}}$, whereas question *b)* deals with the determination of the right place of the individual entries $\tilde{a}_i$ within the economic part of the process vector (see Section 3.3.4).

The two questions will be treated in the following subchapters. But we will not go into the question about forecasts and the development of scenario in the Very Long Run model nor how to deal with restrictions due to limited availability of factors of productions (like availability of certain mineral resources, or of skilled labour, *et cetera*). In Part III, the consequences of the approaches chosen will be discussed based on the example of system models representing the Swiss electricity supply.

Decisions firms are confronted with, and LCI system models that are used to provide information for these decisions have been classified in this subchapter. Thereby, the degree of freedom which depends on the time scope of the decision, is used as the discriminating criterion. The classification fits into the guiding principle stated in Section 3.1.2, and the LCI system models are compatible with the outcome of corresponding economic considerations.

## 5.3 The Representation of Changes

### 5.3.1 Introduction

In this subchapter, the system models are characterised according to the three LCA scopes introduced in Subchapter 5.2 (i.e., Short, Long, and Very Long Run). Short Run decisions aim at an optimisation of existing facilities. This comprises either the supply of changing demand, the emphasis of combined produced products and negotiations with suppliers. Long Run and Very Long Run decisions deal with investment decisions either in the nearer or the far future, respectively. Such decisions show a discrete character. In system models established to solve the attribution problem, only linear and static relationships between unit processes are usually applied. In system models used to analyse changes, however, different kinds of non-linear and dynamic aspects may become relevant.

Emphasising a product manufactured in combined production in the Short Run means continually optimising the output according to the firm's objective. For an accurate system representation, dynamic data may be required as will be shown in Section 5.3.4. Because investment decisions are required in time intervals and because investments cannot be made undone, the usually applied, time-flattened representation of capital equipment does not fit in every situation. How the discrete character of investments may be considered in the Long Run model is shown in Section 5.3.5. Changing conditions in terms of technological possibilities and performance as well as in terms of the state of the environment may influence decisions relevant for the Very Long Run. This requires to abandon the assumption of fixed technical coefficients. In Section 5.3.6 we discuss how such changes in technologies need to be modelled in order reach sufficiently accurate results. For an adequate description of these system models, they are subdivided into a fore- and a background system. Afterwards, a listing of three central and simplifying general assumptions is given.

### 5.3.2 Foreground and Background System

Product systems consist of a large network of activities which take place in many different firms, at different places and different time. If we interpret a firm as an integral decision unit, we may also say, that a product system model represents a large number of decision units that are linked in view of the wanted output, namely the functional unit. Decision units, however, are autonomous economic subjects following their own goals and strategies. As we have seen in the last subchapter, the firm's executives are confronted with a variety of decisions to be made based on signals received from their economic, legal, and environmental surrounding. The interpretation as well as the conclusions drawn based on these signals depend on the values and basic attitudes of the executives which determine the firm's strategies. Hence, the product system is highly heterogeneous not only regarding the technologies and economic sectors involved[23] but also regarding the strategies followed by individual economic actors. That is why the product system is divided into a foreground and a background system according to the influence the decision-maker for which the LCA is carried out may exercise on the processes. In Udo de Haes et al. (1994) a distinction between fore- and background was made the first time in the context of data quality:

> A guiding principle may be the distinction between foreground and background data. Foreground data are related specifically to the product system at stake; they should be as real as possible. Background data are not specifically related to the product system and may consist of averages or ranges.[24]

Several authors (Huppes et al. 1995, Azapagic 1996, Zimmermann et al. 1996) give alternative definitions by focusing more on the knowledge about the relations within the process network. For this thesis, the decision making context of the two subsystems is the central, discriminating aspect. That is why the terms foreground and background system are used according to the following analytical definition:

*Foreground system:* The foreground system consists of processes which are under the control of the decision-maker for which an LCA is carried out. They are called foreground processes.

*Background system:* The background system consists of processes on which no or, at best, indirect influence may be exercised by the decision-maker for which an LCA is carried out. Such processes are called background processes.

[23] A process network may comprise activities of the mining sector where huge amount of material is moved but also of the finishing industry where a different kind of precision is required.
[24] Udo de Haes et al. (1994, p. 11)

### 5.3.3 General Assumptions

Due to the complexity of the behaviour of economic systems and the nearly impossible task to predict and model the activities actually caused by short-, long-, and very long-term changes, we shall postulate three simplifying assumptions, concerning

*a)* Economic behaviour,

*b)* Incremental damages,

*c)* Consistency in modelling.

These assumptions will reduce the complexity in such a way, that modelling of activities caused by changes will be possible and duplicable. However, the validity of the outcome from such simplified models is of course restricted by these assumptions.

*Ad a) Economic behaviour:* All actors involved in the process network of a functional unit are assumed to make their decisions in order to maximise their profits[25]. This is of course a crude and disputed assumption, neglecting other aspects like political influence or philanthropic motives. Other goals such as maximising satisfaction or sales volume (Lipsey et al. 1972, p. 314) are considered neither. However, many of the predictions of theories based on this assumption have been confirmed by observation.

*Ad b) Incremental damages:* In an LCI of a change (i.e., the Short, Long, and Very Long Run case), marginal technologies (distinct ones or mixes) are applied. Hence the environmental damages caused by changes in demand are related to the today's state of the environment. As a consequence, the environmental impacts associated with changes in economic activities (due to additional or reduced consumption) should be represented by incremental damage functions. Tab. 5.3 shows the relation of the type of the system model and the representation of technologies involved as well as the interpretation of the environmental damage functions used in impact assessment.

| Type of System model | Purpose of the LCA | Technology | Requirements and emissions | Interpretation of damage functions |
|---|---|---|---|---|
| Status Quo [1]) | Documentation | average | average | average |
| Short Run | Planning | marginal | marginal | in-/ decremental |
| Long Run | Planning | marginal | average | in-/ decremental |
| Very Long Run | Planning | marginal | average | in-/ decremental |

Tab. 5.3: Documentation (descriptive LCA) and planning in relation to the technology mix and to the interpretation of the damage functions applied in environmental life cycle impact assessment.
[1]): Equals the attribution problem, see Heijungs (1997);

*Ad c) Consistency in modelling:* Because it is hardly possible to establish pure and unequivocal relationships between a change at one place (in one firm) and induced changes at other places (in other firms), we assume that all firms connected by the process network behave in the same manner, underlying the same time horizon. This assumption is made for con-

[25] Hereby, costs and prices may include environmental externalities (cf. hypothesis 3, Section 1.2.4). This is partly in contrast to the current market situation.

sistency reasons and implies, for instance, that if short-term choices are the issue in the foreground system, firms operating in the background system will also act according to their respective short-term strategy. This assumption is in contrast to the approach proposed by Azapagic (1996, p. 35) who pleads for a differentiated use of process representations in the foreground and the background system (see also Subchapter 5.5).

> *a)* Actors of the economic system modelled in environmental LCA are assumed to seek to maximise profits. However, profits are determined on the basis of an economy with (partially) internalised environmental externalities.
>
> *b)* Incremental damage functions are used to represent the effects of changes on the environment.
>
> *c)* All firms connected within a process network of a certain functional unit make their decisions based on the same time horizon.

In the following sections, the different models developed for LCI will be described in relation to the time scope of the decision to be supported.

### 5.3.4 Representation of Changes in the Short Run Model

The Short Run system model is used for short-term changes in demand, and short-term optimisations such as product emphasis and negotiations with suppliers. The main characteristic of such models is the fixed capital equipment available for a change or optimisation of production. As already mentioned, the classification in short- and long-term depends on the economic process under analysis. For an airline company, for instance, the extra passenger may be considered as a short-term decision problem. For an airport, however, an extra landing is a short-term decision problem. Short-term optimisation deals with changes in the product portfolio to optimise the use of production capacities, or with changing suppliers in order to increase the productiveness and to reduce costs, respectively.

**Changes in Demand**

Due to the fact that flows of commercial and ecological commodities caused by the investments in plants and equipment cannot be influenced any more (except the ones for its dismantling, of course), these ecological flows are "sunk effects", or "bygones":

> "Bygones are bygones", and they should have no influence on deciding what is currently the most profitable thing to do. The "bygones-are-bygones" principle extends well beyond economics, and is often ignored in poker, war, and perhaps in love.[26]

Environmental life cycle assessment certainly belongs to the areas where this principle perfectly fits too. At every moment of decision, one should only be concerned with how environmental benefits can be achieved from this time forward compared with current and future environmental impacts. This has been shown by Frischknecht et al. (1993) in the case

[26] Lipsey et al. (1972, p. 177)

of the premature replacement of refrigerators. It means that capital equipment is not to be considered in short-term decisions where plants and equipment are fixed factors of production. However, this implies that such a Short Run analysis is strictly restricted to the short-term. It does not deliver useful information for long-term decisions. Even worse, short-term analyses may be misleading in that environmental impacts caused by products and services are underestimated.

On the other hand, changes concerning the relations to up- and downstream firms caused by a short-term overall change in energy and material flows of the process at issue may be encountered. A firm may have to buy its materials additionally needed from other suppliers. In these cases, short-term marginal suppliers (technologies) are used[27].

| |
|---|
| Short Run system representation of changes of productivity of a unit process in the foreground system does not comprise fixed factors of production like the erection of plants or the production of equipments. The representation of the relations between unit processes reflects the short-term marginal situation in line with the corresponding short run financial flows. The unit processes in the background system are also assumed to increase their productivity and are modelled the same way as the process in the foreground system. |

**Product emphasis**

Short-term product emphasis is used to reach profit maximisation within multiproduct firms. The multiproduct firm's output of longer periods, i.e., a year, is the result of a continuous reaction on changes in selling prices and material costs, of a continuous optimisation of the firm's product mix. But only if linear relationships between product output and flows of commercial and ecological commodities are assumed, the commodity flows attributed and referenced to the amounts of distinct outputs of a multiproduct firm on the basis of a series of short periods equal the commodity flows attributed on the basis of the sum period.

The consequence is, that although the procedure remains the same, the outcome of the Inventory Analysis per unit of distinct outputs of a multiproduct firm depends on the time period considered[28]. Of course the flows of commercial and ecological commodities related to the overall output of a multiproduct firm may vary due to changes in the product portfolio. But also the in- and outputs of commodities allocated to an individual joint product may vary depending on the time period, if non-linear relationships between the product portfolio and the corresponding flows of commercial and ecological commodities are present. Hence, short term adjustments in product portfolio should be used to allocate commodity flows to the independently variable co-products manufactured within a certain time period. In the petrochemical industry, for instance, linear programming is used for that purpose (cf. Azapagic 1996). As long as linear proportions may not be assumed and the outcome proves to be highly variable, an integral, time-dependent modelling of a multiproduct plant may be required to determine appropriate allocation factors.

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[27] The way how marginal technologies are determined within the system model is described in Subchapter 5.4.

[28] Technological parameters like the environmental performance of the processes or their energy efficiency may be other sources of time dependent variations.

The optimisation of the product portfolio of *one single* multiproduct plant is no LCA goal *per se*, because in LCA the demand to be satisfied is given exogenously by the functional unit. An optimisation of the product portfolio is not possible, if some of the outputs cannot be varied. However, the comparison and optimisation in environmental terms of *several* multiproduct plants might be supported by LCA. For such a comparison, it will be analysed which set of individual product portfolios of the plants will show the best performance (e.g., in terms of social costs) for the corresponding product. The firm seeks to cover an additional demand by the best set of individual product portfolios of its plants. This problem is similar to the question of negotiations with suppliers, and changes in productivity respectively, treated in this section.

> System models representing Short Run product emphasis are useful for the determination of long-term allocation factors in order to assign flows of commercial and ecological commodities to the independently variable co-products in a multiproduct plant. These models help to define allocated, single-output unit processes needed to set up the process network of a functional unit. In a strict sense, this procedure is only valid for solving the attribution problem because it relies on the experience of past activities and optimisations. However, depending on the situation, prediction of the multi-function process behaviour may as well be used as a first guess for long-term planning questions.

**Negotiations with suppliers**

For short-term optimisation purposes, spot markets and stock exchange for various homogeneous commodities have been established. Purchasers and suppliers of electricity, for instance, are brought together in Laufenburg, the electricity stock exchange of the European network UCPTE[29]. Although the demand pattern and the price of the product may highly differ between clients, the physical consequences of production remain about the same[30]. Short-term changes of suppliers may result in an overall increase of capacity use for the new, and an overall decrease for the old supplier. But the suppliers concerned may compensate the acquisition or the loss of a client by dropping or establishing other business relations. That is why we assume that the system representation of the changed output situation of a process in the background system equals the situation of changes in output described above.

The relations to up- and downstream firms may change due to the firm's short-term overall change in flows of commercial commodities, similar to the situation when the productivity in- or decreases. Short-term marginal suppliers are used (see above). Hence, the same conclusions as for the model to represent changes in output are drawn.

> Short Run system representation of changes of suppliers of a unit process in the foreground system does not comprise fixed factors of production like the erection of existing plants or the production of existing equipments. The representation of the relations between unit

[29] UCPTE: *Union pour la Coordination de la Production et du Transport de l'Electricité*.
[30] Disregarding differences in efficiency due to differences in size of production batches, which would only be relevant in situations where no or only limited storage capacity for buffering is available.

processes reflects the short-term marginal situation in line with the corresponding short run financial flows. The unit processes in the background system increase their productivity and are modelled the same way as the processes in the foreground system.

**Conclusions**

Short-term problems require a special system model to represent unit processes involved in the process network under the assumptions made in Section 5.3.3. In particular, environmental impacts caused by producing existing plants and equipment are not considered. The relation between unit processes is determined on the basis of short-term marginal changes in marginal technologies used to cover a short-term increase in demand. Product emphasis is a short-term problem which may be solved with, e.g., linear programming (Azapagic 1996). It delivers a solution to allocation problems in combined production that represents physical causality[31]. If its outcome is integrated over a longer time period (e.g., one calendar year), linear programming may be used for allocation in combined production in the Long Run system model.

Based on the "bygones are bygones"-principle, activities have to be identified and excluded, that can no more be influenced by the decision at issue. Care has to be taken not to use results of a short-term analysis to support decisions to be made with a long-term perspective. The gross underestimation of environmental impact may lead to wrong conclusions.

[...]

## 5.5 Conclusions

The main distinction between a system model used for a structural analysis and for a planning analysis of short-, long- or very long-term changes lies in the technology or technology mixes applied for the derived demand within process networks. While all environmental impacts of all final products and services consumed by households determined with structural analyses should theoretically sum up to the world's environmental impacts (100%-additivity[32]), the environmental impacts of all *additionally* consumed products and services determined by Long Run analyses should add up to the world's *additional* environmental impacts (marginal 100%-additivity[33]). The technologies themselves are represented equally in a structural analysis and an analysis of changes. By using Heijungs' linear attribution principle in an analysis of a change, the three requirements of order-independence, amount-independence and 100%-additivity are fulfilled too.

Care must be taken that results from such marginal analyses are not used to explain the environmental impacts of all activities. But in that respect another similarity to economic

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[31] Second step in ISO's three step procedure, (Anonymous 1997b).
[32] Heijungs (1997, p. 18)
[33] This has been recognised, among others, by, e.g., Heijungs (1997), and Frischknecht (1997, p. 3). Heijungs writes, that answers to the attribution problem will often be used for purchase decisions and that *"the attribution must in that case be differently formulated: Which additional environmental problems will result from a certain additional economic activity?"* Heijungs (1997, p. 18).

considerations arises. Relevant or direct costing is performed in order to support specific decisions (i.e., changes) and full cost accounting is made for documenting and controlling purposes.

The characteristics of the four system models distinguished in this thesis are summarised in Tab. 5.9. Today's common practice for the inventory analysis is dominated by the use of generic data representing the average of average technologies ("type 0"-LCA in Tab. 5.9) while the goals of LCAs vary from type 0 to type 2 (sometimes even 3), from information to long term planning. In contrast to Azapagic (1996, p. 35), a consistent modelling of all processes involved in the process network of a product or service is assumed[34]. Azapagic proposes to always model average change of an average technology mix (which is comparable with the Long Run model of this thesis) in the background system. This means that also in a study concerned with a Very Long Run problem, Long Run system representation should be used. Such an approach, however, does not cope with the fact that also processes in the background system will, sometimes dramatically, develop with time.

In Tab. 5.9, a distinction is made between product and technology optimisation, development, *et cetera*. This discrimination in wording is made to highlight the different time horizon needed. Product development takes place within a time period short enough to allow for the assumption of constant technical performances in the background system. The system models used for the Long and the Very Long Run only differ in the variability of the technical performance, and, connected with that, in the need for scenario in the Very Long Run system model. The distinction between the Short and the Long Run system model on the other hand is rather straightforward. In the Short Run, the capital equipment is constant and never enters the analysis whereas in the Long Run investment decisions are made.

[34] One exception is made in relation to the Long Run system model, where the variability of the technical performance may differ between the fore- and the background system. This difference is, however, more a matter of data than of methodology.

| type | goal of the study | system models for inventory analysis | data used in inventory analysis |
|---|---|---|---|
| 0 | The Status Quo [1])<br>- environmental reports (not analysing the *effect* of the choice)<br>- statements to the authorities | complete system at current output<br>- no variation<br>- everything as it is (was) | average* environmental performance of the technologies involved (particular technologies or technology mixes) |
| 1 | The Short Run [2])<br>- short-term system optimisation, e.g.,<br>· "special order"-problem<br>· "one extra passenger"-problem | short-term variation<br>constant:<br>- technology<br>- installed capacity<br>variable:<br>- capacity use | short-term marginal technologies where technology mixes are involved<br>short-term marginal (environmental) performance of the technologies involved |
| 2 | The Long Run [3])<br>- hot spot identification *and* elimination<br>- product system optimisation<br>- product development<br>- product system comparison (analysing the *effect* of a choice) | long-term variation<br>constant:<br>- capacity use<br>- performance of known technologies in the background system<br>variable:<br>- installed capacity (per technology and hence technology mixes)<br>- technical performance in the foreground system | long-term marginal technologies where technology mixes are involved<br>long-term marginal (= average*) environmental performance of the technologies involved |
| 3 | The Very Long Run [4])<br>- very long-term (strategic) planning, e.g.,<br>· technology development,<br>· technology optimisation,<br>· technology comparison. | very long-term variation, large changes in technology(ies) and economic sectors<br>constant:<br>- capacity use<br>variable:<br>- installed capacity<br>- technology mixes (expressed by different scenario)<br>- performance of known and new technologies | anticipated future changes of technologies and technology mixes considered for the whole system model (technology scenario, consistent future)<br>average* environmental performance of the (new and existing) technologies involved |

Tab. 5.9: Purposes and goals for LCA and corresponding models and data for inventory analysis, modified from Frischknecht (1997, p. 4);
*: including the share of capital equipment;
[1]): In a Status Quo analysis, future processes may be documented in a descriptive way (future status quo). This however involves scenario like in the Very Long Run system model;
[2]): at least one fixed factor of production;
[3]): all factors of production are variable but available production technologies are fixed;
[4]): all factors of production are variable, performance and production technologies are variable.

The conclusions may be summarised as follows:

Three different LCI system models are useful to represent changes of the economic system. Hereby, decisions are classified according to their time horizon:

The *Short Run* LCI may be used for an optimisation of the use of existing production facilities when encountered with "one-time-only"-problems such as short-term changes in demand or negotiations with suppliers.

The *Long Run* LCI may be used for product or process development, optimisation and comparison. We suggest to separately record the production of capital equipment and its subsequent operation phase. The production of capital equipment shall be considered in expanding and consolidated markets, where at least replacement investments are made.

The *Very Long Run* LCI is needed for strategic planning problems such as the setting-off of an energy policy. Exogeneously defined consistent scenario are needed to enable accurate predictions. Emphasis shall thereby be put on the accurate representation of the future status and not so much on a detailed modelling of the transition period towards this future status.

In LCAs of a change (Short Run, Long Run, and Very Long Run), marginal technologies shall be applied. They are identified by the "least social cost" principle, including private costs and environmental external costs, but excluding social, legal, or political aspects. The environmental exchange rate is used to consider the variable extent to which environmental aspects are considered in different countries.

For an LCA of basic commodities (which comprise all commodities required by the derived demand) the determination of the minimum social costs requires several iterations, where every alternative technology producing the commodity at issue is considered in a set of different possible system models.

# 6.Allocation of Salaries, Dividends and Taxes

## 6.1Introduction

### 6.1.1Overview

In LCA it is common practice to only allocate the expenditures made for intermediate goods, for 3rd party services, and for the depreciation of plant equipment just to the goods and services produced (see Fig. 3.2 in Chapter 3). The expenditures for salaries, the taxes paid to the authorities as well as interests on credits, including mortgages, and total profits (partly distributed in the form of dividends) are in most cases conceived as environmentally unsullied. Exceptions relating to salaries, for instance, are suggested for transportation and life-support systems in excess of normal requirements such as offshore oil drilling (Spreng 1988, p. 139). Furthermore, subsidies, and capital and credits given are not interpreted as additional "products" of the respective process and no flows of commercial and ecological commodities are allocated to them. In the light of the general procedure formulated in Section 3.3.1 one has to question whether the activities induced by these, sometimes substantial, financial flows should not be included *in general* in the system model representing the process network of a good or service. The salaries paid to the employees will induce consumption and investments, and taxes will help the authorities to provide services like education, social services, national defence and public security (military and police), *et cetera*, to the public. And the distribution of dividends will either lead to further investments or to immediate private consumption.

In this chapter, questions about the system definition in relation to employees (salaries), to the state (taxes and subsidies) and to the shareholders (dividends) are treated. In Subchapter 6.2, the representation of private consumption in economic as well as LCA models is reviewed. The allocation problem is formulated in relation to the in- or exclusion of the worker's private activities in the process network of a good or a service. After a discussion of the driving forces of business activities, the representation of environmentally relevant activities induced by salaries, taxes and subsidies is elaborated in Subchapter 6.3. It is derived how taxes and dividends may be mirrored by corresponding flows of commercial and ecological commodities. On the side of financial inputs, the role of subsidies received from the authorities is discussed and a proposal for allocation is given. The effects of the inclusion of the reproduction of labour in an LCA are shown in Subchapter 6.4 by means of examples from the banking and the energy sector. It is shown that the cumulative flows of ecological commodities of the LCA of the banking institute may double whereas in the energy sector the augmenting effect is only in the order of one percent. In general, however, the effect is of minor importance and its use for traditional LCA goals such as product or process development is limited.

### 6.1.2Allocation Problems on Two Levels

Webster defines the verb "to allocate" [*ad*: to + *locare*: place] as "to distribute or assign, allot or apportion". Or, in the words of Thomas (1977, p. 1), allocation means

> (...) any partitioning of a whole into parts, any division of a subject among objects.[1]

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[1] Thomas (1977, p. 1)

In this thesis, the term "allocation" is used on two different levels: In this chapter, the problem is treated of how to assign the flows of commercial and ecological commodities induced by the production factors capital and labour to the various purposes of these production factors (e.g., private consumption and work). In Chapter 7, allocation deals with the classical problem confronted with in management sciences, and, in particular, in cost accounting. Their, the question about "competitive" or "fair" partitioning of joint private and environmental external costs is further elaborated.

## 6.2Private Consumption and the Reproduction of Labour

### 6.2.1Private Consumption in Macro-economic Models

In Chapter 3, the representation of the economic system of standard economic textbooks is shown (see Fig. 3.2). Here, the question will be discussed whether the strict separation of production and consumption is useful or indispensible in the context of LCA, and whether private consumption as a means for the reproduction of labour needs to be (partly) included in an LCA or not.

The central question in relation to LCA is whether private consumption is interpreted as a means for leisure or for the reproduction of labour. In most macro-economic models (e.g., Leontief (1985)) and in nearly all system models used in Life Cycle Assessment labour does not enter the system models as a basic commodity[2]. Koopmans (1951), for instance, treats labour

> like smoke pollution, as a negatively desired commodity which is also a primary factor. (...) Besides being used in all productive activities, manpower is then introduced as an input of the activity "recreation" of which the sole output is the positively desired commodity "leisure"[3].

In some early models considered by Leontief and von Neumann as well as in one of the models of Piero Sraffa, labour has been treated as the output of an activity, of which consumption of various commodities constitutes the set of inputs (Koopmans 1951, p. 39). Sraffa, for instance, introduces a system model in his book "Production of Commodities by Means of Commodities", summarised by Newman (1962), where

> workers are produced like any other commodity, requiring definite inputs of wheat and wine, etc. in order to produce the given amount of labor time (...).[4]

In his initial system model, he interpretes final consumption as input or production factor for the reproduction of labour. This point of view restricts the purpose of final consumption to the reproduction of labour, an opinion which is as normative as the opposite view[5].

### 6.2.2Private Consumption in LCA

Despite the clear answer given by standard economics about the treatment of consumption and production, we will ask ourselves how to treat consumption (private and public) in LCA system models. Two extreme positions may be formulated in respect to private consumption and work:

[2] See section 5.4.1 for the definition of the terms "basic" and "non-basic commodity".

[3] Koopmans (1951, p. 39ff.)

[4] Newman (1962, p. 58)

[5] Following economic rationalism, one would entirely exclude private consumption for the enjoyment of individuals from LCA because individuals may act as they please without restriction to them as private persons. Only *work* done by persons leaves this private realm and hence would be included in the analysis. Although widely applied, this is of course a normative position.

*a)* Living is a "joint production" process delivering the outputs labour *and* leisure.

*b)* Living is a process for the one and only end, namely, leisure.

*Ad a)* Interpreting life as a "joint production", labour gets an intrinsic value and is an ultimate end like leisure. The (at least) twofold purpose of living leads us to the following question of allocation:

Which shares of total final consumption should be allocated to labour and leisure, respectively?

*Ad b)* If we consider work as a direct intermediate means to leisure, work (e.g., manufacturing, consulting, etc.) does not only deliver products and services as outputs but also satisfaction and enjoyment for the workers. Accordingly, the allocation problem moves from the consumption (the worker) to the production (the firm) and the problem may be reformulated accordingly:

Which shares of flows of commercial and ecological commodities caused by a production process should be allocated to the goods produced and to the satisfaction of the workers, respectively?

While option *a)* would lead to an increase in cumulative flows of ecological commodities attributed to a particular good, option *b)* may lower the cumulative flows of ecological commodities because a part of commercial and ecological flows is directly attributed to the output "leisure" of the individual worker. In the following, I will concentrate on option *a)*, the allocation problem between leisure and the reproduction of labour.

Boustead et al. (1979) reflect on the energy associated with food consumed by workers and their inclusion in the energy analysis of industrial operations and give reasons why it usually is ignored. They first argue on a conceptual level:

> One reason for ignoring the energy associated with the labour force is said to be conceptual. It is argued that if humans are included in an industrial system then not only are they producers of goods and services but they are also consumers. Thus the output of all industries are essentially consumed by the human 'machines' within the industrial system so that there is no net output. It is therefore conceptually unrealistic to identify the output of foodstuffs and their associated energies as 'energy debits' to production activities.[6]

This description of the system corresponds to the Sraffa-model mentioned above, within which workers are "produced" like any other commodity[7]. However, Boustead et al. (1979) are not fully convinced of their conceptual reason, and continue:

> Such an argument is however more apparent than real because it presupposes that an industrial system is defined solely in terms of physical components. As discussed earlier, the nature of a system is defined in terms of identifiable functions and *not* in terms of physical components. There is no reason therefore why the production aspect of human behaviour cannot be separated from the consumption behaviour and included within the defined system. In the same way, the 'consumption' behaviour may also be subdivided. Only if systems are defined solely in terms of physical components does it become necessary to include the whole of human behaviour, but at the same time the *total* behaviour of *all* machines must also be included.[8]

They subdivide human behaviour into two parts, and final consumption serves two purposes, namely, leisure and the reproduction of labour. Hence, they face an allocation problem. If the whole consumption is allocated to the reproduction of labour, the world economic system produces no output, except emissions to air and water and wastes as well as the life experience of 6 billion human beings during a certain period. In this case, life years enjoyed is the "only" valuable output of the whole economic system. However, such a model cannot be used for the aggregation of all flows of

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[6] Boustead et al. (1979, p. 180)

[7] And within which private consumption is completely dedicated to maintain the worker's productive power.

[8] *Op. cit.* (p.180)

ecological commodities to the world's total flows by adding up the LCAs of the entire private consumption. The fact that the whole economic system produces no net valuable output (besides enjoyment) requires that the functional unit is defined as the production of one *additional* good or service, in excess of the actual demand. That is why the outcome of an analysis based on an economic system model that comprises private consumption entirely does not comply with the 100%-additivity[9] and hence may not provide an answer to the attribution problem of Heijungs.

Boustead and Hancock do not further elaborate the allocation problem between life and work but list a pragmatic further reason why to neglect energy associated with the reproduction of labour:

> If this were the only reason for excluding the energy associated with labour, then it is debatable whether its exclusion could be justified. There is however a more concrete and much less philosophical reason for ignoring it: this is the magnitude of contribution.[10]

They then calculate a contribution of energy consumption associated with the food needed by workers of less than 0.1% in relation to the energy consumption of highly industrialised systems[11]. For that purpose they allocate half of the nourishing activity to the maintenance of the person as a living organism and half to its industrial component. Based on their estimate, they recommend to neglect the energy contribution of labour except for

> (...) low energy consuming systems such as agricultural operations in developing countries, where human or animal labour may be the only input (...).[12]

But why should we restrict the analysis to the food the workers consume? The share of consumption attributable to the reproduction of labour involves a normative valuation and dedication of human activities to labour and leisure. Boustead and Hancock used 50% of food consumption. But one might as well think of 10% of food consumption, clothes and water consumption or of a certain share of the entire private consumption (i.e., including holidays, transport, health care, *et cetera*). In the illustrating example in Subchapter 6.4, 50% of the entire private consumption shall be used.

## 6.3 Profit, Taxes, Dividends, and Investments

### 6.3.1 The Purpose of Business as Modelled in LCA

In traditional LCA, the purpose of a firm is interpreted as the production of goods and services. A refinery, for instance, converts crude oil to products such as light and heavy fuel oil, gasoline, bitumen, sulphur, *et cetera*. For the production of these goods, certain amounts of labour, capital, energy (oil and electricity), and working materials (caustic soda, catalysts, *et cetera*) are needed. From that point of view, the process of refining oil is caused by the demand for the various oil products. However, a refinery would not be operated if its profit rate were too low compared to other investment possibilities. The way a refinery is operated is not only determined by the quality standards for the products but also by the aim of maximising profit, of increasing the shareholder value of the company. According to standard management sciences, the economic efficiency is the overall parameter to be optimised:

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[9] The 100% additivity rule states that the sum of the parts equals the total, see also Subchapter 5.5.

[10] Boustead et al. (1979, p. 180)

[11] Due to an increasing labour productivity and structural unemployment, this share may even be lower today and further decrease in the future.

[12] *Op. cit.* (p.181)

> Economic efficiency involves choosing from among the technologically efficient combinations the one that represents the least sacrifice for the firm [in producing a certain output].[13]

Dependent on the economic context, the technically and environmentally most efficient way to manufacture may be economically less efficient than other alternatives. But from the point of view of the shareholder, it does not matter how (technically) efficient his or her capital invested realises the profit as long as the profit is acceptably high[14]. Even more, the kind of goods and services, with which the profit is made, may be insignificant for him or her, whereas the properties and quality of the goods and services are the central issues for a client purchasing them. The shareholder may invest in fisheries, in the wood industry as well as in life sciences, biotechnology or in firms or projects of the energy sector. We therefore may conclude that the driving forces of the activities of a firm are to satisfy

- the demand of consumers, and
- the profit wishes of the shareholders.[15]

These two purposes are closely related but situated on different levels. Whereas proceeds compensate for the activities undertaken to satisfy the consumers, dividends are the costs of capital received from the shareholders. From the point of view of the owners of the firm, the payment of dividends are one part of their income. Hence, the paid-out part of profits is not an additional product, and there is no allocation problem involved in this apparent ambiguity of a firm's activities.

But another aspect is relevant in this context, namely the question whether or not, the payment of dividends is environmentally relevant for the goods and services sold. The same question may be asked for the taxes paid to the authorities.

### 6.3.2 Effects of Distributing Dividends and Paying Taxes

The distribution of dividends leads to private consumption, and further investments. Taxes enable the authorities to cover the costs of their activities. Therefore the question arises, whether or not, the activities induced should be included in an LCA.

Following the methodology described in Chapter 5, plant equipment of processes in expansive and consolidating markets is included in the LCA system model. Hence, the spending of investments for productive capacity is automatically considered when analysing the consumption of goods and services for which these investments have been made. In order to avoid double counting, any investment should only be accounted for as long as it is related to the production or generation of the good or service *at issue*. Investments made for future production should not be considered in an analysis of today's production. This is of course a normative decision and fully based on operability considerations[16]. Theoretically, one might argue that a certain share of a particular investment for

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[13] Lipsey et al. (1972, p. 173)

[14] In this context, LCA may be used to treat another question investors may be confronted with. The question about the most environmentally benign investment for a given profit rate as the functional unit. In that case, the functional unit is the profit rate disregarding the products being manufactured by the economic sectors, industries or particular firms that he or she may invest in.

[15] Taxes to be paid to the authorities (a special kind of "shareholder") is similar to the "expectations of the shareholders", and therefore may be treated the same way as a firm's payments of dividends.

[16] Otherwise one would need to know which share of the investments has already been accounted for in LCAs of *today's* consumer goods, when analysing *future* consumer goods.

future production should be allocated to today's consumption too, because the original causation for these investments partially lies in the consumption of today.

On the other side, a share of future *consumption* enabled by today's profits may well be included in the analysis, when private consumption is partly dedicated to the reproduction of labour. For that purpose, the share of private consumption on the total dividend distributed and the kind of goods and services purchased need to be known. Here, a rough estimation is given by the share of investments on the gross domestic product of a country. In Switzerland about 20% of the gross domestic product has been used for investments in 1977 whereas in 1992, the share of investments has been close to 24%. According to that, between 75 and 80% of salaries and taxes paid, and of dividends distributed would be used for immediate consumption. The second aspect, namely the kind of products consumed, may be approximated similarly by using the national yearly average of private consumption.

### 6.3.3Subsidised Products

Certain products, like for instance milk and milk products in Switzerland, are subsidised to improve their competitiveness and to guarantee the consumption of the amounts produced. By that, the authorities support industrial activities that would otherwise either disappear or be reduced. Hence, the motivation for such industrial activities is not only given by the sale of the goods or services but also by the governmental payments. This twofold motivation raises the question of allocation again. What share of the total flows of commercial and ecological commodities of a subsidised product or production process shall be allocated to the proceeds and to the subsidies, respectively? Both parts of the income are compelling but not sufficient for a firm to sustain. Without subsidies, as well as without customers, the operations may well be shut down. From that point of view, the flows of commercial and ecological commodities may entirely be allocated to each one of the two motivations. A compromise solution to this problem may be found in the reasoning given, e.g., in Huppes (1993):

> The single reason for the existence of this process part [the joint process kernel] is the total value it creates through its products, (...). There, the value generated by each product is the basis for allocation. It can be made operational through the gross sales value method.[17]

Hence, if we interprete the subsidies as payment for a virtual co-product, the allocation between the subsidies and the product may be performed on the basis of the shares in income stemming from the now augmented number of products. High shares of subsidies improve the product's environmental performance from the point of view of the customers but at the same time changes the environmental performance of the state's activities[18]. With such an allocation procedure, market imperfections, which lead to artificially reduced prices, are mirrored by similarly lower cumulative flows of ecological commodities. The elimination of subsidies would not only reestablish the true economic competitiveness of formerly subsidised products but also automatically show their "real" environmental performance (cf. the example of free discharge of waste, described in Section 3.3.2).

In the case of direct payments for services not reimbursed because they are provided for the commons, e.g., conservation of typical Swiss landscapes by farming, preservation of recreation areas by

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[17] Huppes (1993, p. 219)

[18] Whether the environmental performance is impaired or improved depends on the alternative uses of the money if not spent for that particular subsidy.

cultivating a forest, the allocation of flows of commercial and ecological commodities leads to a partitioning among the various services provided by the respective activities. In this case, the improvement of the environmental performance is not artificial but reflects the multi-function character of, e.g., farming or forest cultivation. Direct payments may therefore be interpreted as paying public consumption. There is no difference between direct payments and subsidies in relation to the allocation procedure and allocation outcome of a product having public and private proceeds.

## 6.4Consequences of Partly Including Private Consumption in LCA

### 6.4.1Examples from the Banking and the Energy Sector

For a first rough estimation about the inclusion of a part of private consumption in an LCA, two cases from the banking sector (Credit Suisse and Swiss Bank Corporation) and one case of the energy sector (Royal Dutch/Shell) will be used. For the Swiss Banks considered here, some LCA data for the administrative part are available (SKA 1995, Schweizerischer Bankverein 1997)[19]. However, the considerations in this section are restricted to energy consumption expressed in primary energy due to still missing LCA data about several aspects of private consumption. For Royal Dutch/Shell, data about primary energy consumption per year is derived based on the amount of crude oil processed and the average primary energy needed to process it based on data given in Frischknecht et al. (1996a, Part IV Erdöl). For the energy consumption of the households, data about the energy requirements of Dutch households published in (Biesiot et al. 1995) are used.

The two banking institutes show a similar specific electricity consumption per employee whereas the the Swiss Bank Corporation needs 3.5 times more heating energy per employee compared to Credit Suisse (see Tab. 6.1). The primary energy demand per employee lies between 30 and 36MWh.

| | unit | Total final energy | | unit | Primary energy per employee | |
|---|---|---|---|---|---|---|
| | | Credit Suisse | Swiss Bank Corporation | | Credit Suisse | Swiss Bank Corporation |
| Heat | MWh | 16'400 | 42'600 | kWh | 2'400 | 8'400 |
| Electricity | MWh | 55'500 | 42'800 | kWh | 24'000 1) | 25'000 1) |
| Travelling | km | 21 Mio. | 18 Mio. | kWh | 3'000 2) | 3'000 2) |
| | | | Total | kWh | 30'000 | 36'000 |

Tab. 6.1: Main items of energy consumption in two Swiss banks normalised by the number of employees, (SKA 1995, Schweizerischer Bankverein 1997);
1): Conversion factor electricity to primary energy: 3;
2): 1kWh/km assumed

In 1991, the Royal Dutch/Shell group produced about 100 million tons crude oil per year (Royal Dutch 1992). Assuming an average primary energy consumption of 3MWh (including extraction, long distance transportation, refining and distribution, Frischknecht et al. Part IV Erdöl, p. 261) for the processing of one ton of crude oil to petroleum products, 300TWh primary energy are needed in total per year. Within the oil and gas sector Royal Dutch/Shell gave work to about 90'000 employees.

19 The effects caused by the products (credits given, *et cetera*) are not included in the figures presented here.

The question is now, whether the inclusion of a part of the reproduction of labour leads to a substantial increase of the energy requirements of banking services and petroleum products, respectively. For that purpose we need to know the direct and indirect energy consumption of households.

The energy consumption of households is divided in a direct energy demand for heating, lighting, and transportation, and an indirect energy demand caused by the consumption of food and clothes, by medical care, by education, *et cetera* (See Tab. 6.2). According to investigations made by Biesiot et al. (1995), the total primary energy demand amounts to about 66MWh per average Dutch household.

| category | GJ | kWh | % of total |
|---|---|---|---|
| *Indirect energy requirement* | *130* | *36'000* | *54* |
| Food | 41 | 11'000 | 17 |
| House | 9 | 3'000 | 4 |
| Household effects | 19 | 5'000 | 8 |
| Clothing & footwear | 8 | 2'000 | 3 |
| Medical care | 12 | 3'000 | 5 |
| Hygiene | 5 | 1'000 | 2 |
| Education & recreation | 24 | 7'000 | 10 |
| Transport & communication | 11 | 3'000 | 5 |
| *Direct energy requirement* | *110* | *30'000* | *46* |
| Electricity | 28 | 8'000 | 12 |
| Heating | 60 | 17'000 | 25 |
| Petrol | 22 | 6'000 | 9 |
| Total | 240 | 66'000 | 100 |

Tab. 6.2: Total direct and indirect energy requirement of an average Dutch household in 1990 per main category; from (Biesiot et al. 1995)

These rough estimates show that for each kWh of primary energy required at the place of work in the banking institutes 1 kWh is directly required in the employees household, and another one is required indirectly by the household's consumption. If we allocate 50% of the household's total primary energy consumption to the reproduction of labour and include it in the LCA of the banking institute, the amount of primary energy required doubles.

Due to the high labour productivity and the relatively high specific energy consumption of the activities of the oil industry, the effect of including energy requirements for the reproduction of labour into the energy balance of Royal Dutch/Shell is minor. The amount of primary energy required by Royal Dutch/Shell's activities is augmented by only 1%.

### 6.4.2Discussion of the System Model

The main question that arises when people are confronted with the question about the inclusion of human labour concerns the issue of double counting. The addition of the LCAs of all goods and services consumed in the world (or in Western Europe), based on a system model where the whole private consumption is allocated to the reproduction of labour, would make no sense, because

> there is no surplus in the production of any commodity, i.e. all the output of each product is used to produce other products (including itself), and none goes for final consumption.[20]

[20] Newmann (1962, p.59)

Such a system model consists of self-sustaining unit processes, only fed by external low entropy resources and secreting high entropy wastes. In such a closed model, the responsibilities and causalities become diffuse and indefinite. They change dependent on the object under study. By buying a radio and listening to a broadcast, for instance, I would not only be responsible for the flows of ecological commodities caused by the production of the radio and a tiny part of the broadcasting activity but also for a tiny part of the private consumption of the moderator, the radio announcer, the radio engineer, *et cetera*. On the other hand, the moderator would be responsible for a part of my private consumption (including radio listening, of course), if he commissioned an LCA on broadcasting activities. Such a system model requires the functional units to be defined as the production of one *additional* unit of a good in excess of the actual demand. The activities included in the respective process networks by completely including the reproduction of labour overlap and the 100% additivity rule is violated. But when only a part of final consumption is allocated to the reproduction of labour, then the remaining part is the output of the whole economic system. Hence, this remaining part is the reference flow to which all other activities are allocated to and which may be used for the addition of the world's total flows of ecological commodities.

## 6.5Conclusions

Until now, salaries paid to employees, dividends distributed to the shareholders as well as taxes paid to the authority are environmentally unsullied. Here, we plead, with restrictions, for an inclusion of paying salaries, distributing dividends and of paying taxes to the authorities into the system model of LCA. Thereby an allocation between "work" and private consumption ("leisure") needs to be made.

The principle question about the inclusion of the activities induced by the payment of dividends needs to be discussed similarly because a part of the effects are caused by private consumption (however happening in the future). No allocation problems occur to include the effects caused by paying taxes. In Switzerland however, we are still far from an operationalisation because of missing LCA data of the authorities' activities (cf. BfS et al. 1997, p. 235).

We suggest not to include investments induced by savings[21] in order to avoid possible double counting. The flows of commercial and ecological commodities caused by future investments would otherwise be counted twice (once while analysing today's consumption and once when analysing the consumption of goods for which the investments will be made). However, investments will be considered when analysing the respective consumer goods. But future consumption enabled by the profit made with today's activities may be included in the process network of today's goods and services. By including the consumption induced by taxes and dividends into the process network, the environmental performance of goods and services is impaired. Because a certain share of future consumption is causally related to today's activities, i.e., consumption induced by the distribution of dividends, and by paying taxes, the flows of commercial and ecological commodities of future consumption will only be counted once. This kind of causality is similar to the fact that a certain amount of electricity produced is dedicated to the steel industry, and that all shares defined by such causalities add up to the entire volume of electricity generation. Including future private consumption induced by today's profit (dividends distributed), a part of the effect of an increasing

[21] Savings stem from total income, hence from wages, paid-out profits (private and public savings), and taxes (public savings only).

economy is covered. Future investments which enable the production of goods and services asked for in the future are included indirectly.

While the effect of an inclusion of dividends and taxes could not be determined on the basis of case studies within this thesis, the effect of including a part of private consumption has been proven to be of minor importance. The statement of Boustead et al. about the relevance of private consumption in the energy analysis of energy intensive industrial processes is confirmed even when considering half of the entire private consumption. However, the tendency of increasing per capita consumption and increasing environmental efficiency of industrial processes will make it necessary to reconsider this statement within a couple of years. In the banking sector, (still) involving a high proportion of personnel, the share of primary energy consumption caused by 50% of the private consumption of the employee's household doubles the primary energy consumption attributed to the banking activities. However, the overall energy consumption per employee in the banking sector is low compared to, e.g., the oil and gas industry. Self-evidently, the contribution of the reproduction of labour is of minor importance in the energy-intensive energy sector. Hence, the partial inclusion of private consumption in LCI system models leads to reduced differences in the energy intensity of products.

The production factors labour and capital are mostly neglected in today's LCA. There are, however, some reasons why they may, theoretically or practically, be included in the process network of goods or services. Below, some reasons and preconditions are summarised.

- Activities of the authorities paid by taxes shall in principle be included in an LCA to comply with the general procedure stated in Section 3.3.1, although their relevance is minor.
- The inclusion or omission of private consumption in an LCA system model depends on its perception and the decision to be supported by LCA. If work is interpreted as an equivalent end like leisure, a share of private consumption may be allocated to the product under analysis.
- If private consumption is completely included, the system model would become closed, i.e., all goods and services produced would be used up within the system, and no flows of commercial commodities would leave the system anymore. Such a system has no end, despite the biological end of human life years lived, of self-subsistence of mankind.
- The relative relevance of private consumption of employees depends on the allocation factor, and the labour intensity and environmental impacts of the respective economic sector. Its (partial) inclusion leads to reduced differences in the energy intensity of products.
- Paid-out profits and wages induce further investments and private consumption. We suggest not to include future investments in the analysis of today's consumption of goods and services in order to avoid double counting. The induced private consumption may at least partly be considered if private consumption is perceived as a means for "leisure" *and* for the reproduction of labour.
- Dividends may be interpreted as the functional unit of an LCA of investments. In this case, the goal of an LCA would be to identify the most environmentally benign way to invest money among different alternatives with comparable profit rates.

# 7. Allocation in Joint Production

## 7.1 Introduction

### 7.1.1 Energy as a Joint Product

In 40 km distance from Reykjavik, Iceland, a geothermal power plant named "Blue Lagoon" produces electricity and heat for the region around Keflavík making use of hot salt water of more than 250°C from up to 2'000 metres below surface. Besides the power plant, a small lake has formed into which some 1'000 tons of water are flowing hourly. Today, this "Blue Lagoon" is a thermal spa with a small seaside house, a restaurant and bathing cabins open in summer- and wintertime (NZZ 1995).

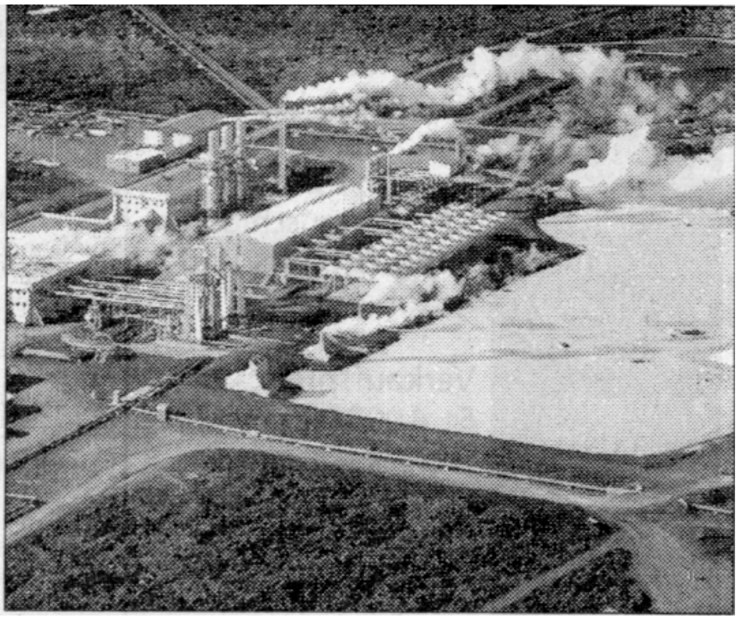

Fig. 7.1: Geothermal power plant and thermal spa "Blue Lagoon" near Reykjavik, Iceland, (NZZ 1995).

This example gives an idea about the complexity encountered when a technical system has to be defined in respect to its functions, and to its boundaries versus other technical systems. The example describes a system which delivers two services (nearly) simultaneously. The questions arising are the following:

- Is the service "taking the waters at the Blue Lagoon" a joint product of the geothermal power plant or is it just a by-product?

  And, if it is interpreted as a joint product:

- How much of the resources (hot water, land, *et cetera*), and working materials and energy used at the plant shall be dedicated to the electricity and heat produced, and how much to the yearly 100'000 visitors of the thermal spa?

Finding generalisable answers to allocation problems is difficult. The answers are seldom clearly right or wrong. Not for nothing, the adequate analysis and modelling of multi-output processes or multi-output manufacturing sites is sometimes seen as one of the fundamental, still unresolved problems in Life Cycle Inventory Analysis (Udo de Haes et al. 1996, p. 168). The proposals made in the recent history of LCA are manifold and the results of an LCA using various approaches are not seldom contradicting. In Lindfors et al. (1995b) seven allocation approaches for cascade systems are discussed and Schneider (1996) describes 21 different approaches used for the analysis of waste treatment options, for the comparison of different products and services and for the analysis of the entire life cycle of resources. However, a clear link between the purposes for which allocation is carried out (the decisions to be supported by an LCA) and the allocation procedures is still missing. One crude attempt is made in the European concerted action LCA-Net documented in the theme report on goal and scope definition and inventory analysis (Frischknecht 1997), where allocation procedures are linked to the various goals of an LCA.

The questions related to allocation treated in this chapter are the following:

- How can the borderline between ecological and commercial commodities, between the useless (or even harmful) and the useful output be defined or located?
- How should the undesired co-products and all other inputs be allocated or apportioned to the intended (wanted) outputs?
- Are there non-arbitrary methods available in the case of joint production?
- Is it possible to link allocation purposes with certain allocation procedures and/ or process types?

After clarifying the terms joint and combined production, the different cases of multi-function systems are described in Subchapter 7.2. The distinction between co-products, by-products and waste as well as between co-production and recycling processes is elaborated. Starting from the question about the purposes of joint product allocation (Subchapter 7.3), a decision tree for allocation procedures in LCA is introduced in Subchapter 7.4. Three new approaches are described and discussed in respect to existing approaches in Subchapter 7.5. Their discriminating features are joint versus combined production, single versus multiple decision-makers, and sufficiently perfect and imperfect markets.

### 7.1.2 Combined versus Joint Production

In this chapter, the allocation problems similar to the ones encountered in cost accounting of production activities are treated[1]. Mill, who is often cited as the first one seeking for a procedure to perform allocation, defines the allocation problem as follows:

> A principle is wanting to apportion the expenses of production between the two [joint products].[2]

The distinction between joint and combined production, between joint and indirect costs of production is relevant in this context[3]. Manes et al. (1988, p. 2ff) report on an exchange between Pigou and Taussig in 1913 in the Quarterly Journal of Economics about the meaning of joint costs. Pigou (1913, p. 691) stated:

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[1] For the allocation problems encountered in the context of the factors of production, i.e., labour and capital, see Chapter 6.

[2] Mill (1848, p. 105)

[3] Joint and indirect costs together are often called common costs (cf. Huppes 1993, p. 203). Indirect costs comprise the costs of overheads or service departments. Some of the overheads may be called nearly joint, because *"an attribution of its function to each product cannot be quantified at a functional level, let alone at a physical level"* (Huppes 1993, p. 208).
Indirect costs result from the production of more than one product using the factors of production to produce several products. But any indirect cost factor can be directed to the production of a single product instead of several products.

> (...) Whereas the supplementary expenses of producing cotton fibre and cotton seed are both common costs and joint costs, the supplementary expenses of producing copper transport and coal transport are common costs only.[4]

For Taussig (1913, p. 693), however,

> (...) the principle of joint costs may be applicable even though a supply of one thing does not necessarily entail the supply of another.[5]

The characteristics of joint production problems are not only its simultaneity and necessity, but also the fact that joint products need to be sufficiently different. This has been pointed out by Viner, cited in Edwards (1952):

> Professor Jacob Viner, an authority in cost problems, suggests that joint products are "commodities which are sufficiently distinguishable from each other to have different markets and to command different prices even under competitive conditions but which are partly or wholly the outcome of a common process of production."[6]

In line with Pigou, the term joint production is restricted here to sufficiently distinguishable joint products produced in fixed proportion. The term combined production is used for products produced in controllably variable proportions. The procedure developed in this chapter applies to joint production only.

## 7.2 Multi-function Systems

### 7.2.1 Overview

Dellmann (1980) classifies the process types in throughput, analytic, synthetic and regrouping production, dependent on the use of inputs (see Fig. 7.2). His distinction focuses on the main, intended output and also on the main inputs. In reality, nearly all processes are regrouping processes, using several inputs (intermediate goods, services, *et cetera*) and producing a variety of intended, tolerated and undesired outputs (products, by-products, wastes and emissions), the latter sometimes called undesired co-products.

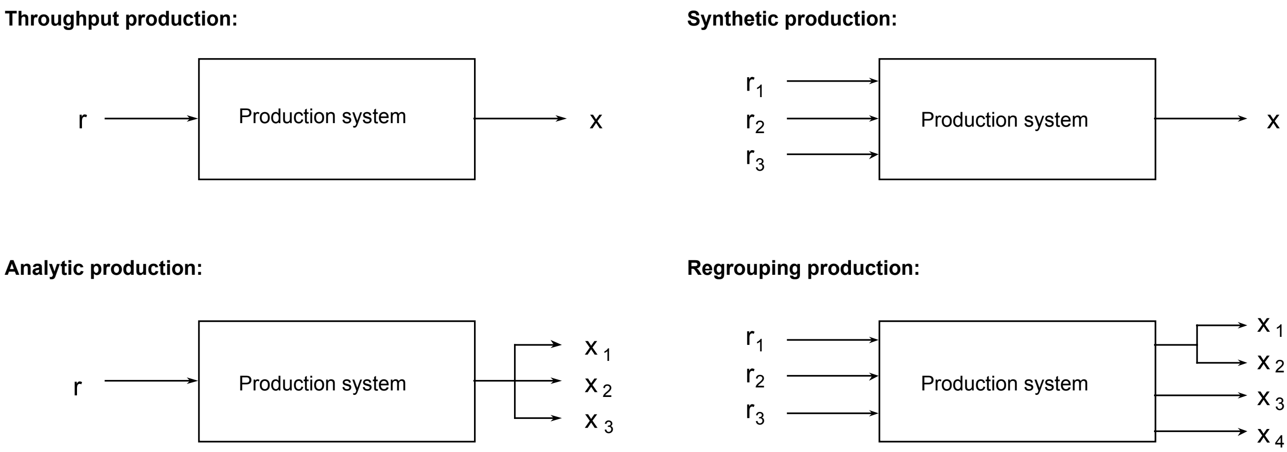


Fig. 7.2: Typology of processes according to the use of inputs, after (Dellmann 1980, p. 46); own translation

In LCA, three situations are usually distinguished in relation to allocation problems, namely (Huppes 1992, p. 59ff., Consoli et al. 1993):

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[4] Manes et al. (1988, p. 2)

[5] *Op. cit.* (p. 2)

[6] Edwards (1952, p. 311)

- Co-production (multi-output processes),
- Waste treatment processes (multi-input processes), and
- One-input-one-output (recycling) processes.

Based on the financial-flows-based definition of the production function (see Chapter 3), it is sufficient to discriminate mono- and multi-function or mono-, and multi-output processes. In the process model developed in this thesis, all unit processes do have positively valued outputs or "cost" objects (either material or immaterial) although the physical flow and the monetary flow may have the same direction[7].

This distinction follows the classification established by Thomas (1977, p. 2) who distinguishes three kinds of allocation problems, namely

- one-to-one,
- many-to-one, and
- one-to-many allocation.[8]

If we interprete the outputs $x_i$ in Fig. 7.2 as "cost" objects, we recognise that the two upper production situations (throughput and synthetic production) represent the one-to-one and the many-to-one situation, where all inputs $r_i$ (subjects) are allocated to the one and only cost object. These situations offer only a few theoretical problems. In analytic and regrouping production situations, however, inputs (subjects) have to be allocated to the various outputs ("cost" objects).

| | **characteristics** | **examples** |
|---|---|---|
| **mono-function** | one single money flow to the process | |
| **multi-function** | more than one money flow to the process due to: | |
| - multi-output | several physical outputs | co-production, cascade systems [1]), plants and equipment [2]) |
| - multi-input | several physical inputs | combined waste treatment (without heat recovery) |
| - multi-throughput | several physical, unchanged in- and outputs (goods transported) | combined transportation (e.g., passengers and freight) |
| - mixed | several positively priced physical in- and outputs | combined waste treatment (with heat recovery), recycling processes |

Tab. 7.1: Distinction between mono- and multi-function processes made in this thesis, and its further discrimination according to the SETAC Code of Practice.
[1]): Cascade systems show multi-function characteristics on a system level (not on a unit process level), see e.g., Schneider (1994), Karlsson (1994), Schneider (1996);
[2]): A process delivers products and partly depreciated plants and equipment (Georgescu-Roegen 1971, p. 216).

In LCA, one-to-many processes (or systems) are called multiple-function systems (Azapagic 1996, p. 34), multiple processes (Huppes 1994, p. 75, Huppes et al. 1995, p.64), or multi-function systems (Frischknecht 1994, p. 122). They may be subdivided in multi-input, multi-output, multi-throughput, and mixed processes (see Tab. 7.1) according to the classical categorisation of the SETAC Code of Practice. Multi-use systems like cascade systems of certain materials (see, e.g., Schneider

[7] This is the case, for instance, when a firm has to pay for wastes to be treated (see also Section 3.2.2).
[8] More precisely, Thomas speaks about one-subject-to-one-object, many-subjects-to-one-object, and one-subject-to-many-objects allocation.

(1994), Karlsson (1994)), and the multiple use of plants and equipment (see, e.g., Georgescu-Roegen (1971, p. 216ff.)) are classified in the category of multi-output systems.

In line with the process model described in Chapter 3, combined waste treatment is defined as a multi-function process delivering the purchased services "treatment of waste $W_1$", "treatment of waste $W_2$", *et cetera* as well as district heat and electricity. The same perspective applies for transportation and recycling processes (see Tab. 7.1).

I will now turn to two central characteristics to distinguish mono- from multi-function systems on the one hand, and co-production from recycling processes on the other. The distinction between product, by-product and waste is needed to determine the outputs to which all other flows of commercial and ecological commodities are allocated. The distinction between co-production and recycling processes is important in view of the allocation approach applied in these different types of processes.

### 7.2.2 Mono- and Multi-function System, By-product and Waste

Multi-output processes appear in nearly all industrial processes. Beside of the intended product(s), emissions to air and water as well as wastes are produced. The latter outputs are unwanted and may therefore be called "undesired joint products" (Müller-Fürstenberg 1995, p.35). The usefulness of the various outputs should be determined to be able to identify the "cost" objects amoung the outputs, for which a separate measurement of economic and ecological costs is desired. In Consoli et al. (1993) the key-words are "'beneficial use' for other systems". Most common is the use of economic values of the output. A positive economic value indicates that there is a demand for the output in question. Outputs with a negative economic value can be seen as wastes (Frischknecht 1992, p. 2, Huppes 1992, p. 58, Heijungs et al. 1992b, p. 24, Schneider 1996, p. 85). Horngren et al. discern joint or main product, by-product, scrap and waste (see Fig. 7.3) based on their relative sales values. However, the criteria used for a distinction within the "useful" products are not clear at all. For Bierman et al. (1990)

> (...) the distinction between a joint product and a by-product is primarily a result of accounting convention and of minimal use to management in decision situations.[9]

However, the distinction between product and by-product is useful to discriminate different approaches in joint product allocation in LCA. In this thesis, the outputs to which no flows of commercial and ecological commodities are allocated to but which are used by other economic processes are called by-products. They cause no or only little money flow to the process they stem from. When the sales value is negative, i.e., the firm has to pay for a disposal service in today's economy, the output is called waste.


[9] Bierman et al. (1990, p. 536)

Fig. 7.3: Joint product, main product, by-product, and waste defined on the basis of relative sales values within a firm, adapted from Horngren et al. (1991, p. 528).

The application of the "economic value"-criterion is an implicit valuation. The prices of products and services in economies depend on demand and supply and are influenced by the legal, social and political conditions the economy is embedded in. The classification of wastes and by-products may change if environmental external costs are included into the consideration (see Fig. 7.4). On the one hand, an initial waste (such as used tires) may be perceived as an environmentally benign alternative to primary raw materials (e.g., in cement production) and by that become a by-product. On the other hand, an initial by-product may loose its competitiveness due to high environmental impacts and may become a waste.

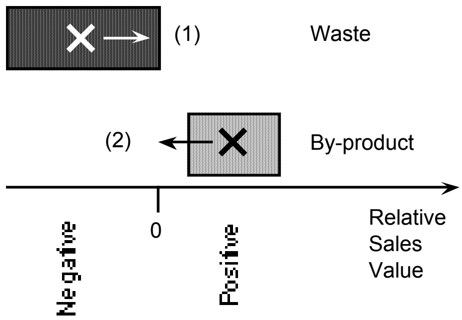


Fig. 7.4: Two scenario when environmental external effects are included, which influence the way these commercial commodities are represented in the LCI system model:
(1) Waste may get a positive sales value because it is wanted due to its good environmental performance compared to competing goods.
(2) The price of by-products may be driven down towards zero, or even worse, the firm will have to incur costs to dispose of it because of the by-product's poor environmental performance.

Because the effects mentioned above are hard to predict, we need to confine ourselves to the information provided by today's economy. Therefore, (main) products, by-products, and waste are defined according to its actual sales value, which leads to the following definition:

> By-products contribute little to the total proceeds of a process. No flows of commercial and ecological commodities are allocated to by-products, nor are they allocated to the main products. In distinction to by-products, wastes are tangibles leaving a process for the treatment of which a price has to be paid. Thus an output with a negative economic value is called "waste" and is allocated to the main product(s).

After we have defined how to discriminate main products from by-products and the latter from waste, the distinction between co-production and recycling is discussed.

### 7.2.3 Co-production and Recycling Processes

The opinions whether such a distinction is needed and whether the three cases mentioned in section 7.2.1 need distinct approaches has frequently been discussed. On the one hand the discrimination between recycling and co-production is questioned. According to Anonymous (1997, p. 16ff.), for instance, the stepwise allocation procedure formulated for co-production does also apply for recycling, although reuse and recycling situations require additional elaboration *Op. cit.* (p. 17). But also Finnveden (1994) states that

> [i]n practice, it may be hard to distinguish between multi-output and open-loop recycling, since the material recycled in an open-loop into a secondary product can be seen as a coproduct (...).[10]

On the other hand, I advocated in Frischknecht (1994a) for a strict distinction between open-loop recycling and co-production because of the imperative sequence of the former. This necessary sequence of activities or functions fulfilled within material or energy cascades is due to the entropy law and the irrevocable tendency of increasing disorder, and may be observed in nearly any product system. For instance, electricity cannot be generated using the waste heat emitted by the cooling tower of a thermal power plant. I then argued that the allocation procedure must consider this fact and proposed that

> (...) upstream activities should be allocated to the process using virgin and offering downcycled materials (or energy), and processing and transportation of the recovered material or energy to the process using secondary raw materials or waste heat (...).[11]

However, this is only one of several possible and plausible reasonings. In Lindfors et al. (1995b, p. 5ff.) many other approaches are described and discussed. Discussions are caused by the fact that the outcome of these approaches usually differ substantially.

The following systems will be discussed in order to highlight differences between and conformities of co-production and recycling processes:

*a)* co-production,

*b)* cascade systems, and

*c)* plants and equipment.

*Ad a)* Co-production is a process where several products (i.e., goods and services) are produced simultaneously but not necessarily[12]. Recycling processes (one-input-one-output processes) which produce new commodities out of wastes also belong to this category. Co-production may be distinguished according to different criteria. They help to evaluate adequate allocation procedures.

According to the variability of product shares:

- fixed proportions. The product portfolio of the production process may not be influenced by the decision-maker. The most frequently cited examples may be found in agriculture and in the chemical industry (e.g., slaughter house, chlor-alkali plant).
- narrowly variable proportions. The product portfolio of the production process is varied on a short-term basis in view of profit maximisation. Trade-offs need to be considered. An oil refinery is probably the most prominent example. Large combined heat and power (CHP) plants delivering power and heat, and petrochemical plants show similar properties.
- variable proportions. The product portfolio may be changed in a way that renders the multi-function process into a single-function one. Examples are common transportation (for instance copper wires and rockwool insulation material might be transported jointly as well as separately), or combined waste treatment.

  The variability is of course dependent on the treatment after the split-off point. The heat from a CHP plant may or may not be used (nearly) without affecting the production of mechanical

[10] Finnveden (1994, p. 65)
[11] Frischknecht (1994a, p. 127)
[12] E.g., freight and passenger transport in an airplane.

energy. But due to economic reasons, both joint products (heat and mechanical energy) will be used.

According to the time scale:

- time coincidence. The co-production process delivers immediately several products, which may be further processed.
- time lag. The various co-products are produced in sequence. This option comes close to the plants and equipment case (see below). Back and forth transportation services are an example of a time-shifted co-production process.

  In the terminology of Rummel, quoted in Riebel (1955, p. 77), this former kind of co-production is called "horizontal" joint production. For successively produced joint products, the term "vertical" joint production is applied. In the case of combined heat and power production, Riebel renounces to call this a "vertical" joint production process because both products are generated nearly simultaneously[13] and because the term "vertical" is needed for other co-production processes like batch production of different steel qualities. Any kind of cascade systems and recycling processes may also be classified as "vertical" joint production according to this definition.

According to the decision context:

- single decision-maker[14]. The co-products produced are under the control of the same decision-maker. He or she is autonomous in fixing allocation factors.
- multiple decision-maker. The co-products produced are under the control of different decision-makers. They have to negotiate for and agree on allocation factors.

  The situations of single or multiple decision-maker are independent of the kind of multi-function process at issue.

*Ad b)* Cascade systems involve the multiple use of one or more resources. According to Schneider (1996, p. 80ff.), it is composed of a sequence of life cycles of a certain material (resource). In that sense, they might be interpreted as a special case of a long-term investment and by that of the "plants and equipment" category described below. For instance, the service of "radio listening" may resurrect as "radio listening" again, because the electricity generated in the waste incinerator that burned the broken radio may be used to (partially) run the next radio. Usually, distinct decision-makers are involved in cascade systems. In a two function cascade system, for instance, two different decision-makers may be involved which control the first and the second life cycle, respectively. They will have to negotiate the allocation procedure to attribute jointly caused flows of ecological and commercial commodities to the two life cycles and its corresponding functional units. Also in this respect, cascade systems are closely related to plants and equipment (see below). The share of outputs from the distinct life cycles of a cascade system is fixed because all material stemming from the former life cycle is available to the subsequent one. But the shares of useful outputs depends on the degree to which waste material will be recycled at the end of each life cycle.

*Ad c)* Plants and equipment may be interpreted as a special case of a cascade system. One or several resources are used to produce equivalent products. Each batch during the life-time of the equipment may be interpreted as a process, where not only products leave the system as outputs but also a

[13] Furthermore, both products can hardly be stored, which even more underlines the simultaneousness.
[14] Following the nomenclature "single" and "multiple decision-maker" used by Azapagic (1996, p. 62).

slightly depreciated equipment (Georgescu-Roegen 1971, p. 217ff.). This equipment then enters anew the next production phase. The question is here, how to allocate the depreciation of plants and equipment among the life-time production. This is less difficult as long as plants and equipment remain under the influence of one single decision-maker (or the same group of decision-makers). If however, plants and equipment change hands, the question arises how to determine the remaining value of plants and equipment and subsequently how to allocate depreciation among the different owners or users.

The characteristics of multi-function processes are summarised in Tab. 7.2. Co-production processes and their joint products are not always under the control of one decision-maker. The variability of the product shares is case dependent, and the co-products may be produced simultaneously or successively. Cascade systems and plant and equipment may involve a single or a multiple decision-maker. The different life cycles are in sequence, and the shares of outputs are fixed, although the amount of material recycled is variable. The output shares of plant and equipment are fixed too, assuming that plants and equipment depreciate linearly with the amount of output produced. And of course, plants and equipment produce in sequence. In this chapter, the focus is on joint production processes (co-production with outputs in fixed shares).

| | **variability of outputs** | **time aspect** | **decision making** [5]) |
|---|---|---|---|
| **co-production** | from fixed [1]) to entirely variable [2]) | simultaneous or successive | <u>single</u> or multiple decision-maker |
| **cascade systems** | fixed [3]) | successive | single or <u>multiple</u> decision-maker |
| **plants and equipment** | fixed [4]) | successive | <u>single</u> or multiple decision-maker |

Tab. 7.2: Selected characteristics of three types of multi-function systems.
[1]): Joint production (see Section 7.1.2);
[2]): Combined production;
[3]): The amount of spent material from a life cycle is fixed. The amount of material recycled and fed into the subsequent life cycle is of course variable.
[4]): Assuming a linear homogenous correlation between output and depreciation.
[5]): The normal case is underlined.

## 7.3 The Need for Allocation in Joint Production

### 7.3.1 The Purposes of Joint Product Allocation

Arthur L. Thomas, one of the main representatives who denies the usefulness of nearly any one-to-many allocation procedure because of its arbitrariness stated:

> Trying to defend a one-to-many allocation is like clapping one's hands, then trying to defend how much of the sound is attributable to each hand.[15]

This aphorism shows quite nicely the twofold problem we face in joint production, namely:

- when do we need to allocate, and
- how to do it when it is necessary.

In this section, the first question will be treated. The second one is postponed to Section 7.3.2.

In LCA, allocation in joint production is needed in the following situations:

*a)* Investment decisions such as product choice, design and development, process development, and setting off of environmental policies,

*b)* Environmental and social "pricing" of products[16], and

*c)* Inventory valuation for environmental reporting.

Decision support about further processing and product line emphasis are other purposes which however will not be treated in this thesis.

*Ad a)* In cost accounting, the profitability of an investment in a joint production facility is assessed based on information about costs and proceeds of each alternative. The investment costs and the running costs are compared to the total expected earnings. Investment decisions may therefore be made on the basis of unallocated costs. In contrast to this, allocation is needed in LCA in order to evaluate the environmental performance of the investment compared to other alternatives, if the share of joint products differs.

*Ad b)* Pricing of joint products is not needed in competitive markets where the firms are price takers[17]. But environmental information is not regulated by market mechanisms. We may compare the process network analysed in LCA with an organisation divided up in segments. There is a large number of unit processes and decision units involved which act rather independently. This is also true, if the system model used in LCA represents the segments of a firm. Hence, allocation may be applied on an intra- *and* inter-firm level. It is used to determine the amount of potential environmental impacts[18] which shall be attributed to each individual joint product.

*Ad c)* Inventory valuation in terms of potential environmental impacts may be needed in the context of internal or external environmental reporting. It is identical to inventory costing for financial reporting purposes. However, this aspect is (yet) of minor importance in LCA.

[15] Thomas (1977, p. 3)
[16] See Subchapter 4.2 for an explanation of "social" costs as applied in this thesis.
[17] A firm is a price taker when it "*can alter its rate of production and sales within any feasable range without this having any significant effect on the price of the product it sells*" (Lipsey et al. 1972, p. 235).
[18] due to ecological commodities flowing from and to the environment caused by the joint product's network.

Allocation in joint production in the context of LCA shows to be more important than could be anticipated based on the economists' view. The most important applications which also lead to great controversies may be found in decision-making about investments and in social "pricing" (either for intermediate or final goods).

### 7.3.2 The Arbitrariness of Joint Cost Allocation

As we have seen in the previous section, joint product allocation is needed in several situations. However, due to the inherent characteristic of joint production, there is room for arbitrariness as has been stated by, e.g., Spreng (1988). Spreng identified joint energy allocation as one additional source of arbitrariness in energy analysis and states that

> [t]here is no logical, obviously correct, unambiguous way of charging a given energy expenditure to the different products and the problem of joint production has added to the arbitrariness of energy accounting.[19]

If it is true that allocation is a source of arbitrary and subjective decisions, it is crucial to establish a well-defined objective for which allocation is carried out. Because of the arbitrariness of joint product allocation, Hamlen et al. (1980), quoted in Demski (1981), advise to allocate based on a set of criteria which would then enable to identify the corresponding allocation principle.

> The value of allocating joint costs may be questioned. However, allocating is an unavoidable problem faced with accountants in many situations at this time. In a large number of these cases, the particular allocation used will be clearly arbitrary and unrelated to direct efficiency criteria. The best approach in such cases is to choose an allocation procedure that is based on a set of axioms which can be described in some sense as both fair and understandable (Hamlen et al. 1980, p. 282).[20]

In order to focus the debate about allocation in LCA on the criteria applied to choose a certain procedure, we adapt a proposal made by Horngren et al. (1991, p. 460). The objectives may be classified as follows:

*a)* cause and effect,

*b)* benefits received,

*c)* fairness or equity, and

*d)* ability to bear.

*Ad a)* Using this criterion, the relations between cost objects and costs caused by them is established. It corresponds to the second step in the ISO allocation procedure in LCA:

> 2) where allocation cannot be avoided, the system inputs and outputs should be partitioned between its different products or functions in a way which reflects the underlying physical relationships between them; i.e., they must reflect the way in which the inputs and outputs are changed by quantitative changes in the products or functions delivered by the system.[21]

If decisions are to be supported by LCA and in particular by allocated data, causal relationships need to be established. However, in completely joint production processes no such relationships exist because a change in any of the joint outputs causes the same change in all other inputs and outputs. The physical causality criterion is therefore not applicable in joint production situations as Huppes (1993) points out:

[19] Spreng (1988, p. 140)
[20] Demski (1981, p. 142)
[21] Anonymous (1997b, p. 17)

> There is no alternative in terms of physical causation since the units to be allocated to are outputs, and outputs cannot cause inputs in a physical sense.[22]

On the other hand, outputs can cause inputs in a social sense through expectations, expressed by criteria *c)* and *d)*, see below.

*Ad b)* Using this criterion, the beneficiaries of the outputs of the joint production process are identified. The flows of commercial and ecological commodities of the joint production process are then allocated in proportion to the benefits each beneficiary receives. This economic criterion may be used in LCA for the allocation of combined processes with one function specifiable and quantifiable for all products this process contributes to. Other criteria may be applied for such combined processes such as "total time of telephone calls" and the like (Huppes 1993, p. 208ff.). This criterion is neither applicable in fully joint production situations and situations with nearly joint overheads.

*Ad c)* Using this criterion, allocation factors are established satisfactory for all parties involved. It implies that there is a problem of decision-making which includes negotiations in view of a solution everybody involved may agree. Although the need of satisfying all parties involved is rather accepted in goal and scope definition and in life cycle impact assessment, it is (still) rather unique to be used in inventory analysis.

Physical measures are sometimes used in rate-regulation setting, when the objective is to make a fair allocation. Physical measures may facilitate negotiations between several firms. But they may not substitute for a firm's objective, because any

> physical approach does not usually relate to any of the aims of managers of firms. Therefore it can hardly play a useful role in a decision support system.[23]

The objective of fairness or equity is relevant in LCA as soon as more than one single decision-maker is involved in joint production. This situation occurs in the case of voluntary coalitions, and it will be further evaluated in Subchapter 7.4.

*Ad d)* Using this criterion, costs are allocated in proportion to the cost object's ability to bear them. The gross sales value and the estimated net realisable value method[24] are representatives of an operationalised concept relying on this criterion. This is an interesting approach for which an analogous concept for joint production allocation in LCA is developed in Subchapter 7.4. It is based on the reasoning that the choice of an allocation method may be influenced by position-specific tactics and strategies (cf., e.g., Linneweber 1997, p. 5), considering the "enviro-economic competitive capacity" of a product, i.e., the competitiveness of products considering private costs and environmental impacts (see Subchapter 4.2).

In the cost allocation context, Horngren et al. put forward the self-interest of a firm and its party to a deal as a driving force in bargaining:

> When external parties are involved, self-interest quite naturally influences perceptions about the propriety of joint-cost allocations. For instance, taxpayers may favour one method, and income tax collectors may favour another method.[25]

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[22] Huppes (1993, p. 212)
[23] Huppes (1993, p. 204ff.)
[24] See Appendix 1 for a short description of several methods used in cost accounting.
[25] Horngren et al. (1991, p. 537)

As we have seen, not all of the criteria mentioned above are applicable in the case of joint production. This is particularly true for the ones that consider physical causal relationships to differentiate between the co-products, because no such relationships occur in joint production.

That is why one has to stick to a criterion which either reflects fairness or competitiveness in the case of joint production. But is it possible to defend the arguments underlying accounting principles based on these two concepts? Thomas (1969) gave the minimum requirements necessary for a theoretical justification of a non-arbitrary allocation method which may also be applied for joint product allocation in LCA:

1. The method should be unambiguous.
2. It should be possible to defend the method. (...)
3. The method should divide up what is available to be allocated, no more and no less. The method should be *additive*.[26]

Any allocation method should be unambiguous or unique, which means that for a given allocation method there should be one and only one partitioning of the flows of commercial and ecological commodities. Furthermore, conclusive arguments for choosing a method should be provided, defending the method against all possible alternatives. The allocating agent needs to proof that no other unambiguous, additive allocation method serves better. Additivity, sometimes also described as "tidiness" (cf. Demski 1981, p. 148), means that the allocation method choosen shall allocate the total of whatever is to be allocated. It does not mean to allocate all flows of commercial or ecological commodity by means of an allocation factor but all flows *relevant* in a certain context (either short-, long- or very long-term decisions). For instance, flows caused by the production of jointly used capital equipment need not to be considered in short-term allocation, because the environmental impacts caused by the production of capital equipment are bygones.

Thomas questions the usefulness of allocation methods if they are self-serving, if they are useful in advancing the economic or political interests of the allocator. He states that

> this sense of "usefulness" is a poor basis upon which to develop a defense of financial accounting allocations.[27]

According to him, the major difficulty is that there is no way in which the allocation method can be neutral in their effects on different classes of users. However, joint product allocation needs not to be neutral in any case. In the next subchapter, a classification of joint product situations is given which discriminates between neutral and non-neutral approaches.

[26] Thomas (1969, p. 7)
[27] Thomas (1974, p.9).

## 7.4 Choosing the Method for Joint Product Allocation in LCA

### 7.4.1 The Need for Context-specific Allocation

As long as the valuable outputs of a co-production process are variable, physical causality may be applied to allocate the flows of commercial and ecological commodities. But in co-production processes where the valuable outputs are produced in fixed proportions no such relationships exist (see previous section). Nevertheless, several physical measures have been proposed for allocation in LCA, such as the mass, the volume, the number of molecules, the inherent energy, the exergy, the number of electrons (cf. Huppes 1993, p. 198), or the concentration. But these physical measures do not reflect physical causality besides the fact that in some processes the jointly produced outputs to not have the same physical unit. In waste treatment, for instance, the service "treatment of waste", and "district heat" and "electricity" are produced, the former reported maybe in mass, the latter in energy units. The joint mining, smelting and refining of platinum group metals, nickel and copper is another example. Here, the concentration[28] of the metals in the ore has been used in Frischknecht et al. (1994, Appendix A, p. 81) as the allocation criterion to attribute the vast amounts of $SO_X$-emissions to the jointly produced metals. The resulting allocation factors are similar to the ones using the sales value as has been done in Frischknecht et al. (1996a, Appendix A, p. 96). However, it is only by chance that the physical measure reflects the revenue-producing power of the metals.

In cases where no physical causality for the different functions (or products) may be established or where it is not reasonable to apply physical causality[29], the use of relations on a higher level of abstraction, such as the values of each of the functions, is suggested. This is a transformation of the criteria "fairness and equity" and "ability to bear". In Chapter 4 the "enviro-economic competitiveness" is introduced as the firm's disutility function which considers economic *and* environmental information (i.e., private and environmental external costs). This disutility function is applied for the adjustment of allocation methods based on mere economic parameters and applied in joint production. The main purposes relevant for joint production allocation, namely "fairness and equity", and "ability to bear" is redefined such that they reflect the enviro-economic fairness and competitiveness, respectively.

### 7.4.2 The Decision Tree

In Frischknecht (1997, p. 13), an attempt was made to attribute certain allocation procedures to certain goals of an LCA. Hereby, the focus was set on a distinction which relies on the difference in time horizon for which the decision is intended to be valid. It has been stated that for a descriptive LCA, system expansion[30] does not apply, because nothing changes in the system analysed. Hence, in *reality* nothing would be avoided, nothing would be put in operation. However, system

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[28] In kg metal per ton ore.

[29] In Huppes (1993, p. 208), the case of passengers and freight is described. Both might be measured by mass and a physical relationship may be established between a change in mass and the change in amount of kerosene required. But the functional characteristic of "having mass" does not apply to the passengers. Hence, the functional characteristics need to be defined differently.

[30] With the system expansion approach allocation may be avoided by broadening the system boundaries and including several functional units (Heintz et al. 1992, p. 43ff., Fleischer et al. 1995, p. 594ff., Azapagic 1996, p. 35ff.). For instance, consider a comparison of products $A_I$ and $A_{II}$, where $A_I$ is jointly produced with $B_I$ by System I and System II only produces $A_{II}$. To make the product systems comparable, either an alternative way of producing B ($B_{III}$ from system III) is added to system II or subtracted from system I. The latter may be interpreted as the production of $B_{III}$ by system III being substituted for the production of $B_I$ by system I.

expansion may well be used to show what *would* happen *if* a joint production process *were* put out of operation. Hence, we judge the goal dependency of an LCA as no suitable criterion to discriminate various options of allocation. We need another classification system. Among the three requirements for allocation approaches stated in Section 7.3.2, the crucial one is the defensibility of the approach chosen. If allocation is arbitrary, as it is the case in joint product allocation, then the surrounding conditions determine whether and how an allocation approach is defensible or not. Hence, we suggest to discern the allocation situations according to the context within which allocation is required (see Fig. 7.5).

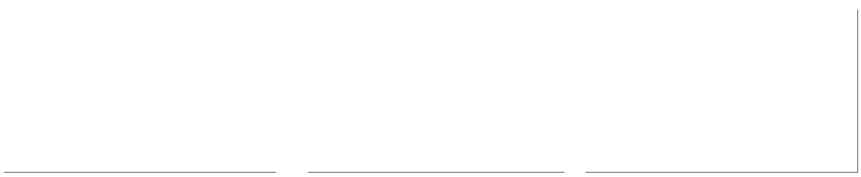

Fig. 7.5: Decision tree for allocation approaches in joint product allocation;
[1]): Perfect in the sense that the firms are price-takers, but *not* in the sense that environmental external costs would already have been internalised.

First, one needs to check whether physical causality is applicable or not. If physical causalities may be established and make sense, other approaches such as linear programming may be applied. If not, the production process delivers really fully joint products or products whose identical physical units do not correspond to the real cause of the combined process. One then moves to the second and major discriminative characteristic within joint production, namely, the number of decision-makers involved in the allocation process. Here, the two categories "single", and "multiple decision-maker" are discerned. Third, the characteristics of the market in which products or services are sold are relevant for the single decision-maker situation. If several decision-makers are involved, a fair allocation key is required which results from a bargaining process. The enviro-economic benefits are then attributed equally among the coalition parties. In the "single decision-maker, perfect market" case, the firm may evaluate the allocation key according to the "enviro-economic competitiveness" of the joint products. In the "single decision-maker, imperfect market" case, allocation is not needed for comprehensively priced joint products, because prices evolve simultaneously when the optimal output is determined. Hence it is a price-output optimisation problem considering social instead of mere private costs. For all three approaches, the joint production process is described by one single production function, the one that is divided up among the joint products.

The decision tree allows to find an adequate approach for practically any joint product allocation problem. The approaches suggested in a particular situation consider the context in which the allocation is made, but not so much the situation for which the LCA is carried out. Due to several reasons, existing classifications do not provide help in discriminating situations for which a certain defensible allocation method may be applied.

First, whether a process is in the background or in the foreground system of an LCA (see Section 5.3.2) does not change the way allocation is performed in the respective firms that run the joint production process. Generic data, often used in LCAs due to a lack of specific data, should theoretically be based on individual, company-specific data and projected to average data related to a time period and a geographic area. Any particular value for an emission factor of a production process of a particular firm contributes to a higher level average. Hence, allocation should ideally be performed by the corresponding firm and suchlike allocated data should be used to calculate average, generic data for processes in the background system.

Second, the kind of process (whether it is a multi-input, a multi-output or a recycling process) may not easily and unequivocally be defined. From the point of view of waste treatment, a waste incineration plant may be classified as a multi-input process. From the point of view of products produced in the waste incinerator, i.e., waste treatment services, district heat, and electricity, it should be classified as a multi-output process. And finally, from the point of view of cascades, a waste incinerator is a switching module between various successive life cycles (e.g., PET bottle -> electricity, kitchen-refuse -> district heating, *et cetera*) and therefore may as well be classified as a several-inputs-several-outputs recycling process. We think that the way how allocation is carried out is independent of the category the process is more or less accidentally related to.

In the next Subchapter, the three new allocation approaches are further described and illustrated with simplified, fictional examples.

## 7.5 Joint Product Allocation in Three Different Contexts

### 7.5.1 Competitive Allocation in Perfect Markets

In a perfect, competitive market, the price of a commodity is assumed to be invariant to changes in the amount supplied to the market by one single firm. The firm is a price-taker and may therefore base its decision about the investment in a joint production facility on the expected revenues for the joint products and the total costs of production[31]. If the expected revenues do not cover total costs, or if the profitability is too low, the investment will not be realised. Now, environmental information shall be included into the decision-making process. This brings along some complications because the market does not yet cope with the damages caused on the environment, i.e., environmental external costs are not yet internalised. We therefore need to compare *ceteris paribus* social costs plus a profit rate of an investment in a joint production facility with the social costs and the profit rates of competing products, either produced individually, or also jointly.

[31] Of course the firm will rely its decision on other information like legal aspects, taxation, infrastructure, social services, *et cetera*, as well. But they will be disregarded here.

The terminology and concept is introduced on a simple example, a product manufactured in a mono-function process and sold to a perfect, competitive market.

The price $r_1=r^{(\alpha)}$ of the product brand α (one brand of commodity 1) is composed of the costs of production $z^{(\alpha)}$ and a profit rate $w^{(\alpha)}$. When environmental impacts are to be included, expressed in environmental external costs, then $ce^{(\alpha)}$ are added to the price resulting in the"comprehensive" price, where $c$ is the environmental exchange rate[32]. It is assumed that environmental external costs do not affect the profit rate[33]. The "comprehensive" price is computed for alternative, competing product brands (i.e., β, γ, δ), and may show substantial differences due to differences in production technology, efficiency, *et cetera*. Fig. 7.6 shows the composition of prices due to the inclusion of environmental external costs in an fictive situation. For products sold in perfect markets (equal prices) the considerations may be restricted to the discussion of the environmental external costs.

Let us introduce a joint production process, and assume that product brand α is jointly produced with product brand ρ (one brand of commodity 2). Per unit of α, ξ units of ρ are produced. It is assumed that no further processing is needed to sell the jointly produced products. The problem is whether to invest in the joint production process (α,ρ) or not, given the alternative brands β, γ, and δ on the one hand, and σ, τ, and υ (competing product brands of commodity 2) on the other.

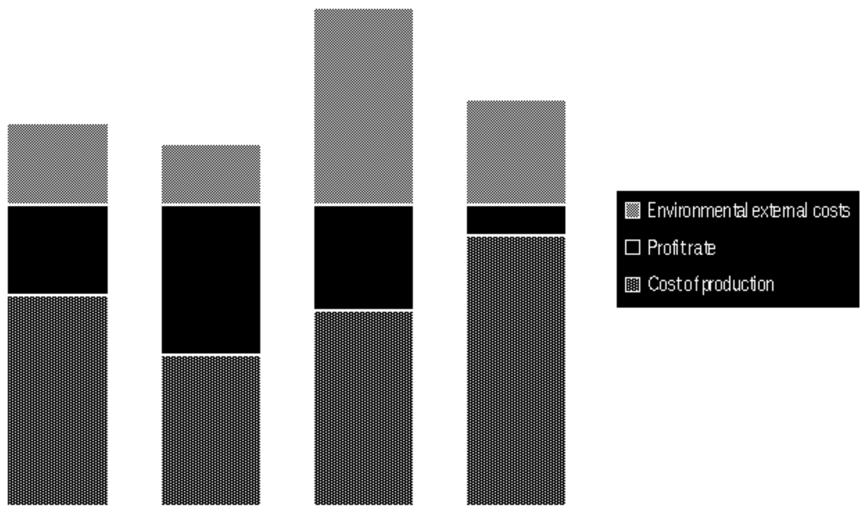


Fig. 7.6: Production costs, profit rate and environmental external costs for four alternative brands of the same commodity traded in a homogeneous, perfect market.

The joint production of α and ρ in one facility costs $z^{(\alpha,\rho)}$ and $e^{(\alpha,\rho)}$(private costs and environmental external costs) for one unit α and ξ units ρ. On the market, commodity 1 is sold at $r_1$ and commodity 2 at $r_2$. The environmental external costs of the products β, γ, and δ amount to $ce^{(\beta)}$, $ce^{(\gamma)}$, and $ce^{(\delta)}$ respectively, and $ce^{(\sigma)}$, $ce^{(\tau)}$, and $ce^{(\upsilon)}$ for the products σ, τ, and υ respectively. The condition under which the investment leads to the least expensive production is formulated in equation (7.1):

[32] See Chapter 4 for its definition.

[33] The profit rate is assumed to be constant and shall therefore not come into question as a possibility for the competitors to decrease their "comprehensive" price.

$$z^{(\alpha,\rho)} + c \cdot e^{(\alpha,\rho)} + w \leq \begin{cases} r_1 + c \cdot e^{(\beta)} + \xi \cdot (r_2 + c \cdot e^{(\sigma)}) \\ r_1 + c \cdot e^{(\beta)} + \xi \cdot (r_2 + c \cdot e^{(\tau)}) \\ r_1 + c \cdot e^{(\beta)} + \xi \cdot (r_2 + c \cdot e^{(\upsilon)}) \\ r_1 + c \cdot e^{(\gamma)} + \xi \cdot (r_2 + c \cdot e^{(\sigma)}) \\ r_1 + c \cdot e^{(\gamma)} + \xi \cdot (r_2 + c \cdot e^{(\tau)}) \\ r_1 + c \cdot e^{(\gamma)} + \xi \cdot (r_2 + c \cdot e^{(\upsilon)}) \\ r_1 + c \cdot e^{(\delta)} + \xi \cdot (r_2 + c \cdot e^{(\sigma)}) \\ r_1 + c \cdot e^{(\delta)} + \xi \cdot (r_2 + c \cdot e^{(\tau)}) \\ r_1 + c \cdot e^{(\delta)} + \xi \cdot (r_2 + c \cdot e^{(\upsilon)}) \end{cases}, \tag{7.1}$$

where $w$ is the profit rate, and $\xi$ the production share of joint products $\alpha$ and $\rho$. Because $z^{(\alpha,\rho)}$, $w$, $r_1$, and $\xi r_2$ are constant, the equations may be simplified to

$$\Delta z^{(\alpha,\rho)} + c \cdot e^{(\alpha,\rho)} \leq \begin{cases} c \cdot e^{(\beta)} + \xi \cdot c \cdot e^{(\sigma)} \\ c \cdot e^{(\beta)} + \xi \cdot c \cdot e^{(\tau)} \\ c \cdot e^{(\beta)} + \xi \cdot c \cdot e^{(\upsilon)} \\ c \cdot e^{(\gamma)} + \xi \cdot c \cdot e^{(\sigma)} \\ c \cdot e^{(\gamma)} + \xi \cdot c \cdot e^{(\tau)} \\ c \cdot e^{(\gamma)} + \xi \cdot c \cdot e^{(\upsilon)} \\ c \cdot e^{(\delta)} + \xi \cdot c \cdot e^{(\sigma)} \\ c \cdot e^{(\delta)} + \xi \cdot c \cdot e^{(\tau)} \\ c \cdot e^{(\delta)} + \xi \cdot c \cdot e^{(\upsilon)} \end{cases}, \tag{7.2}$$

where $\Delta z^{(\alpha,\rho)} = z^{(\alpha,\rho)} + w - (r_1 + \xi r_2)$. In our example, nine combinations are possible and need to be com– pared with the joint production alternative $(\alpha,\rho)$.

The approach shown may lead to completely different statements concerning the competitiveness of joint production processes and its competitors compared to mere economic considerations (see Fig. 7.7).

The example shows that there are two combinations of separately produced commodities, i.e., $(\delta,\tau)$ and $(\delta,\upsilon)$, which result in equal or lower social costs than the joint production alternative $(\alpha,\rho)$. The environmental exchange rate has no influence on the ranking of the alternatives, but on the absolute differences between them. A environmental exchange rate of zero (no environmental external costs included), would result in the same prices for all alternatives except the joint production process (a consequence of the perfect market assumption).

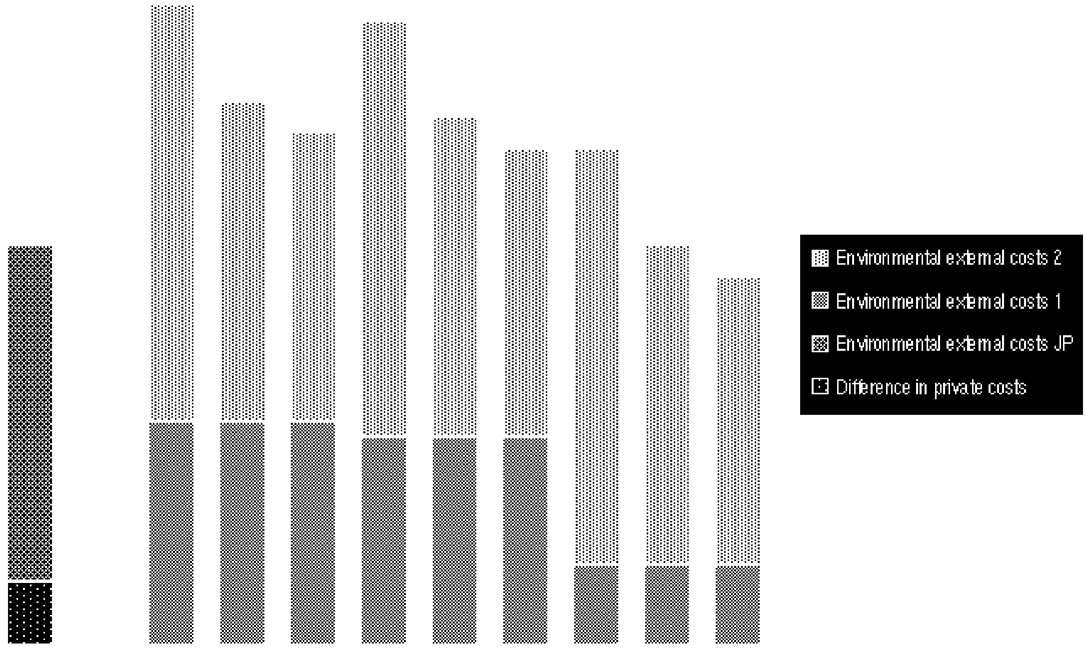


Fig. 7.7: Difference in private costs and environmental external costs for joint product brands α and ρ (commodity 1 and 2, respectively), and for nine combinations of separately produced brands (β, γ, δ of commodity 1, and σ, τ, υ of commodity 2). The difference in price and the environmental external costs JP of joint production alternative (α,ρ) represent the total relevant costs

The diagramm in Fig. 7.7 may be translated in a two dimensional diagramm which shows the interdependencies of the "comprehensive" prices of the two jointly produced brands α and ρ. For that purpose, the difference in selling price, and the environmental external costs are allocated using a variable parameter from 0 to 1[34]. The graph immediately shows, whether a product combination exists with lower social costs, and may be used to identify the maximum allocation factors with which either of the products shows a better environmental performance than product brands from competing single-function technologies. In mathematical terms, this relation may be expressed for alternative product brand *i* by

$$\lambda^{(\alpha)}_{\max} = 1 - \lambda^{(\rho)}_{\min} = \frac{1-0}{z^{(\alpha)}_{s,1/0} - z^{(\alpha)}_{s,0/1}} \cdot \left(z^{i}_{s} - z^{(\alpha)}_{s,0/1}\right), \tag{7.3}$$

where $z^{(\alpha)}_{s}$ are the social costs for the joint product α with allocation factors equal 1 and 0, respectively, $z^{i}_{s}$ are the social costs for the alternative *i* of commodity 1. The numerator shows the difference between the respective maximum and minimum allocation factors, usually 1 and 0. For the maximum allocation factor for product ρ (and the minimum allocation factor for product α), the procedure is analogous.

[34] It is assumed that the allocation factor is the same for both the difference in private costs and environmental external costs. Different allocation factors would not affect the principle considerations and conclusions.

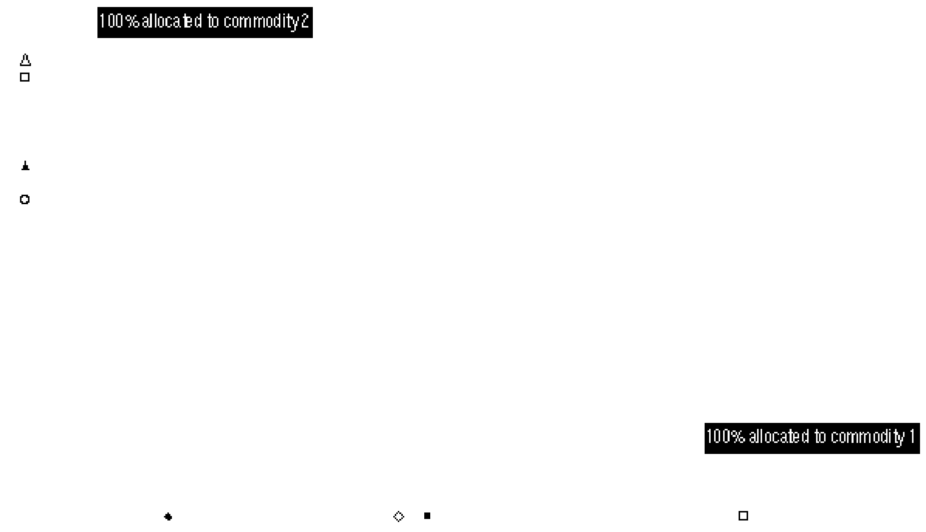


Fig. 7.8: Graphical solution for a comparison of alternative combinations of commodities 1 and 2 based on the difference in private costs and environmental external costs (social costs). The scales show social costs in arbitrary units. Intersections above the $(\alpha,\rho)$-line (heavy type) show combinations with higher social costs.

The example shows that for investment decisions in perfect markets with no demand constraints, it is not necessary to allocate joint costs and joint environmental impacts to the individual joint products. However, the prices of the commodities 1 and 2, and the environmental performance of all possible alternative brands of commodities 1 and 2 need to be known.

If allocation is needed all the same, e.g., for the determination of "comprehensive" transfer prices within one company or, for the purpose of LCA, between companies, a comparison with the alternatives for all individual joint products helps to choose the adequate allocation factor leading to competitive social costs of production. In our example, no allocation factor exists, where the allocated "comprehensive" prices are lower for both commodities compared to all alternative combinations.

If, however, alternatives $\delta$ and $\upsilon$ would not be available, the allocation factor may be choosen between 0.2 _ $\lambda_{\alpha}$ _ 0.52 for product $\alpha$, and 0.8 _ $\lambda_{\rho}$ _ 0.48 for product $\rho$, respectively. Within this range, the social costs of both commodities are lower than the social costs of any alternative combination (i.e., $(\beta,\sigma)$, $(\beta,\tau)$, $(\gamma,\sigma)$, and $(\gamma,\tau)$).

Now consider the situation where commodity 1 would be sold on a supply-side monopolistic market and competing products, i.e., $\beta$, $\gamma$, $\delta$, do not exist. Then, the allocation factor for product $\alpha$ may be varied between 0.28 _ $\lambda_{\alpha}$ _ 1.0, and product $\rho$ may be charged less if necessary (0.72 _ $\lambda_{\rho}$ _ 0). This shows that a producer of joint products for a monopolistic market has a higher degree of freedom how he or she allocates costs and environmental impacts to the individual products. The same holds true for a situation where competing products are available but where a completely inelastic demand is experienced. If the demand for commodity 1 is completely inelastic, product $\alpha$ may bear as high a load as necessary. Again, the allocation factors vary between 0.28 _ $\lambda_{\alpha}$ _ 1.0, and 0.72 _ $\lambda_{\rho}$ _ 0, respectively. The inelasticity in demand of commodity 1 may also be restricted to environmental impacts only. In such a case, environmental information is not asked for and the commodities are purchased disregarding its environmental impacts.

If markets for all joint products are imperfect, e.g., monopolised markets, allocation may be used to steer the demand. This is treated in the next section.

### 7.5.2 Competitive Allocation in Imperfect Markets

In imperfect markets, a firm may well have an influence on the price of a commodity due to an increase or decrease in production and supply to that market. It this section, we consider the case where a firm produces two commodities jointly ($\alpha$, and $\rho$) and where the demand functions for these commodities are independent. Per unit of $\alpha$ , $\xi$ units of $\rho$ are produced with one unit of input, $\Omega$. One unit of $\Omega$ and its processing into the two joint products costs 40SFr.. For simplicity reasons, profit is assumed to be zero. Furthermore, we assume again that no further treatment is necessary after the split-off point and that excess production may be discarded costlessly.

Let the demand curve for product $\alpha$ be:

$$r^{(\alpha)} = 100 - 4q^{(\alpha)} \text{ [SFr.]}, \tag{7.4}$$

and for product $\rho$ be

$$r^{(\rho)} = 70 - 3q^{(\rho)} \text{ [SFr.]}, \tag{7.5}$$

where $r$ is the price and $q$ the corresponding saleable quantities. These demand functions are supposed to be valid in both cases, namely with and without environmental external costs included (the environmental external costs are introduced *ceteris paribus*).

Now, the profit maximising level of production shall be determined. Maximum profits are achieved where marginal revenue equals marginal costs of production, where the costs comprise environmental external costs. The optimum is found using constrained optimisation, Lagrange multipliers and Kuhn-Tucker theory. The optimisation problem may be formulated as:

$$\text{maximise } r^{(\alpha)} \cdot q^{(\alpha)} + r^{(\rho)} \cdot q^{(\rho)} - r^{(\Omega)} \cdot \Omega, \quad \text{subject to } q^{(\alpha)} \le \Omega \text{ and } q^{(\rho)} \le \xi \cdot \Omega . \tag{7.6}$$

This optimisation problem is solved with the Lagrangean method which may be summarised as follows (Taha 1992, p. 735ff., Weil 1968, p.1343):

1. Determine the optimum by using Lagrange multipliers for each inequality, assuming that each inequality is a strict equality.
2. If all Lagrange multipliers are nonnegative, the optimum obtained is also the optimum subject to the inequality constraints.
3. If any Lagrange multiplier shows to be negative, resolve the problem without considering the particular constraint for which the Lagrange multiplier is negative. Usually, the resulting optimum satisfies the disregarded constraint and is the solution to the problem.

The demand functions (7.4) and (7.5) may now be introduced into (7.6), which results in

$$\text{max. } (100 - 4q^{(\alpha)}) \cdot q^{(\alpha)} + (70 - 3q^{(\rho)}) \cdot q^{(\rho)} - 40 \cdot \Omega, \text{ subject to } q^{(\alpha)} \le \Omega \text{ and } q^{(\rho)} \le \xi \cdot \Omega \tag{7.7}$$

with $\xi$=0.6. The associated Lagrangean function is

$$\begin{aligned} &\text{maximise } \prod (q^{(\alpha)}, q^{(\rho)}, \Omega, \lambda_\alpha, \lambda_\rho) \\ &\quad = 100q^{(\alpha)} - 4q^{(\alpha)2} + 70q^{(\rho)} - 3q^{(\rho)2} - 40 \cdot \Omega - \lambda_\alpha (q^{(\alpha)} - \Omega) - \lambda_\rho (q^{(\rho)} - \xi \cdot \Omega) \end{aligned} \tag{7.8}$$

where $\lambda_\alpha$ and $\lambda_\rho$ are the Lagrange multipliers which may be interpreted as marginal opportunity costs of the two products (Jensen 1974, p. 468).

The partial derivatives of $\Pi$ are

$$\frac{\partial \Pi}{\partial q^{(\alpha)}} = 0 = 100 - 8q^{(\alpha)} - \lambda_\alpha , \tag{7.9}$$

$$\frac{\partial \Pi}{\partial q^{(\rho)}} = 0 = 70 - 6q^{(\rho)} - \lambda_\rho , \tag{7.10}$$

$$\frac{\partial \Pi}{\partial \Omega} = 0 = -40 + \lambda_\alpha + \xi \cdot \lambda_\rho , \tag{7.11}$$

$$\frac{\partial \Pi}{\partial \lambda_\alpha} = 0 = -q^{(\alpha)} + \Omega , \tag{7.12}$$

$$\frac{\partial \Pi}{\partial \lambda_\rho} = 0 = -q^{(\rho)} + \xi \cdot \Omega . \tag{7.13}$$

Equations (7.12) and (7.13) show that the whole production may be sold. Equation (7.11) confirms the additivity of the optimisation in that the marginal opportunity costs of the two products sum to the costs of input and joint processing. The solution is summarised in Tab. 7.3.

| Parameter | | Case 1: Private costs | Case 2: Social costs |
|---|---|---|---|
| $q^{(\alpha)}$ | Units | 10.0 | 8.6 |
| $q^{(\rho)}$ | Units | 6.0 | 5.2 |
| $\Omega$ | Units | 10.0 | 8.6 |
| $\lambda_\alpha$ | SFr. | 19.7 (49%) | 31.5 (57%) |
| $\xi \cdot \lambda_\rho$ | SFr. | 20.3 (51%) | 23.5 (43%) |

Tab. 7.3: Numerical solution of the constrained optimisation problem for private and social costs.

We now add, *ceteris paribus*, environmental external costs to the costs of input $\Omega$ and of joint processing to get the "comprehensive" price $r_s$.

$$r_s^{(\Omega)} = r^{(\Omega)} + c \cdot e^{(\Omega)} . \tag{7.14}$$

In our example environmental external costs amount to 15SFr. which results in a "comprehensive" price of 55SFr. (assuming an environmental exchange rate $c$=1). At the optimal level, less products are produced and sold in total. Furthermore, due to the different demand functions, the share of costs between the two joint products changed substantially from 49%/51% to 57%/43% (see Tab. 7.3). It shows that the consideration of environmental external costs in addition to private costs changes *a)* the level of output of joint production as well as *b)* the marginal revenues (absolutely and relative to each other) and, subsequently, the allocation of social costs. Fig. 7.9 shows the relationships between marginal revenue and product output, where the solution of the optimisation problem can be identified graphically.

If a firm encounters increased costs due to an internalisation of environmental external costs, production level should *ceteris paribus* be reduced in order to keep trace of the optimal situation, the situation where profits are maximal. The share of achievable marginal revenues changes which means that the optimal allocation parameter changes in value too. The crucial point of this approach is the availability of reliable and sufficient information about the shape of the demand function.

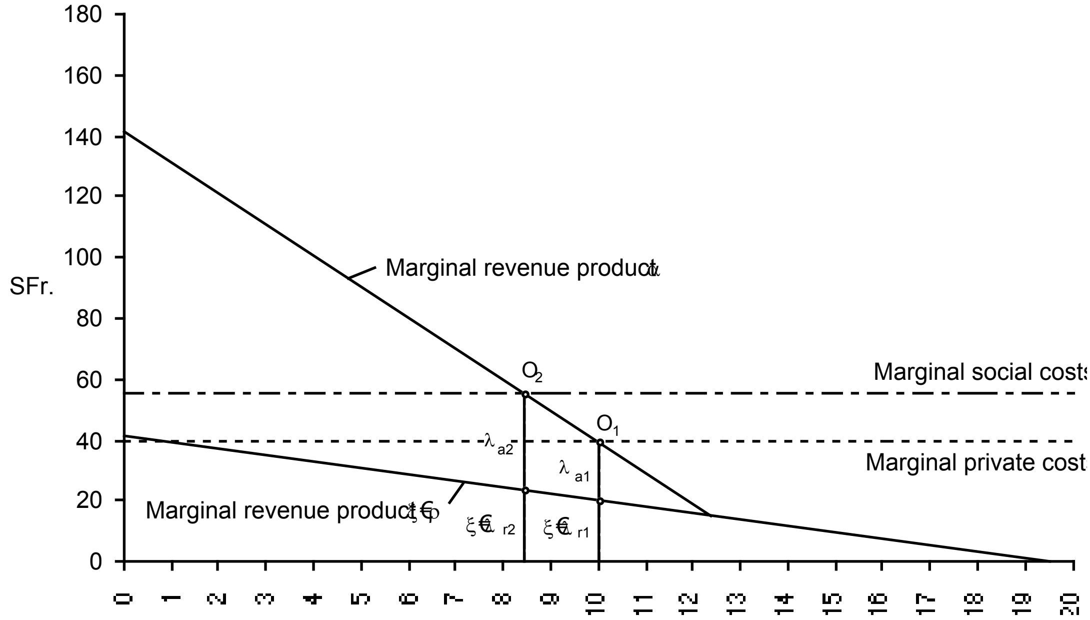


Fig. 7.9: Relationship between marginal revenues and marginal costs (private (case 1) and social (case 2) costs) for a non-linear model (square revenue functions).
$O_1$, $O_2$: Optimal output case 1 and case 2, respectively

If the joint production process delivers one or several basic commodities, a feedback problem occurs. The appropriate allocation factors may be determined only after the environmental impacts and subsequently the social costs have been computed. But allocation needs to be done before the calculation of the cumulative environmental impacts because otherwise the matrix would not be invertible because it is not square[35]. In order to render the matrix square one may start with a completely arbitrary allocation key with which the environmental impacts of the individual and, by summing them up, of the entire joint production process is computed. Then, the social costs of the joint production process and its optimal price-output relation may be determined which delivers the "right" allocation key for the second and last iteration.

Boustead considers prices as no serious contender in LCA because of the variability of economic parameters. He uses the historical development of prices of chlorine and sodium hydroxide to underpin his viewpoint. Fig. 7.10 shows the prices for the two joint products since the late 1970's as reported in Chenier (1992, p. 103). The allocation factors would twice have changed from about 1:1 to 1:2 (see Tab. 7.4, and Boustead (1994, p. 3)). Of course, these fluctuations have nothing to do with the efficiency of the process. But the relation of demand and supply of the two joint products must have changed over the years. As we have seen, changes in prices are one important way to adjust the demand of joint products in a way that guarantees maximal profits, and/ or that the whole production of chlorine and sodium hydroxide may be sold. This has already been recognised by J.S. Mill (1848) who sought for a principle how to apportion the expenses of production between two (or more) jointly produced commodities. He retrieved to the law of demand and supply and stated that the natural values of the jointly produced commodities relatively to each other

[35] See Heijungs et al. (1997b) for further details about invertible matrices.

are those which will create a demand for each, in the ratio of the quantities in which they are sent forth by the productive process.[36]

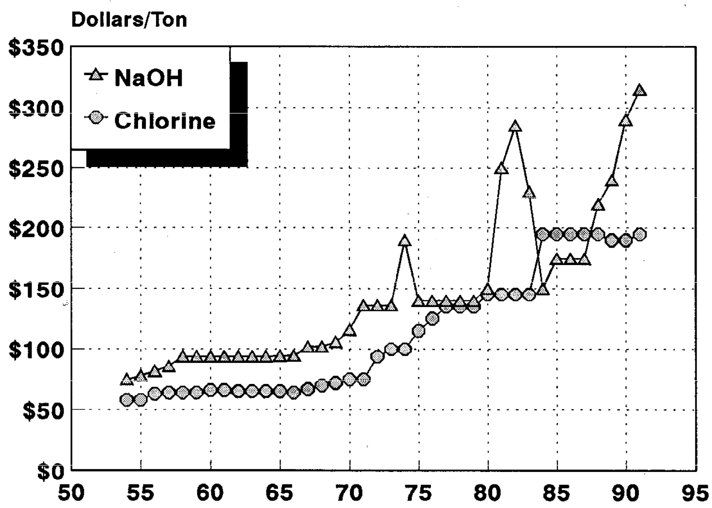


Fig. 7.10: Prices of chlorine and sodium hydroxide between 1954 and 1991; Chenier (1992, p. 107).

The observed price fluctuations of chlorine and caustic soda show the general mechanisms that are encountered in joint production for imperfect markets. The overall level of output and the demand curves mainly determine the share of revenue the individual joint products are able to contribute while the whole production can be sold. Joint products with a relatively higher demand elasticity need to be charged overproportionally when the sales need to be reduced compared to the other joint product.

| Year | Chlorine $Cl_2$ | Sodium hydroxide NaOH | Allocation factors |
|---|---|---|---|
| | $/tonne | $/tonne | %/% |
| late 1970's | 140 | 140 | 50/50 |
| 1984 | 150 | 280 | 35/65 |
| 1986 | 190 | 175 | 53/47 |
| 1990 | 200 | 320 | 38/62 |

Tab. 7.4: Allocation factors for chlorine and sodium hydroxide according to Boustead (1994, p.3) who relies on economic data given in Chenier (1992, p.103).

Hence, as long as the demand of joint products fluctuates independently one from the other, their prices do the same. And if we consider the adjustment of the "comprehensive" price as the driving force to optimise the output, it is in principle not sensible to flatten out the fluctuations of prices as proposed by, e.g., Huppes, because these fluctuations are intentional. Of course, this would make high demands on the continuous data processing for the LCI of such products.

In an economy where environmental external costs are internalised, price-output optimisation based on social costs provides the respective solution. This allocation procedure may therefore be applied in cases where one decision-maker is able to determine the "comprehensive" prices of his or her jointly produced products autonomously. Similar to the short-term decision aspect "Product emphasis" described in Section 5.3.4, an integral, time-dependent modelling may be required to determine appropriate allocation factors.

[36] Mill (1848, p. 107)

One might argue that the optimal price-output level may as well be achieved by only adjusting the private costs, leaving environmental external costs constant. For the client it would be irrelevant which share of the price are private and external costs, respectively. Hence, the firm might keep the "environmental" allocation factor constant while the "economic" allocation factor undergoes larger variations (or *vice versa*). In this case, the allocation factor that is kept constant (either the environmental or the economic one) needs to be determined arbitrarily because neither physical nor social causation is available.

If a firm interacts with public authorities, or if the firm seeks coalitions in order to increase its efficiency, the "ability to bear" strategy does not hold anymore. In such cases "fair" or "just" solutions for the allocation problem need to be found. For that purpose we propose the "democratic" approach, which is described in the next section.

### 7.5.3 Fair Allocation in Voluntary Coalitions

In cases where several decision-makers are involved in negotiations about a voluntary joint production, such as the erection of a dam for power generation, flood control, irrigation, and drinking water supply, approaches based on game theory may be helpful to establish fair allocation factors. In the case of perfect markets, prices of course anticipate the result of the "game". However, in situations of no or imperfect markets and when environmental impacts are included in the bargaining process, the "democratic" approach has its merits. In this section a simple example of a three party coalition is used to illustrate how this approach may be applied in LCA.

| Coalition | Social costs $z_s$ [SFr.] | Least incremental social costs | | | |
|---|---|---|---|---|---|
| | | {α,β} | {α,γ} | {β,γ} | {α,β,γ} |
| ø | 0 | - | - | - | - |
| {α} | 80 | 75 | 70 | - | 55 |
| {β} | 70 | 65 | - | 40 | 25 |
| {γ} | 150 | - | 140 | 120 | 100 |
| {α,β} | 145 | - | - | - | 95 |
| {α,γ} | 220 | - | - | - | 175 |
| {β,γ} | 190 | - | - | - | 165 |
| {α,β,γ} | 245 | - | - | - | - |

Tab. 7.5: Social costs and least incremental social costs for the production of products α, β, and γ in various coalitions.

The three firms, let us call them $F_A$, $F_B$, and $F_C$ are negotiating about possible coalitions to improve their enviro-economic efficiency of their respective products α, β, and γ. Tab. 7.5 shows the social costs for all possible coalitions[37].

The condition that the production in any coalition should result in less social costs than the sum of the corresponding single production is met. Now, the following conditions lead to upper and lower

[37] The procedure is similar for private costs or for environmental impacts. However, the core of the characteristic function (see Fig. 7.11) may be clearly differing.

limits of how much may be attributed to the single firms. They are called the stand-alone cost test, and the incremental cost test (Young 1985b, p.8)[38]:

- The *stand-alone cost test* requires that no firm - or group of firms - is charged more than their stand-alone (opportunity) costs. Its rationale is evident because the coalitions are voluntary.
- The *incremental cost test* implies that no firm shall be charged less than its marginal costs of being included in the coalition. Otherwise a firm may be subsidised by the rest of the coalition.

The core of the social cost function is the set of all allocations for which both conditions are met. It may be solved either graphically or numerically. The Shapley approach adds another condition to these two. The order in which a partner joins the coalition does not influence the share or profits received. This implies that all benefits are partitioned equally among the coalition partners.

The maximum social costs ($z_s$) allocateable to one single firm are the costs of the grand coalition $\{\alpha, \beta, \gamma\}$, namely SFr. 245. The social costs for stand-alone production of product $\alpha$ are SFr. 80 and the lowest incremental social costs are SFr. 55. Hence, firm $F_A$ would enter a coalition with either of the two or both if social costs remain in between SFr. 55 and 80. For product $\beta$ from firm $F_B$ the corresponding limits are SFr. 25 and 70, respectively, and for product $\gamma$ of firm $F_C$ SFr. 100 and 150, respectively.

The core in this example is rather small so that the room for negotiations is restricted. The benefits minimally or maximally allocatable to each of the products lies within the core for all products. Hence, the reductions achievable may reach 31% for firm $F_A$, 64% for firm $F_B$, and 33% for firm $F_C$. According to the additional property of the Shapley approach, which states that benefits should be allocated equally among the coalition partners, the result of allocated costs is $z_{s\alpha}$=69.2, $z_{s\beta}$=49.2, and $z_{s\gamma}$=126.6. Compared to the stand-alone alternatives, firm $F_B$ profits most by the coalition. It may reduce its social costs by nearly 30%, compared to some 14% for firm $F_A$ and about 16% for firm $F_C$.

[38] These two conditions are usually met in normal joint production processes where one decision-maker is involved.

Fig. 7.11: The core of the social cost function for the coalition of firms A, B, and C to jointly produce products $\alpha$, $\beta$, and $\gamma$ respectively.

We may recognise a similarity to the "system expansion"- or "avoided burden"-approach, proposed, for instance, in the ISO-standard 14041. The "democratic" approach also uses information from "outside the system", about alternative systems delivering additional function(s) separately. However, not the total amount of environmental impacts avoided by joint production is allocated to one individual joint product. The environmental impacts "escaped" are rather allocated evenly or "fairly" among the coalition partners. With the "democratic" approach applied in a two parties coalition we therefore come close to the time-honoured fifty-fifty rule proposed in the "Technical Framework for Life-Cycle Assessment" published by SETAC in 1991, where it is suggested to

> equally divide impacts added to the system because of recycling. The inputs and outputs associated with recycling are: reduced disposal of Product 1, reduced virgin material production for Product 2, inputs and outputs associated with recycling, and any converting net inputs and outputs incurred as a result of using recycled materials over virgin materials in product 2.[39]

There are difficulties in the transformation of the "democratic" approach, and some disadvantages are to be accepted. First, the determination of environmental (and economic) benefits is in many cases not easy, or the alternative "stand-alone" solution does not exist. In the case of burning polymer waste in cement kilns, for instance, the alternative would be to burn it in a waste incineration plant, which is in its turn a multi-function process. Hence the owner of the plastic waste does not know the real costs and environmental impacts of his "stand-alone" position.

Second, the "democratic" approach abstracts from differences in bargaining positions and negotiation power. It may be argued that, as long as the products for which firms bargain are traded on the market and as far as costs are concerned, these different starting positions are reflected by prices. This would bring us back to an "ability to bear"-approach. But for environmental external costs which still are almost completely outside the market economy, bargaining solutions for emissions and resource consumption may well be an adequate solution. However, the negotiating power of potential business partners may strongly influence the outcome of the bargaining about environmental benefits of a joint venture.

Third, if one party to a deal is not yet existant, bargaining solutions become obsolete by evidence. This occurs in the analysis of product systems where far distance future uses of materials are anticipated and benefits are claimed for its present use. In such cases, "democratic" allocation is not possible and we are again faced with a single decision-maker approach based on the "ability to bear", or "enviro-economic competitiveness" criterion.

Forth, in some instances, a large number of potential coalition partners would be involved in negotiations about a "fair" allocation of environmental impacts to products. The managers of a waste incineration plant with heat recovery and electricity production, for instance, would need to negotiate with each single potential client of district heat about a "fair" charge of environmental impacts on the kWh heat delivered. Such negotiations may alternatively be based on experience about how much environmental impacts a client is ready to "cause" per kWh heating energy. Based on a reference system indicating the "avoided environmental impacts"[40], the managers may try to set up a "demand-environmental impact" function to be able to determine the share of clients willing to

[39] Fava et al. (1991, p. 80)

[40] In the case of district heating this may be an oil boiler, indicating both reference private costs and reference environmental impacts of heating energy.

join the district heating network in dependence on the level of both private costs and environmental external costs. Hereby, the environmental exchange rate may play an important role to compensate for the drawback of higher costs of production. By varying the exchange rate, more or less emphasis may be put on the lower environmental external costs of district heat from waste incinerators compared to alternative technologies.

### 7.5.4 The Relation to Current-practice Allocation Approaches

Currently, several allocation approaches are used in LCA (such as the sales value, avoided burden (or system expansion), physical causalities, *et cetera*). In the decision tree presented in Subchapter 7.4, the application field of currently used or recently developed allocation approaches is not obvious. We therefore comment on some selected approaches and their relation to the new approaches.

The marginal allocation in multiple-function systems as developed by, e.g., Azapagic (1996), is by definition not applicable in fully joint production. However, it serves very well to allocate environmental impacts in combined production where the product shares are variable to a certain extent (e.g., refineries) in a Status Quo type of LCA. The managers of a multi-function plant optimise its output according to their objectives (e.g., profit maximisation) which may be achieved by product-portfolio changes. The modelling of "real-life" behaviour of firms, either based on private or on social costs, may best be represented by the marginal allocation approach[41].

The allocation concepts "enviro-economic competitiveness" as well as "enviro-economic fairness" apply environmental external costs of competing alternatives. Information of competing alternatives is also used when applying the "system expansion"- or "avoided burden"-approach. From that point of view, system expansion may very well be interpreted as a part of the allocation procedure[42] and may be applied in a descriptive LCA as well as in analysing long-term decision problems. The main difference lies in its transformation. In a Status Quo type of analysis the choice of alternative technologies is totally arbitrary (because nothing changes in a descriptive analysis, and no technology is affected) whereas in the analysis of a change in a Long Run LCA the behaviour of the enlarged system needs to be modelled as "real" as possible. But the fact remains that in the "systems expansion"-approach, the whole benefit of avoiding single production processes is allocated uniquely to one of the joint products. Hence, this approach is only suitable for a single decision-maker, perfect market situation.

The numerous attempts to solve the allocation problem in cascade systems documented in, e.g., Ekvall (1994) and Schneider (1996) show the negotiating character of that problem, and reflect the fact that for this type of problems, several (mostly two) decision-makers are involved with sometimes diverging interests. With the allocation carried out on the level of the single, one-input-one-output or recycling process, cascades may be broken open. For that purpose the common processes need to be identified and the achievable benefits of joining two or more functional units to (material) cascades need to be quantified. We suggest to refrain from a universally valid

[41] However, Azapagic (1996) optimises on the basis of environmental effect minimisation although firms usually optimimise costs and tend to maximise profits, *inter alia*.

[42] In the ISO standard 14041 it is emphasized that step 1 (subdividing unit processes and system expansion) does formally not belong to the allocation procedure (Anonymous 1997b, p. 16), probably because system expansion is seen as one option for allocation which avoids to do it (Heijungs 1997, p. 5).

allocation key and to apply either the "enviro-economic competitiveness" approach (single decision-maker) or the "enviro-economic fairness" approach (multiple decision-maker) instead.

Finally the important question remains, why not to use the gross sales value as the method which expresses the ability to bear, the competitiveness of products best. The gross sales value method appropriately shows the competitiveness as far as the shares in environmental impacts allocated per individual joint product is concerned. It allocates among jointly produced valuable outputs according to their "ability to bear". But as soon as we want to compare the allocated environmental impacts or the social costs of these joint products with competing products, we see that the competitiveness may have changed completely. Competing products of one joint product may cause much less environmental impacts than this joint product. When environmental impacts are allocated with the same key like private costs (i.e.,by applying the gross sales value), the overall "value" of the corresponding joint product may rise much higher than that of the competing products. In the same time, the other joint products may show much lower social costs compared to their competing products. By that, comparative advantages are lavished on these joint products. To avoid such situations, we suggest to apply the overall "value" of the products, which may be approximated with social costs. This presupposes of course the inclusion of environmental information in the disutility function of the corresponding firm and its clients.

## 7.6 Conclusions

Joint product allocation leads to controverse discussions because no technical causality may be established. Until now, allocation approaches are often classified according to the kind of multi-function process under analysis. However, the decision-context within which such a process is situated is judged to be the decisive criterion to choose an allocation approach. Based on that, a decision tree for the choice of an approach has been developed and three major allocation situations have been identified, namely, one decision-maker producing joint outputs for perfect and for imperfect markets, and several decision-makers negotiating for a voluntary coalition. The decision-makers' objective for joint product allocation varies accordingly. Their objective is "enviro-economic competitiveness" and "enviro-economic fairness", respectively, expressed by the decision function. These proposals do not help to avoid controversial discussions about joint product allocation in LCA. But they help to structure and focus these discussions on the relevant issues.

The findings of this Chapter may be summarised as follows:

Joint product allocation situations which require distinct allocation procedures may be classified according to their context, i.e., the decision process and the market situation related to the joint production process. Three categories are distinguished, namely, allocation performed by:

*a)* single decision-maker, selling the joint products in perfect markets,
*b)* single decision-maker, selling joint products in an imperfect market, and
*c)* multiple decision-maker.

*Ad a)* In perfect markets, the criterion "enviro-economic competitiveness" is applied in single decision-maker situations. This concept helps to operationalise the firm's strive to maximise profits and to ensure and expand its substance.

*Ad b)* In imperfect markets no allocation is needed for "comprehensive" pricing because prices evolve simultaneously with the determination of the optimal output. The price-output optimisation is applied for the same reason as above.

*Ad c)* When several decision-makers are involved, fair allocation solutions must be found. Game theory is one approach for allocating benefits that are not traded on the market. Hence the criterion "enviro-economic fairness" is applied for these situations which allow for a rational discussion about the allocation of shared benefits.

Approach *b)* is an *ex post* procedure and may be applied in situations where the corresponding joint production process already exists. Approaches *a)* and *c)* in contrast are *ex ante* procedures, used to decide on investments and to establish coalitions on a voluntary basis, respectively.

# PART III:

# CASE STUDIES

# 8. Eco-indicator 95[RF]

## 8.1 From Eco-indicator Points to Environmental External Costs

### 8.1.1 Introduction

In Chapter 4, a simplifying disutility function is introduced. It is used to model default decisions occuring in the background system of an LCI which represents changes within the economic system. It is argued that the disutility function must be able to aggregate environmental information to one single indicator. Furthermore, economic and environmental information must be convertible to reach an easy manageable, one-dimensional disutility function. That is why, emphasis is put on the development of a method which allows for a full aggregation of ecological commodities and where a link to monetary units is feasible.

This chapter describes an adapted version of the valuation method Eco-indicator 95. The present Eco-indicator 95 methodology is revised applying knowledge from recently published studies about environmental externalities. Based on an assumption of the total environmental external costs in Europe, the Eco-indicator points are transformed into monetary units. The Eco-indicator 95 method is adjusted so that the "real" damage costs published by externality studies approximately coincide with the "Eco-indicator costs".

The valuation method developed is suitable to demonstrate the methodological changes in the LCI system model and in the allocation parameters derived in Part II. However, it is a conceptual mixture, it is not (yet) complete in terms of environmental impacts considered and it does not represent a consensus in weighting the various damages. However, one may easily adapt the method to environmental information resulting from more sophisticated and more complete environmental and social models.

### 8.1.2 General Considerations

Based on the Eco-indicator 95 concept (Section 8.1.3) and externality studies described in Appendix 2, a set of environmental damage figures (expressed in monetary units) is derived. These figures are used for the case studies. The choice for this combined approach is thereby substantiated by the following aspects:

*a)* actuality in terms of knowledge (e.g., in epidemiology) and in valuing external effects,

*b)* transferability and representativeness,

*c)* completeness in terms of ecological commodities considered, and

*d)* operationality (versus methodological pureness).

*Ad a)* In the last five years new knowledge about the health effects of in particular particulates with a diameter smaller than 10 micron ($PM_{10}$) became available. It has been shown that also small increases in pollution lead to small but definite increases in risks. The setting of standards for $SO_X$ and particulates was in former times made jointly, based on the knowledge from pollution episodes like the smog periods in London in the 1950s. It was implicitely assumed that no adverse effects would occur as long as the pollutants' concentration is below these standard limits (European Commission 1995b, p. 64). That is why, the external costs per kg particulate matter emitted (including the secondary particulates, i.e., sulfates and nitrates) is higher in recent studies compared to the ones reported in the eighties. This new knowledge is included in both the ESEERCO (Rowe et al. 1995a&b) and the ExternE studies (European Commission 1995a-f, European Commission 1997, Krewitt et al. 1997), but not in the Eco-indicator 95 (Goedkoop 1995). In Goedkoop (1995, p. 33) the category winter smog relies on the air quality guidelines of WHO published in 1987, where only particulates and sulphur oxides are limited. Finally, Infras et al. (1996) use a top-down approach where the attribution of external effects to single pollutants is made in a different, rather rough way. Furthermore, the costs represent the Swiss situation, whereas emissions related to a product system analysed in LCA may occur all over the world.

*Ad b)* The weights given to certain pollutants need to be generally applicable if they are to be used in current LCAs. Important parameters for effects on human health, which mainly dominate the total score of external costs in the case of fossil energy systems, are

- the population density,
- the economic value of human and other species' life, i.e., VSL or VLYL[1],
- the inclusion or exclusion of chronic effects,
- the height of the stack, and
- the exposure-response function.

The ExternE and the ESEERCO study show large differences in the effects of heavy metals which, according to Krewitt (1997), may stem from differences in the exposure-response functions more than from differences in population densities or in stack heights. The variation of the site shows the strong dependence on the population density. For this thesis, data evaluated underlying an urban/ suburban situation are chosen to reflect the situation in Europe and in Switzerland, where investments in new energy systems will most probably be discussed. Because the life cycle inventories of energy systems (Frischknecht et al. 1996a) focus on the Swiss and the Western European situation, more weight is given to the results produced within the European ExternE studies compared to the results of the US-american ESEERCO studies. The two ExternE studies described in Appendix 2 are based on different concepts concerning the value of human life and concerning the chronic effects. In European Commission (1997), the value of statistical life (VSL) is used and chronic effects are not considered, whereas in Krewitt et al. (1997), the value of life year lost (VLYL) is used and chronic effects are included. These changes compensate each other to a certain extent. That is why the results of the two studies are nevertheless rather similar.

The external effects of radionuclides are shown in the ExternE study (European Commission 1995e). The radionuclides released by the French nuclear fuel cycle mainly cause long-term global external effects[2]. Furthermore, the varying population density of the different steps in the fuel cycle is taken into account by calculating the weighted average. Due to the importance of the French nuclear power plants in the European electricity network, the representativity may be judged as being sufficient.

*Ad c)* Both the ExternE and the ESEERCO study mainly focus on a limited number of airborne pollutants. In order to be able to further use the large number of ecological commodities reported in Frischknecht et al. (1996a) other information is indispensible. The Eco-indicator 95, based to a large extent on Heijungs et al. (1992a&b), allows to aggregate a large number of air- and waterborne pollutants which makes it attractive to apply this method. Aspects like resource degradation (fossil and fissile fuels, minerals, etc.), land use, or changes in the ground- and surface water system are not considered in the Eco-indicator 95 and will neither be considered in the adapted version Eco-indicator95$^{RF}$[3].

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[1] VSL: Value of statistical life; VLYL: Value of life year lost. See, e.g., Friedrich et al. (1997, p. 55ff.) for a description of the two approaches.

[2] The main contribution stems from collective doses. Although the occurrence of effects of low doses is disputed, they are considered in the impact assessment method developed here.

[3] If we consider land use as proposed in MŸller-Wenk et al. (1996, p. 230), i.e., a reduction factor of 10 and 2'100'000 $km^2a$ as normalisation value, the Eco-indicator 95 value of 1TJ electricity from nuclear energy would increase by 30% due to the long time period during which land used for mining and milling of uranium is adversely affected. For a hard coal and a heavy fuel oil power plant, the inclusion of land use would result in an increase of between 0.5 to 1.5%, and

*Ad d)* Although very different in their methodology, the Eco-indicator 95 and ExternE studies show some similarities. Some pollutants and their environmental damages (expressed in environmental damage costs and Eco-indicator 95 points) can be used as terms of references between the two approaches. Because the damages caused by primary and secondary particles cover about the same safeguard subject in Eco-indicator 95 and ExternE, namely, human health[4], the corresponding pollutants, i.e., $NO_X$, $SO_X$, and particulates, may be used to adjust and calibrate the Eco-indicator 95 approach. This leads to a conceptually mixed but operational approach. Damages to human health are weighted based on the "willingness to pay" principle. Damages to ecosystems, however, are determined indirectly using the equivalency factor introduced by Goedkoop (1995) between excess deaths and ecosystem impairment.

The additional safeguard subject "ecosystem health" and the multitude of pollutants considered in Eco-indicator 95 is its advantage. It helps to broaden the scope of environmental impacts to be taken into account. But the substantial differences between the Eco-indicator 95 and ExternE studies in weighting pollutants is an important disadvantage. Pollutants affecting the same safeguard subject should approximately show a similar relative weighting in both concepts. Because ExternE tries to predict actual, incremental damages based on regional and continental system models, we prefer this knowledge. Therefore the Eco-indicator 95 methodology is adapted. The adaptations are listed and reasoned in Subchapter 8.2.

### 8.1.3 Eco-indicator 95

The Eco-indicator 95 allows to weight a large number of air- and waterborne pollutants and to aggregate them to a single figure[5]. The valuation of the Eco-indicator impact categories is made

*a)* under the subjective assumption that 1 additional death per million inhabitants equals 5% ecosystem impairment (Goedkoop 1995, p. 31), and

*b)* using an objective extrapolation model with a linear damage function by dividing the current total impact by the target value.[6]

Or, in the notation used in Goedkoop (1995, p. 31):

$$I = D_k \cdot \sum_i \frac{E_i}{T_i} = \sum_i r_i \cdot \frac{E_i}{N_i} \text{ ; with } r_i = \frac{N_i}{T_i}, \tag{8.1}$$

where $I$ is the impact score (Eco-indicator points), $D_k$ is the damage (which is dimensionless and equal to 1 for 1 additional death per million inhabitants and for 5% ecosystem impairment), $E_i$ is the contribution of a product life cycle to effect $i$ (e.g., global warming), $T_i$ is the target value for effect $i$, and $N_i$ is the current extent of effect $i$ (normalisation value). The reduction or damage extrapolation factor $r_i$ is calculated by dividing the current extent of an effect by the respective target value. Hence, one Eco-indicator point equals 1 additional death per million people. Consequently, the current European environmental impacts, which amount to 165 Eco-indicator 95 points cause a damage equivalent to 165 additional deaths per one million people and year, or 82'500 additional deaths per year in Europe (500 million people).

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2 to 3%, respectively. But because of methodological uncertainties and data incompatibilities, land use is not considered here.

[4] In the externality studies, damages to crops and buildings *et cetera* are included. However, their contribution is minor compared to the damage costs caused by excess deaths.

[5] For a comprehensive description and discussion of the method, I refer to Goedkoop (1995), and MŸller-Wenk et al. (1996).

[6] The target value is the impact score which causes 1 additional death per million inhabitants or 5% ecosystem impairment.

To be able to convert the environmental impacts expressed in points in Goedkoop (1995) to monetary units, total environmental external costs in European countries are divided by the total European Eco-indicator score. It is assumed that total environmental external costs in Europe amount to 10% of Europe's gross domestic product (GDP)[7]. In 1990, the GDP of the western European countries amounted to about 7'100 billion US-$ (OECD 1997), and the total flow of ecological commodities expressed in Eco-indicator 95 points amounts to 121 points. If eastern European countries are included, the GDP rises to 7'300 billion US-$ (UN 1996), and the total flow of ecological commodities amounts to 165 Eco-indicator 95 points. Hence, the environmental external costs amount to 5.8US-$ and 4.4US-$, respectively, per $10^{-9}$ Eco-indicator 95 points.

Applying the specific Eco-indicator "external costs" (4.4US-$/$10^{-9}$ points) to the pollutants for which "real" environmental external costs have been determined in externality studies (see Appendix 2, Subchapters A2.1 to A2.4), we recognise that the effects of particulates, $SO_2$, $NO_X$ and NMVOC are strongly underestimated by more than one order of magnitude (see Tab. 8.1). The effect of arsenic and chromium are also underestimated, whereas this approach leads to substantially higher external effects for nickel, and cadmium. The external costs of $CO_2$ are below the lower end of the ranges presented in the literature (see Tab. 8.1).

The Eco-indicator 95 relies on knowledge of the eighties (until 1990) in particular concerning the effect of particulate matter (primary and secondary particulates). That is why the Eco-indicator is not directly applied in this thesis for the valuation of flows of ecological commodities. Adjustments are indispensible in order not to provide inaccurate environmental information.

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[7] Infras et al. (1996, p. 20) state that the quantifiable environmental external costs of energy and transport in Switzerland amount to 3 to 5% of the Swiss GNP. According to Hofstetter (1998), "*10% can be interpreted as an upper level for all expenditures to prevent environmental damages*". Valuing the life of a human being with 1.7 and 6.6 million US-$, the environmental external costs caused by the current flows of ecological commodities based on Goedkoop (1995) amount to 140 and 540 billion US-$, respectively. This also shows the "upper limit"-character of the assumption made.

| | Eco-indicator 95<br>ECU (1990)/t | Environmental damage costs<br>ECU (1990)/t |
|---|---|---|
| Carbon dioxide, $CO_2$ | 1.4/1.8 [1]) | 3-193 |
| Particulate matter, PM10 | 390/510 | 17'000-29'000 |
| Sulphur oxides as $SO_2$ | 1'030/1'400 | 7'400-14'000 |
| Nitrogen oxides, $NO_X$ | 910/1'160 | 2'300-16'000 |
| NMVOC via $O_3$ | 440/580 | 2'500 [2]) |
| Arsenic, As | 33'000/44'000 | 1'000'000 [3]) |
| Cadmium, Cd | 9'100'000/12'000 '000 | 81'000 [3]) |
| Chromium, Cr | 330'000/440'000 | 820'000 [3]) |
| Nickel, Ni | 330'000/440'000 | 17'000 [3]) |
| Dioxines, cancers | - [4]) | 2'000'000'000 |

Tab. 8.1: Eco-indicator 95 values in ECU per metric ton for selected pollutants calculated based on the assumption that 10% of the European country's GDP is the monetary value of environmental external effects; Environmental damage costs based on European Commission (1997), Krewitt et al. (1997), and Eyre et al. (1997), see Appendix 2, Tab. A2.1).
[1]): Excluding/ including eastern European countries.
[2]): Referred to total organic carbon.
[3]): Only cancers.
[4]): Not included in the Eco-indicator 95.

## 8.2 Eco-indicator 95^RF

### 8.2.1 Introduction

The changes in the Eco-indicator 95 are made on different levels. First, additional substances are added and/or characterisation factors are adapted to new knowledge. Second, a new impact category "ionising radiation" is added to the existing set of impact categories. Third, the normalisation values are adapted according to new knowledge, and forth, the weighting of the impact categories is changed in order to fit into the relative importance of the pollutants as reported by the externalities studies.

### 8.2.2 Summer Smog

The impact category "summer smog" is completed with substances for which emission data are available in Frischknecht et al. (1996a) and for which characterisation factors are reported in Heijungs et al. (1992a). It comprises mainly individual alkanes, olefins and some aldehydes. Furthermore, $NO_X$ is assumed to be critical in troposperic ozone formation. The contribution of $NO_X$ is determined on the basis of the annual Swiss emissions of NMVOC and $NO_X$ (211'000 and 136'000 t per year, (BUWAL 1995, p. 15)). We assume that these overall amounts are equally responsible for the formation of ozone[8]. Under these assumptions, the characterisation factor for nitrogen oxides in relation to ozone creation amounts to 0.645kg ethylene-equivalents per kg $NO_2$.

### 8.2.3 Winter Smog

The impact category "winter smog" is adapted according to recent knowledge about the health effects of particulate matter. For that reason, $NO_X$ is included (formation of secondary particulates via nitrate) and the equivalency factors are adjusted according to external cost figures determined by European Commission (1997), Krewitt et al. (1997), Rowe

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[8] In contrast to most other characterisation factors, the factor for $NO_X$ relies on average instead of incremental environmental effects. But the influence on the results of the case studies is minor.

et al. (1995), and IVM et al. (1997). In simplifying the outcome of these studies, it is assumed that particulate matter shows twice the effects compared to $SO_X$ and that $NO_X$ is of lower importance than $SO_X$.

A correction is needed to separate the particulate matter with diameters below 10 microns from the rest, because Frischknecht et al. (1996a, Part III Methodik, p. 28) only report total particulate matter. For processes burning fuels such as boilers (oil and wood), turbines and spark ignition engines, the share of $PM_{10}$ is close to 100%. It is therefore generally assumed that 1kg of mobile and stationary particulate emissions registered in Frischknecht et al. (1996a) equals 1kg $PM_{10}$. Process-specific particulate matter emissions (such as dusts caused in mining) are assumed to have greater diameters and are therefore not considered. The characterisation factors used in the case studies amount to 2kg $SO_2$-equivalents for total particulate matter, and 0.6kg $SO_2$-equivalents for $NO_2$.

### 8.2.4 Global Warming

The recently published IPCC report of working group 1 has been used to adapt the characterisation factors in the "global warming" impact category. The main difference to the values used in Goedkoop (1995) lies in the consideration of indirect effects of ozone depleting gases that also directly contribute to global warming. This effect results in negative characterisation factors for halon 1301, tetrachloromethane, and for 1,1,1-trichloroethane, whereas the amplifying contribution to global warming of CFCs and H-CFCs is diminished. Houghton et al. (1996, p. 119) name upper and lower estimates of indirect cooling effects. As a first guess, the arithmetic mean value has been chosen (see also Tab. A2.12 in Appendix 2). Some H-CFCs (e.g., H-CFC 114, 115) are not considered because no GWP is given in the actual IPCC report.

| | Damages in ECU (1990)/t | | | |
|---|---|---|---|---|
| Discount rate | 0% | 1% | 3% | 5% |
| Base Case | 104 | 56 | 20 | 8.5 |
| No equity weighting [1]) | 46 | 24 | 7.5 | 3 |
| Low climate sensitivity, 1.5¡C | 61 | 33 | 11 | 5 |
| High climate sensitivity, 4.5¡C | 193 | 105 | 36 | 16 |

Tab. 8.2: Marginal damage costs for global warming; Eyre et al. (1997, p. 41).
[1]): Constant marginal utility of income.

Three damage costs scenario are used in the case studies. They are defined based on the Global Warming Sub-Task report (Eyre et al. 1997). Eyre et al. determined the marginal damage costs of global warming based on the IPCC scenario IS92a, emissions in 1995-2005 and 2100 as the time horizon of damages. Socially contingent effects of climate change such as migration, hunger, conflict, *et cetera*, are not included in the figures given in Tab. 8.2[9].

| per t $CO_2$ | Eco-indicator $95^{RF}$ points | SFr. |
|---|---|---|
| Low | 7.52á$10^{-10}$ | 4.20 |
| Medium | 7.52á$10^{-9}$ | 42 |
| high | 3.76á$10^{-8}$ | 210 |

Tab. 8.3: Three scenario for environmental external costs in SFr. (1ECU = 1.68 SFr., 1990) of $CO_2$ used in the case studies.

[9] Marginal damages due to socially contingent effects may reach 3'300ECU (1990) per t $CO_2$ (Eyre et al. 1997, p.38).

Based on the Eco-indicator $95^{RF}$, the external costs for these scenario are 4.2, 42 and 210SFr. per ton $CO_2$ (see Tab. 8.3)[10]. The costs for other greenhouse gases are determined based on the global warming potentials published in Houghton et al. (1996, p. 119/121).

### 8.2.5 Ionising Radiation

The priority impacts for the nuclear fuel cycle considered in this thesis comprise radiological health impacts due to routine releases to the environment. The release of ionising radiation is not included in the impact assessment methods available. For an improved assessment of nuclear energy the environmental effects of ionising radiation should be taken into account. Accidental releases and occupational exposure are not applied due to lacking data and methodological difficulties. The following considerations are based on the results of the ExternE nuclear fuel cycle report (European Commission 1995e). For the most relevant radionuclides, emission-dose factors are calculated and combined with the occurrence of fatal, and non-fatal cancer, and severe hereditary effects. Together with the economic value for fatal cancer, for severe hereditary effects, and for non-fatal cancer, the external costs due to health risks per radionuclide emitted in the nuclear fuel cycle can be determined. In addition to that, a connection to the Eco-indicator 95 method is established with the definition of a separate impact category.

The specific emissions per year as well as the collective doses due to these emissions are listed in European Commission (1995e, p. 95ff.) for each step in the nuclear fuel cycle (see Appendix 2, Tab. A2.6). The collective doses are determined considering four pathways for gaseous releases (inhalation, exposure from the cloud, and from the ground, and consumption of contaminated food), and one for liquid releases (ingestion of drinking water, fish, and irrigated products, see Tab. A2.7). The study is based on French sites' data and their specific demographic, topographic and meteorological situation. However, for some of the radionuclides (Tritium ($^{3}H$), Carbon-14 ($^{14}C$), Krypton-85 ($^{85}Kr$), and Iodine-129 ($^{129}I$)) a global assessment has been performed over a time period of 100'000 years and a world population of 10 billion human beings[11]. Based on these data, the collective doses per kBq emission are determined (Tab. A.2.8). Some of the radionuclides are emitted during power plant operation and reprocessing of spent fuel rods (e.g., $^{14}C$, $^{3}H$, $^{131}I$, $^{133}I$, and $^{85}Kr$ in air) whereas others are emitted in mining/ milling, conversion, enrichment and fuel fabrication (e.g., $^{226}Ra$, $^{222}Rn$, $^{234}U$, $^{235}U$, $^{238}U$ in air and water). Due to demographic, topographic and meteorological variations, the collective dose (in man.Sv) per kBq varies for these radionuclides. Mean values have been determined for the case studies applying the weighted average based on specific emissions caused by the individual fuel cycle steps per TJ electricity. The data for these emissions is also taken from European Commission (1995e). Fresh water and sea water discharges are discriminated, the former applied for power plant effluents, the latter for the discharges from re-processing facilities which are situated on the coast (La Hague, France, and Sellafield, UK).

[10] In the high external costs scenario, the total external costs of greenhouse gases emitted in Europe (6.65á$10^{12}$ kg $CO_2$-equiv.) would rise to about 1'000 billion dollars or 14% of European GDP in 1990.
[11] 0% discount rate has been applied although a social time preference rate of 2 to 4% seems to be appropriate according to European Commission (1995b, p. 450).

| Radionuclide | man.Sv/kBq | kBq $^{129}$I-Equiv. | Radionuclide | man.Sv/kBq | kBq $^{129}$I-Equiv. |
|---|---|---|---|---|---|
| *Gaseous:* | | | *Liquid:* | | |
| C14 p | 1.4E-07 | 9.4E-02 | Ag110m f | 3.3E-10 | 2.2E-04 |
| Co58 p | 2.8E-10 | 1.9E-04 | Am241 s | 2.1E-08 | 1.4E-02 |
| Co60 p | 1.1E-08 | 7.2E-03 | C14 s | 7.8E-10 | 5.2E-04 |
| Cs134 p | 7.9E-09 | 5.2E-03 | Cm alpha s | 3.8E-08 | 2.5E-02 |
| Cs137 p | 8.9E-09 | 5.9E-03 | Co58 f | 2.7E-11 | 1.8E-05 |
| H3 p | 1.7E-11 | 1.1E-05 | Co60 f | 2.9E-08 | 1.9E-02 |
| I129 p | 1.5E-06 | 1.0E+00 | Co60 s | 2.6E-10 | 1.7E-04 |
| I131 p | 1E-10 | 6.8E-05 | Cs134 f | 9.5E-08 | 6.3E-02 |
| I133 p | 6.2E-12 | 4.1E-06 | Cs134 s | 5.2E-11 | 3.4E-05 |
| Kr85 p | 9.3E-14 | 6.2E-08 | Cs137 f | 1.1E-07 | 7.4E-02 |
| Pb210 p [2]) | 1.0E-09 | 6.7E-04 | Cs137 s | 5.2E-11 | 3.5E-05 |
| Po210 p [2]) | 1.0E-09 | 6.7E-04 | H3 f | 2.5E-13 | 1.7E-07 |
| Pu alpha p | 5.5E-08 | 3.6E-02 | H3 s | 8.3E-16 | 5.5E-10 |
| Pu238 p | 4.4E-08 | 3.0E-02 | I129 s | 2.1E-10 | 1.4E-04 |
| Rn222 p | 1.6E-11 | 1.0E-05 | I131 f | 3.3E-10 | 2.2E-04 |
| LT Rn222 p [1]) | 1.6E-11 | 1.0E-05 | Mn54 f | 2.1E-10 | 1.4E-04 |
| Th230 p [2]) | 3.0E-08 | 2.0E-02 | Pu alpha s | 4.9E-09 | 3.3E-03 |
| U234 p | 6.4E-08 | 4.3E-02 | Ra 226 f [3]) | 8.5E-11 | 5.6E-05 |
| U235 p | 1.4E-08 | 9.0E-03 | Ru106 s | 9.5E-11 | 6.3E-05 |
| U238 p | 5.4E-09 | 3.6E-03 | Sb124 f | 5.4E-10 | 3.6E-04 |
| Xe133 p | 9.4E-14 | 6.2E-08 | Sb125 s | 9.8E-12 | 6.5E-06 |
| | | | Sr90 s | 2.7E-12 | 1.8E-06 |
| | | | U 238 f | 1.7E-11 | 1.2E-05 |
| | | | U 238 s | 1.1E-11 | 7.4E-06 |
| | | | U234 f | 1.8E-11 | 1.2E-05 |
| | | | U235 f | 2E-11 | 1.3E-05 |

Tab. 8.4: Collective dose per activity released and equivalency factors of radionuclides based on European Commission (1995e), see Appendix 2 for details.
[1]): LT: long term. Radon emission from mill tailings occuring during 80'000 years (Frischknecht et al. 1996a, Part VII Kernenergie, p. 48).
[2]): specific doses given in UNSCEAR (1993, p. 137)
[3]): based on the assumption that the $^{226}$Ra-emission of 2kBq/kg natural uranium released during mining and milling (Frischknecht et al. 1996a, Part VII Kernenergie, p. 56) leads to the $^{226}$Ra concentration in rivers of 40Bq/m$^3$ used in European Commission (1995e, p. 109).
p: process specific air emissions; f: liquid discharges in fresh water; s: liquid discharges in sea water (mainly from reprocessing plants)

With the data on collective doses, the number of fatal and non-fatal cancers, and of severe hereditary effects may be calculated applying their specific occurrence[12] given in European Commission (1995e, p. 56). For the extension of the Eco-indicator 95, the effects of the radionuclides are expressed in kBq $^{129}$I-equivalents based on their respective collective dose per activity[13]. The specific collective doses as well as the equivalency-factors are listed in Tab. 8.4.

In the Eco-indicator 95, target values of yearly emissions for impact categories concerned with health effects are defined based on the assumption that at these levels one additional fatality per one million people per year will occur. The weighting factor is then calculated by dividing the actual emission level by the target emission level. The life cycle emissions of nuclear power and its collective dose calculated on the basis of the factors shown in Tab. 8.4 multiplied by the electricity generated with nuclear power plants in the European countries (2'900PJ$_e$, in 1990 including eastern Europe, BP (1995, p.30)) results in about 1'100 additional fatal cancers in Europe. With 500 million people living in

[12] 0.05, 0.12 and 0.01 cases per man.Sv for fatal cancer, non-fatal cancer, and severe hereditary effects, respectively.
[13] This is mainly done to comply with the structure of the Eco-indicator 95 methodology. The integration of this category into the Eco-indicator 95 may however be made directly via the damage per kBq emission.

Europe, and aiming at 1 additional death per 1 million people, the reduction factor is 2.2, and the total amount of radionuclides emitted, i.e., the value for normalisation, is 1.46á$10^{10}$kBq $^{129}$I-equivalents[14].

### 8.2.6 Other Impact Categories

The heavy metal characterisation factor of cadmium emitted to air is reduced to 1kg Pb-equiv. per kg Cd (from 50), because of its discrepancy with environmental damage cost figures. For dioxins a characterisation factor (0.5á$10^{-9}$kg Pb-equiv. per ng TCDD-equiv.) is introduced which approximately corresponds to damage costs of 2 bio. ECU per t TCDD-equivalents. However, these changes show only little relevance in the outcome of the case studies.

### 8.2.7 Normalisation Values

The normalisation values of five impact categories are changed based on new knowledge. The normalisation value for the impact categories "global warming", "winter smog", and "summer smog" change because new characterisation factors are applied, and additional substances are considered, respectively. The European emissions of both heavy metals and carcinogenic substances have shown to be substantially higher than estimated in Goedkoop (1995). The total score of these impact categories amounts to about 3.5á$10^{7}$kg Pb-equivalents for heavy metals, and 1.4á$10^{7}$kg PAH-equivalents for carcinogenic substances (1.3, and 2.6 times higher, respectively, than in Eco-indicator 95, see Tab. A2.9 in Appendix 2)[15].

### 8.2.8 Reduction Factors

As has been shown in the last section, the relative importance of greenhouse gases, NMVOC, $PM_{10}$, $SO_X$ and $NO_X$ is much lower in the Eco-indicator 95 weighting scheme compared to the ExternE figures. In order to reflect the results from the externalities studies, some reduction factors are changed or newly introduced. Concerning the impact categories "greenhouse effect", "ozone layer depletion", "acidification", "eutrophication", and "pesticides", the reasoning of MŸller-Wenk et al. (1996) is followed and their proposals are used. In addition to that, the reduction factor of the impact category "winter smog" is augmented to 100 (instead of 5), and the reduction factor for the additional impact category "ionising radiation" equals 2.2 as already stated above (see Tab. A2.9 in Appendix 2).

### 8.2.9 Discussion

Based on this new weighting scheme, the Europe's total environmental impacts amount to 182.2 Eco-indicator points. Under the assumption that the total environmental external costs equal 10% of Europe's GDP, the environmental external costs amount to 4.0US-$/$10^{-9}$ points or 5.6SFr./$10^{-9}$ points (1990). For some pollutants, the environmental external costs per ton are given in Tab. 8.5. With the new weighting scheme, the order of magnitudes for the classic air pollutants $SO_X$, $NO_X$, and particulate matter are rather accurate, whereas the costs for heavy metals still show large differences. However, these differences are of minor importance in the impact assessment of the energy systems used in this thesis.

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[14] The same result is achieved by directly relating the damage (dose related effects) to Eco-indicator points. The emission of 1kBq $^{129}$I-equivalents results in 1.51á$10^{-6}$ man.Sv and therefore causes 7.5á$10^{-8}$ fatal cancers. Hence the emission of 6.7á$10^{9}$kBq $^{129}$I-equivalents equals 1 Eco-indicator point (1.46á$10^{10}$kBq $^{129}$I-equiv.á500/1'100=6.7á$10^{9}$kBq $^{129}$I-equiv.).

[15] Due to the changes in the characterisation factor of cadmium, the effect score for heavy metals shows only a minor change of some 30% compared to Eco-indicator 95.

In alternative scenario, greenhouse gases are weighted with external costs ten and fifty times higher than in the base case. The complete list of the characterisation factors and the Eco-indicator 95$^{RF}$ values are shown in Appendix 2 (Tab. A2.12).

| | Unit | Eco-indicator 95$^{RF}$ SFr. (1990) |
|---|---|---|
| $CO_2$, Carbon dioxide | t | 4.20/42/210 [1]) |
| $CH_4$, Methane | t | 88.2/882/4'410 [1]) |
| Particulate matter, $PM_{10}$ | t | 21'200 |
| Sulphur oxides as $SO_2$ | t | 11'400 |
| Nitrogen oxides, $NO_X$ | t | 10'400 |
| NMVOC | t | 2'150 |
| Arsenic, As | t | 127'000 |
| Cadmium, Cd | t | 576'000 |
| Chromium, Cr | t | 254'000 |
| Nickel, Ni | t | 1'270'000 |
| TCDD-Equivalents | t | 2'010'000'000 |
| *Radionuclides to air:* | | |
| $^{14}C$ | MBq | 57 |
| $^{129}I$ | MBq | 604 |
| $^{85}Kr$ | MBq | 3.7á10$^{-5}$ |
| $^{222}Rn$ | MBq | 6.3á10$^{-3}$ |

Tab. 8.5: Environmental external costs in SFr. (1ECU = 1.68 SFr., 1990) per metric ton and MBq, respectively, for selected pollutants calculated on the basis of the Eco-indicator 95$^{RF}$ and the assumption that 10% of the European country's GDP is the share of environmental external effects. The complete list of the characterisation factors and the Eco-indicator 95$^{RF}$ values are shown in Appendix 2 (Tab. A2.12)
[1]): Three damage costs scenario according to Tab. 8.3.

## 8.3. What is Missing in Costing Ecological Services?

The Eco-indicator 95$^{RF}$ derived in the last section shows some important shortcomings, which may be related to the following two aspects:

*a)* conceptual mixture, and

*b)* missing environmental impacts,

*Ad a)* In the externality studies used to adjust the Eco-indicator 95, nature as such is given no intrinsic value. Damages to animals, forests and crops are only valuated in terms of economic proceeds foregone in the world (or regional) market due to a decrease in the respective yields. Free living birds, reptiles, mammals, wild flowers, primary forests, *et cetera*, do not have a monetary value unless they would be traded. On the other hand, Eco-indicator 95 and the adapted version Eco-indicator 95$^{RF}$ do include ecosystem impairment as one safeguard subject. In this model, about 20% of the European Eco-indicator 95$^{RF}$ score is due to ecosystem impairment[16].

[16] Global warming (5 Eco-indicator 95$^{RF}$ points), acidification (10), eutrophication (5), waterborne heavy metals (a share of 5), and pesticides (10).

*Ad b)* Resource oriented impacts are not yet fully considered. First, the degradation of mineral and energy resources is still not included in the weighting scheme. Several attempts mainly based on mere physical and/or geological data have been made so far, but none of them is satisfactory to us. In our opinion, the characterisation of resource consumption should include a classification of resources according to their usefulness to society[17]. Second, parameters for land use, or direct ecosystem impairment are still premature. Several attempts are made but either the approach is not satisfactory (see also (Heijungs et al. 1997a)), or the data given in Frischknecht et al. (1996a) would need substantial reworking in order to match methodologies proposed. Furthermore, environmental impacts caused by accidents with high specific damage potential but very low probabilities (e.g., core melt down in nuclear power plants, failures of dams, *et cetera*) are not included. Proposals how to treat such events are for instance made in MŸller-Wenk (1994).

- The Eco-indicator $95^{RF}$ developed for the case studies is a conceptual mixture, and focuses on damages on human health and the economic aspects of damages to flora and fauna. Damages on nature not commercially traded (i.e., ecosystem impairement) contribute to less 20% of the total European effect score.
- The method delivers uni-dimensional results in monetary units. It is suitable to demonstrate the changes in the LCI system model and in the allocation parameters.
- The characterisation factors based on the effects caused by the release of radionuclides can readily be implemented into the original Eco-indicator 95 methodology.
- Land use aspects, mineral resource and energy degradation and depletion, environmental impacts related to accidents with low probabilities, as well as occupational effects are not or only insufficiently included.
- We do not claim that the Eco-indicator $95^{RF}$ accurately represents the relative damage caused by the emission of pollutants although care has been taken to at least partly include recent environmental knowledge. The main purpose of the aggregation scheme lies in its application in the case studies which illustrate the methodologies developed in Chapters 3, 5 and 7.

[17] Resources may, for instance, be classified according to their use for basic needs, competitive goods, luxury goods, see Frischknecht (1994b).

# 9. National Electricity Mixes

## 9.1 Introduction

### 9.1.1 Overview

In Chapter 3 it is argued that the relations between unit processes forming a process network and thereby representing a product system should be based on economic and not physical information. If we would not stick to this general procedure, problems arise with process types whose main output is a non-material service, like treatment of waste or transportation of goods. But even with apparently non-problematic physical flows, physical considerations may lead to an inadequate or even wrong system representation. In Subchapter 9.2, the differences in cumulative flows of ecological commodities between physically and monetary based modelling will be shown based on the example of the average, yearly Swiss electricity mix.

In Chapter 5, system models are developed in relation to the planning horizon of the decision to be supported. One important aspect of such models is the use of marginal technologies or technology mixes. The Swiss electricity supply system is one of the product systems where the difference between average technology mix and marginal technology (mix) is assumed to be very large. In Subchapters 9.3 and 9.4, the various competing electricity generating technologies for the Long Run will shortly be described and the concept of choosing a technology based on social costs will be illustrated.

### 9.1.2 The Relevance of National Electricity Mixes

Electric power generation is often of key relevance for the overall results of an LCA. Because of the major differences in the environmental profiles of the various means used for power generation, the question of which electricity mix to choose in a given case is decisive for the results. Depending on the question to be answered with the help of LCA, different models may be applied. The guiding principle formulated in Section 3.1.2 shows us the way how electricity supply shall be modelled in LCA. The production facilities (and/ or contracts) and the corresponding production volumes of the utility which delivers the electricity are relevant. The electricity mix of individual utilities, for instance, is required for the evaluation of a firm's new production site within a country. Nevertheless, data on a higher level of aggregation may be useful[18]. National electricity mixes are appropriate if only the country is known in which a certain good is produced. Country-specific mixes are also adequate when the average performance of a product used in a certain country shall be analysed. For the upstream processes of a product manufactured anywhere in Western Europe, or for European ecolabelling purposes (Frischknecht et al. 1996b), an international electricity mix, e.g., the UCPTE electricity mix[19], may be used.

The question whether to use marginal or average technology (mixes) needs to be answered in addition to the question of the adequate representation of the geographic scope of the electricity supply. While we suggest to use average electricity mixes (see Subchapter 9.2) for environmental reporting purposes, we propose to use marginal electricity generating technologies (Subchapters 9.3 and 9.4) when LCA information is used in decision-making. Hereby, the marginal power plant related to the electricity supply of a regional utility may be a power plant of another utility, maybe located in a foreign country.

[18] Theoretically, the LCA data of national as well as the international electricity mixes consist of LCA data of the electricity mixes of individual utilities.
[19] UCPTE: *Union pour la Coordination de la Production et du Transport de l'ElectricitŽ*

Subchapter 9.2 deals with the aspect of physically- versus economically-based modelling using data for the Swiss national electricity mix. The choice of the example is substantiated more by data availability than by the supposed importance of national mixes. As stated above, several levels of aggregation of electricity mixes are equally useful even within one single LCA. In Subchapter 9.3, various electricity generating technologies are described. In Subchapter 9.4, marginal power plants are determined based on social costs applying a variable environmental exchange rate. The cumulative environmental external costs are determined using average electricity mixes in the up- and downstream processes of potential marginal power plants. The effect is shown when using the respective marginal power plant instead. The example of small-size electric heat pumps used in single-family dwellings demonstrates the effect exerted by macro-economic forecasts on the outcome of an LCA. Finally, in Subchapter 9.5 the disutility function is taken for a "moose test"[20] by comparing the results based on the disutility function with a forecast on investments in the European electricity supply industry, and a marginal electricity mix for the European Union is proposed.

## 9.2 Models of Average National Electricity Supply

### 9.2.1 The Underlying Assumption of Electricity Supply Models

In Frischknecht et al. (1996a), two distinct electricity mix models have been introduced for descriptive LCAs. The first electricity mix model is based on the domestic net production and shows the shares of electricity production of different technologies located in a certain country. Electricity mixes based on net national production is also applied in the PWMI studies on polymers, e.g., Boustead (1992). In this model, electricity trade only consists of pure transit contracts, and any net import of electricity is neglected. The second model is based on the assumption that all electricity imported will be used in the country and that all electricity exported stems from the country's power plant mix. Hence, no concurrent transit contracts are included, and the electricity exported shows the same share of technologies like the domestic electricity *production* mix. The domestic electricity *supply* mix, however, is composed of the amount of domestic production minus the amount of electricity exported plus the amount of electricity imported. This model is used, e.g., in the packaging materials study (BUWAL 1996, p. 40). Both models are based on simplifying assumptions and cannot describe the real situation on the electricity market which will be somewhere in between. However, the two approaches represent the two opposite extreme cases which allow for an easy modelling and an approximation of the real situation by combining them in adequate portions[21]. For a more extensive discussion of the various models, we refer to Frischknecht et al. (1996a, Part XVI Strommix, p. 6ff.).

The electricity exchanged between countries may be measured based on the physical flows crossing the borders or based on the contracts signed between the producers and the utilities. In Chapter 3, the latter is advocated for because economic relationships allow for an adequate representation of the causalities. The question remains, however, whether there are relevant differences in the outcomes if the physically based information is applied.

### 9.2.2 Physically- and Economically-based Electricity Models

[20] Economist (1997)

[21] If in the system model some of the electricity imported from one country is exported to a third country, artificial (non-real) feedback loops occur. If modelled alike, Switzerland, for instance, will import electricity from Germany, whose mix contains a share of imported Swiss electricity mix, whose mix contains a share of imported German electricity mix, *et cetera*. In reality, each power plant produces for clearly defined owners. No feedback loops will therefore occur. Hence, these artificial feedbacks would heavily distort the accounting of cumulative flows of commercial and ecological commodities.

The situation of the Swiss electricity generation and trade in the year 1994[22] is used to show the effects on the cumulative flows of ecological commodities to cope with, when modelling is either based on physical or on monetary flows. The references used for that purpose are the UCPTE annual report and the Swiss electricity statistics of the year 1994, where the physical and the contractual exchanges, respectively, are listed.

| | BEW [4]) | UCPTE | Electricity mix, economic | Electricity mix, physical |
|---|---|---|---|---|
| Unit | [GWh] | [GWh] | [%] | [%] |
| *Domestic production* | *63'661* | | *56.15* | *71.05* |
| - run of river | 16'590 | | 14.63 | 18.51 |
| - hydro storage | 22'622 [1]) | | 19.95 | 25.25 |
| - pumping storage | 344 [2]) | | 0.30 | 0.38 |
| - nuclear | 22'984 | | 20.27 | 25.65 |
| - fossil thermal | 421 | | 0.37 | 0.47 |
| - others [3]) | 700 | | 0.62 | 0.78 |
| *Import* | *22'723* | *15'071* | *43.85* | *28.95* |
| - Germany | 2'997 | 6'087 | 5.78 | 11.69 |
| - France | 17'665 | 7'763 | 34.09 | 14.91 |
| - Italy | 405 | 21 | 0.78 | 0.04 |
| - Austria | 373 | 1'200 | 0.72 | 2.31 |
| - Others | 1'283 | - | 2.48 | 0.00 |
| *Export* | *34'566* | *26'680* | | |
| - Germany | 7'165 | 6'012 | | |
| - France | 755 | 617 | | |
| - Italy | 20'283 | 19'079 | | |
| - Austria | 275 | 972 | | |
| - Others | 6'088 | - | | |
| *Net production (Domestic production minus Export)* | *29'095* | *36'981* | | |

Tab. 9.1: Domestic production, import and export of electricity in Switzerland, and calculated electricity mixes based on economic and physical data.
[1]): Total hydro storage minus pumping storage production;
[2]): Frischknecht et al. (1996a, Part VIII Wasserkraft, p. 11);
[3]): Assumption. In 1993 the electricity from waste incineration amounted to 692GWh (with an increasing tendency in the past years).
[4]): BEW (1995) is the primary source of domestic production figures reported in UCPTE (1994).

In 1994, the Swiss domestic production amounted to 63.7TWh, whereof 62% were generated by hydroelectric, 36% by nuclear and 1.8% by fossil thermal power plants (including electricity from waste incineration). According to BEW (1995, p. 23) the electricity imported based on contracts amounted to 22.7TWh, the export to 34.6TWh, which leads to a domestic consumption of 46.9TWh[23]. UCPTE (1994, p. 34) shows the physical exchanges of electricity which amount to 15.1TWh imports and 26.7TWh exports. The figures are lower by 7.6 and 7.9TWh, respectively, compared to the contractual exchanges. They comprise the long-term exchanges, the physical exchange and control deviations. In Tab. 9.1, the key figures for both models are shown. Electricity does not care about the economic relations and contracts signed between producers and utilities or single clients. For instance, some of the electricity bought by Swiss utilities causes less physical export from Switzerland. This explains the differences in the trade figures of BEW and UCPTE.

The share of imported electricity in the electricity supply is 44% for the economic and 29% for the physical model. Compared to the domestic production structure, the share of Swiss hydroelectric power plants is reduced from more

[22] One single year is chosen in order to facilitate the duplication of the results. The year 1994 is exceptional because of an extraordinarily high excess of net exported electricity. This amplifies the effect to be shown here.
[23] 1.3TWh were used by the storage pumps, and the losses amounted to 3.7TWh.

than 60% to 25 and 44% for the economic and the physical system model, respectively. The share of nuclear and fossil power plants is increased due to the imports from France and Germany, respectively.

The differences in the cumulative flows of ecological commodities as well as in environmental external costs are shown in Tab. 9.2.

| Per 1 TJ electricity | Unit | Electricity mix, economic | Electricity mix, physical | Difference [%] |
|---|---|---|---|---|
| *Output:* | | | | |
| Electricity delivered from the power plants | TJ | 1 | 1 | |
| *Emissions to air:* | | | | |
| Waste heat in air and water [1]) | TJ | 1.969 | 1.727 | 12.3 |
| $CH_4$, Methane | kg | 62.7 | 70.8 | -12.9 |
| CO, Carbon monoxide | kg | 11.3 | 11.4 | -0.9 |
| $CO_2$, Carbon dioxide | kg | 3.04á10$^{4}$ | 3.23á10$^{4}$ | -6.3 |
| Non-Methane Volatile Organic Carbon (NMVOC) | kg | 14.9 | 11.2 | 24.8 |
| $SO_X$, Sulphur oxides as $SO_2$ | kg | 150 | 145 | 3.3 |
| $NO_X$, Nitrogen oxides as $NO_2$ | kg | 53 | 48 | 9.4 |
| Particulate matter | kg | 21.9 | 22.1 | -0.9 |
| $^{14}C$ | kBq | 2.80á10$^{3}$ | 2.67á10$^{3}$ | 4.6 |
| $^{85}Kr$ | kBq | 1.50á10$^{8}$ | 1.25á10$^{8}$ | 16.7 |
| $^{222}Rn$ | kBq | 2.14á10$^{8}$ | 1.78á10$^{8}$ | 16.8 |
| *Environmental external costs:* | | | | |
| $CO_2$ low | SFr. | 6'100 | 5'500 | 8.9 |
| $CO_2$ medium | SFr. | 7'300 | 6'800 | 6.4 |
| $CO_2$ high | SFr. | 12'600 | 12'400 | 1.0 |

Tab. 9.2: Selected flows of ecological commodities and environmental external costs for the Swiss electricity supply mix applying a economic (contractual) and a physical model for the representation of electricity trade. National average power plant performance is applied based on Frischknecht et al. (1996a).
[1]): including 1TJ electricity produced in the power plants and consumed elsewhere.

Some specific flows of ecological commodities listed in Tab. 9.2 change markedly in amount. The specific amount of NMVOC emitted is higher by nearly 25% using contract information. The $CO_2$ emissions are lower by more than 6% if economic data are used. Furthermore the flows of $SO_X$, $NO_X$ and radionuclides are higher by 3%, 9%, and 5 to 17%, respectively in the economic model. The electricity mix based on contract information shows higher environmental external costs than the one based on the measurements of physical flows due to a smaller share of hydroelectric power (35 compared to 44%). However, the differences are rather small, amounting to 9% in the low $CO_2$-scenario case, and 1% in the high $CO_2$-scenario case.

Although more adequate than the physical electricity model (see Section 3.1.2), the economic model is by far not satisfactory because relevant information about foreign holdings in particular domestic power plants is not included (e.g., the 17.5% Swiss holdings in the nuclear power plants Bugey 2-3 in France or the 17.5% German holdings in the Swiss nuclear power plant Leibstadt, UNIPEDE (1996, Appendix C)). Ideally, the ownership of all power plants and the utility-specific dedication of their production would be needed in order to be able to establish average electricity mixes on the level of utilities but also on a national level. The national frontiers would be virtually drawn along the power plants and holdings in power plants producing for the respective nation. This approach follows Ohmae (1996), who suggests to substitute borders along the contours of flows of goods, capital and information for the traditional national frontiers[24].

[24] However, his objective is different, namely the improvement of the economic efficiency by aggregating markets with similar needs to new political entities.

### 9.2.3 Conclusions

The effect due to the use of physical instead of economic system models to represent national average electricity mixes is rather small if expressed in one-dimensional figures such as environmental external costs. On the level of either single ecological commodities or impact scores, however, the deviation may be much more significant. Then, the differences in the shares of particular electricity generating technologies becomes important.

As long as one-dimensional parameters are used to describe the environmental performance of power plants, both physical and economic information may produce sensible results for descriptive LCAs. For countries with high share of trade compared to the domestic production (e.g., Luxembourg, Switzerland) economic information should be preferred whereas for other countries the error made when using physical information is usually negligible.

While physical information may be adequate on the level of electricity mixes, economic information (e.g., contractual or market information) should *always* be decisive in establishing process networks on the level of unit processes. Hence, a production site's vicinity to a particular power plant should not be a reason to model the site's electricity consumption with the performance of that power plant unless contracts exist concerning the purchase of electricity.

## 9.3 Potential Marginal Electricity Generating Technologies

### 9.3.1 Introduction

The choice of a marginal technology in an LCA of the Long Run type will be shown on the example of the LCA of earth coupled electric heat pumps for one-family houses in Switzerland. The central point of discussion concerns the technology or technology mix applied for electricity generation. Various possible scenario are modelled and the cumulative flows of ecological commodities and the corresponding environmental external costs are computed.

As stated previously, the marginal technology shall be choosen based on the principle of the enviro-economic competitiveness expressed in social costs. Hence, data on the private costs of production are needed too. The electricity producing systems used in this and/or the next chapter are[25]

- average fuel oil power plant in Italy,
- average lignite and hard coal power plant in Germany,
- average gas-fired power plant in The Netherlands,
- average nuclear power plant in France,
- average run-of-river hydroelectric power plant in Switzerland, *
- natural gas gas combined cycle power plant,
- hard coal pressurized fluidized bed combustion power plant,
- roof and wall integrated photovoltaic power plant, monocristalline, 3kWp, *
- wind power plant on the Grenchenberg, Switzerland, *
- energy saving measure, replacement of an incandescent bulb by a energy saving bulb. *

The new technologies based on traditional fuels like, i.e., pressurized fluidized bed combustion and natural gas combined cycle power plant, represent marginal technologies to be put into operation. However, emphasis is put on

[25] The systems with an asterisk are used in Chapter 10 only.

existing power plants. This has two main reasons. First, there are massive power plant overcapacities available in Europe. Hence, for the time being, the existing power plants are able to cover an eventual additional demand of electricity. The fact that data about particular marginal power plants (i.e., a particular coal power plant in Germany) are not available implies the use of national but technology-specific averages. Second, existing power plants are suitable for Chapter 10, where the situation of additional heat demand covered by CHP plants is analysed. In this case, it may be assumed that existing power plants are displaced.

The average, country specific power plants do not necessarily represent the potential marginal technology. Other national average and even more single power plants of European countries show higher social costs than the one with the same energy carrier analysed here. This fact underlines the illustrative character of the data used.

The new renewable energy systems as well as hydroelectric power plants considered here are only used for comparisons in the CHP plant case study in Chapter 10. Furthermore, the considerations in this and the next chapter abstract from questions about availability, generating pattern, and determinability of electricity generation with these technologies.

In the following sections, the systems will shortly be described in technical and ecological terms. The economic aspects are described in Appendix 3. The technical information is based on the respective Parts in Frischknecht et al. (1996a). It is emphasized that the economic information given does not necessarily represent the situation in the respective country. Here, generalisations and assumptions are required using information on a European and in some cases, a German[26] and a Swiss[27] level.

### 9.3.2 Average Heavy Fuel Oil Power Plant in Italy

In Italy, nearly 50% of the electricity production stems from fuel oil power plants. The average efficiency of Italian oil power plants is 38.3%. The emission limits for air pollutants from fossil power plants require primary and secondary measures[28]. It is assumed that half of the power plants is equipped with once-through cooling using surface water, the rest with cooling towers. The upstream processes, refineries, long-distance transport of crude oil and production methods are represented by processes used in a European average supply situation. Some selected flows of ecological and commercial commodities and environmental external costs for the heavy fuel oil power plant in Italy are listed in Tab. 9.3.

| Per TJ electricity | Unit | Unit process | Life Cycle |
|---|---|---|---|
| *Input:* | | | |
| Heavy fuel oil from European refineries | t | 62.5 | - |
| *Output:* | | | |
| Electricity | TJ | 1 | 1 |
| *Emissions to air:* | | | |
| Waste heat in air and water [1]) | TJ | 2.71 | 3.32 |
| $CH_4$, Methane | kg | 12.8 | 305 |
| CO, Carbon monoxide | kg | 26.1 | 74.1 |
| $CO_2$, Carbon dioxide | kg | 191'000 | 227'000 |
| Non-Methane Volatile Organic Carbon (NMVOC) | kg | 12.8 | 583 |

[26] Figures on hard coal power plants are reported in Friedrich (1997). For a planned lignite power plant, information is given in Hlubek et a. (1997).
[27] Figures on hydro power are reported in Prognos (1996b), on photovoltaics in SOFAS (1997), and on wind power in Buser et al. (1996). Figures on energy saving measures stem from own investigations.
[28] Until the end of 1997, one third of the power plants with a thermal capacity of more than 500 $MW_{th}$ should fulfill the limits for $SO_2$, $NO_2$, particulate matter and CO (400, 200, 50, and 250 mg/$Nm^3$, respectively).

| | | | |
|---|---|---|---|
| $SO_X$, Sulphur oxides as $SO_2$ | kg | 2'120 | 2'340 |
| $NO_X$, Nitrogen oxides as $NO_2$ | kg | 351 | 501 |
| Particulate matter | kg | 72.4 | 96.2 |
| $^{14}C$ | kBq | 0 | 52 |
| $^{85}Kr$ | kBq | 0 | 3.2á$10^6$ |
| $^{222}Rn$ | kBq | 0 | 4.6á$10^6$ |
| *Environmental external costs:* | | | |
| $CO_2$ low | SFr. | 43'600 | 53'000 |
| $CO_2$ medium | SFr. | 50'800 | 61'900 |
| $CO_2$ high | SFr. | 83'000 | 101'200 |

Tab. 9.3: Selected flows of commercial and ecological commodities and environmental external costs for the unit process and the life cycle of an average heavy fuel oil power plant in Italy. For the complete documentation of this unit process it is referred to Frischknecht et al. (1996a, Part IV Erdšl, p. 222ff.).
[1]): including 1TJ from the electricity produced in the power plant and consumed elsewhere.

NMVOC, methane as well as $^{14}C$, $^{85}Kr$, and $^{222}Rn$ emissions occur predominantly in the upstream processes. About 84% of the total $CO_2$ emissions occur at the power station, and also the main share of $SO_X$, $NO_X$, and particulate matter is emitted during the operation of the power plant.

The environmental external costs determined based on the methodology described in Chapter 8 amount to 0.19, 0.22, and 0.36SFr. per kWh electricity for the low, medium and high, scenario of $CO_2$-damage costs. More than 80% are caused by the operation of the power plant.

According to Mutzner (1997, p. 63) the private costs of electricity production in an heavy fuel oil power plant vary between 0.1 and 0.16 SFr. per $kWh_e$. Prognos (1996b, p. 64) uses 0.08SFr. full costs per $kWh_e$ for fossil thermal power plants. Based on information given in Friedrich (1997), interest rates of 2 and 5%, a life time of 30 years, and a base load character of the power plant with a load factor of 85%, full costs of between 0.073 and 0.077SFr. per $kWh_e$ result (excluding costs for downstream activities, i.e., transport and distribution costs of 0.104SFr./$kWh_e$). A detailed derivation of energy costs is given in Appendix 3. The environmental external costs are higher than the private ones (excluding transport and distribution) by a factor between two and more than four.

### 9.3.3 Average Lignite and Hard Coal Power Plant in Germany

In the western part of Germany, the emission control measures have been accomplished whereas in the eastern part, retrofitting activities are still on the way. Because lignite is the major energy carrier in the eastern part of Germany, the emission factors of lignite power plants are substantially higher than the ones of hard coal power plants. The average annual net efficiency amounts to 30.9 and 34.7% for lignite and hard coal, respectively. It is assumed that 25% of the power plants are equiped with once-through cooling systems. The upstream processes, i.e., extraction, storage and transportation of hard coal, are represented by country specific data. The specific provenience of the hard coal as well as its extraction techniques are considered. For lignite, the average european situation is used because country-specific differences in technologies used are minor. Some selected flows of ecological and commercial commodities and environmental external costs for the lignite and hard coal power plant in Germany are listed in Tab. 9.4.

| Per TJ electricity | Unit | Unit process, Lignite | Life Cycle, Lignite | Unit process, Hard coal | Life Cycle, Hard coal |
|---|---|---|---|---|---|
| *Input:* | | | | | |
| Lignite for UCPTE-Europe | t | 413 | - | - | - |
| Hard coal for Germany | t | - | - | 109 | - |
| *Output:* | | | | | |
| Electricity | TJ | 1 | 1 | 1 | 1 |
| *Emissions to air:* | | | | | |

| | | | | | |
|---|---|---|---|---|---|
| Waste heat in air and water 1) | TJ | 3.82 | 3.91 | 2.96 | 3.12 |
| $CH_4$, Methane | kg | 3.2 | 29.5 | 2.9 | 1'230 |
| CO, Carbon monoxide | kg | 32 | 45 | 14.4 | 49 |
| $CO_2$, Carbon dioxide | kg | 359'000 | 364'000 | 267'000 | 277'000 |
| Non-Methane Volatile Organic Carbon (NMVOC) | kg | 6.5 | 12.5 | 5.8 | 22.2 |
| $SO_X$, Sulphur oxides as $SO_2$ | kg | 2'640 | 2'660 | 334 | 409 |
| $NO_X$, Nitrous oxides as $NO_2$ | kg | 485 | 500 | 202 | 249 |
| Particulate matter | kg | 49 | 205 | 35 | 207 |
| $^{14}C$ | kBq | 0 | 54 | 0 | 80 |
| $^{85}Kr$ | kBq | 0 | 3.3á$10^{6}$ | 0 | 4.9á$10^{6}$ |
| $^{222}Rn$ | kBq | 641 | 4.8á$10^{6}$ | 1'120 | 7.0á$10^{6}$ |
| *Environmental external costs:* | | | | | |
| $CO_2$ low | SFr. | 52'000 | 52'900 | 10'400 | 18'600 |
| $CO_2$ medium | SFr. | 65'500 | 66'700 | 20'500 | 30'000 |
| $CO_2$ high | SFr. | 125'600 | 128'000 | 65'100 | 80'600 |

Tab. 9.4: Selected flows of commercial and ecological commodities and environmental external costs for the unit process and the life cycle of an average lignite and hard coal power plant in Germany. For the complete documentation of these unit processes it is referred to Frischknecht et al. (1996a, Part VI Kohle, p. 80ff.).
1): including 1TJ from the electricity produced in the power plant and consumed elsewhere.

The lignite mined is in most cases used directly at the site. This is why only minor transport activities are required, and why upstream processes contribute little to the overall score. However, there are some exceptions. Particulate matter mainly stems from coal mining and storage, where the wind sweeps along substantial amounts of coal dust. But this dust is not comparable to particulates from combustion processes and is not considered in the weighting of environmental damages. The release of radionuclides from the power plants is minor compared to the indirect emissions caused by electricity consumption within the process network. Methane is predominantly emitted in hard coal mining.

The environmental external costs vary between 0.19 and 0.46SFr. per $kWh_e$ for the lignite, and 0.067 and 0.29SFr. per $kWh_e$ for the hard coal power plant, depending on the $CO_2$ damage costs scenario. In the lignite fuel cycle more than 98% of the costs is caused by the operation phase. In the hard coal fuel cycle this share varies between 55% and 80% depending on the $CO_2$-damage costs scenario.

The private costs are about equal for lignite and hard coal electricity and vary between 0.054 and 0.061 SFr. per $kWh_e$ for lignite, and 0.059 and 0.067 SFr. per $kWh_e$ for hard coal power plants (excluding transport and distribution).

### 9.3.4 Average Natural Gas Power Plant in The Netherlands

In The Netherlands, about 6% of the electricity from gas-fired power plants is produced with blast furnace gases, whose upstream processes are not considered in the process network for the generation of electricity. The rest is covered by natural gas, mainly of domestic provenience. The share of gas used for heating purposes in large CHP plants amounts to nearly 2.5% using the exergy content as the allocation parameter. The efficiency of natural gas power plants is 40%. The upstream processes, i.e., the long-distance transport and the extraction are represented by country-specific and region-specific data, respectively. Some selected flows of ecological and commercial commodities and environmental external costs for the natural gas power plant in the Netherlands are listed in Tab. 9.5.

| Per TJ electricity | Unit | Unit process | Life Cycle |
|---|---|---|---|
| *Input:* | | | |
| Natural gas, high pressure for The Netherlands | TJ | 2.34 | 1 |
| *Output:* | | | |
| Electricity | TJ | 1 | 1 |
| *Emissions to air:* | | | |
| Waste heat in air and water [1]) | TJ | 2.8 | 2.89 |
| $CH_4$, Methane | kg | 2.56 | 107 |
| CO, Carbon monoxide | kg | 51.3 | 68 |
| $CO_2$, Carbon dioxide | kg | 175'000 | 181'000 |
| Non-Methane Volatile Organic Carbon (NMVOC) | kg | 9.3 | 38 |
| $SO_X$, Sulphur oxides as $SO_2$ | kg | 1.2 | 7.6 |
| $NO_X$, Nitrogen oxides as $NO_2$ | kg | 221 | 244 |
| Particulate matter | kg | 2.56 | 6.4 |
| $^{14}C$ | kBq | 0 | 3.2 |
| $^{85}Kr$ | kBq | 0 | 1.9á$10^5$ |
| $^{222}Rn$ | kBq | 0 | 2.8á$10^5$ |
| *Environmental external costs:* | | | |
| $CO_2$ low | SFr. | 4'100 | 4'800 |
| $CO_2$ medium | SFr. | 10'600 | 11'600 |
| $CO_2$ high | SFr. | 39'500 | 41'800 |

Tab. 9.5: Selected flows of commercial and ecological commodities and environmental external costs for the unit process and the life cycle of an average natural gas power plant in The Netherlands. For the complete documentation of this unit process it is referred to Frischknecht et al. (1996a, Part V Erdgas, p. 71ff.).
[1]): including 1TJ from the electricity produced in the power plant and consumed elsewhere.

Due to the relatively clean combustion and the low contents in sulphur, and other elements, the majority of total emissions of VOC, $SO_X$, and particulate matter stems from upstream activities. The $NO_X$ emitted by the power plant dominate the total score. No direct releases of radionuclides by the gas-fired power plant are reported in Frischknecht et al. (1996a). That is why all radioactive releases are caused by electricity generation required in up- and downstream processes.

The environmental external costs vary between 0.017 and 0.15SFr. per $kWh_e$, depending on the $CO_2$-damage costs scenario. The natural gas power plant shows a relatively high sensitivity in relation to global warming impacts. Its operation phase contributes 85 to 95% to the total environmental external costs.

Based on the information given in Friedrich (1997), interest rates of 2 and 5%, a life time of 25 years, and a base load character of the power plant with a load factor of 85%, full costs amount to between 0.085 and 0.089SFr.. The costs are above the costs for hard coal electricity, which is in coincidence with the figures given in Dupuis (1997) for a medium and high fuel cost scenario (see Tab. A3.1).

### 9.3.5 Average Nuclear Power Plant in France

In France, nearly all nuclear electricity is generated in pressurised water reactors. French nuclear power plants use fuel rods with an average $^{235}$U-content of 3.4%. The specific energy extractable amounts to 39.5$MW_{th}$d/kgU, and the average efficiency of the power plant is 31%. The upstream processes, i.e., fuel rod fabrication, enrichment, and reprocessing, are - as far as possible - represented by country-specific data. The power plants are assumed to be equipped with cooling towers. Some selected flows of ecological and commercial commodities and environmental external costs for the average nuclear power plant in France are listed in Tab. 9.6.

| Per TJ electricity | Unit | Unit process | Life Cycle |
|---|---|---|---|
| *Input:* | | | |
| Uranium 3.4% in fuel rods | kg | 0.95 | - |
| *Output:* | | | |
| Electricity | TJ | 1 | 1 |
| *Emissions to air:* | | | |
| Waste heat in air and water [1]) | TJ | 3.20 | 3.35 |
| $CH_4$, Methane | kg | 0 | 5.3 |
| CO, Carbon monoxide | kg | 0 | 5.8 |
| $CO_2$, Carbon dioxide | kg | 0 | 2'260 |
| Non-Methane Volatile Organic Carbon (NMVOC) | kg | 0 | 4.0 |
| $SO_X$, Sulphur oxides as $SO_2$ | kg | 0 | 20 |
| $NO_X$, Nitrogen oxides as $NO_2$ | kg | 0 | 7.4 |
| Particulate matter | kg | 0 | 5.5 |
| $^{14}$C | kBq | 3'650 | 4'200 |
| $^{85}$Kr | kBq | 21'300 | 3.1á$10^8$ |
| $^{222}$Rn | kBq | 0 | 4.4á$10^8$ |
| *Environmental external costs:* | | | |
| $CO_2$ low | SFr. | 290 | 4'800 |
| $CO_2$ medium | SFr. | 290 | 4'900 |
| $CO_2$ high | SFr. | 290 | 5'300 |

Tab. 9.6: Selected flows of commercial and ecological commodities and environmental external costs for the unit process and the life cycle of the average nuclear power plant in France. For the complete documentation of this unit process it is referred to Frischknecht et al. (1996a, Part VII Kernenergie, p. 121ff.).
[1]): including 1TJ from the electricity produced in the power plant and consumed elsewhere.

The *in situ* emissions from the nuclear power plant are limited to radionuclides, disregarding waste heat emissions. All other pollutants stem from up- and downstream processes and are lower by one to two orders of magnitude compared to the emissions of fossil-fueled power plants. On the other side, the releases of radionuclides are significantly higher than the ones directly and indirectly caused by the generation of fossil electricity.

The environmental external costs, mainly caused by up- and downstream processes (i.e., mining/ milling and reprocessing) are hardly influenced by the variation of the $CO_2$-damage costs and amount to between 0.017 and 0.019SFr. per $kWh_e$. Compared to the private costs they are lower by a factor of four to five.

Based on the information given in Friedrich (1997) and Mutzner (1997), interest rates of 2 and 5%, a life time of 30 years and a base load character of the power plant with a load factor of 85%, full costs amount to between 0.081 and 0.097SFr.. The costs are slightly lower than the ones published in Mutzner (1997, p. 63) and Prognos (1996b, p.64) but substantially higher than the figures given in Dupuis (1997).

### 9.3.6 Average Run of River Hydroelectric Power Plant in Switzerland

The data on run of river hydroelectric power plants are based on detailed investigations and inventories available for the Swiss power plants. Besides three different steel qualities, cement, gravel, and explosives, energy and transport services as well as waste treatment activities are included. For the operation phase, land and water use are registered. Some selected flows of ecological and commercial commodities and environmental external costs for the average run of river hydroelectric power plant in Switzerland are listed in Tab. 9.7.

No *in situ* emissions are considered during the operation phase, disregarding waste heat. All flows of ecological commodities stem from up- and downstream processes and are lower by two to three orders of magnitude compared to the emissions of fossil-fueled and nuclear power plants. There is, however, still a lack of specific parameters that would allow to measure hydro-specific environmental impacts caused by, e.g., water management, *et cetera*.

| Per TJ electricity | Unit | Unit process | Life Cycle |
|---|---|---|---|
| *Input:* | | | |
| Water turbined | $m^3$ | 12'000'000 | - |
| *Output:* | | | |
| Electricity | TJ | 1 | 1 |
| *Emissions to air:* | | | |
| Waste heat in air and water [1]) | TJ | -1 | 0.09 |
| $CH_4$, Methane | kg | 0 | 2.2 |
| CO, Carbon monoxide | kg | 0 | 5.3 |
| $CO_2$, Carbon dioxide | kg | 0 | 980 |
| Non-Methane Volatile Organic Carbon (NMVOC) | kg | 0 | 1.0 |
| $SO_X$, Sulphur oxides as $SO_2$ | kg | 0 | 2.5 |
| $NO_X$, Nitrogen oxides as $NO_2$ | kg | 0 | 3.4 |
| Particulate matter | kg | 0 | 1.9 |
| $^{14}C$ | kBq | 0 | 2.7 |
| $^{85}Kr$ | kBq | 0 | 1.4á10$^{5}$ |
| $^{222}Rn$ | kBq | 0 | 2.0á10$^{5}$ |
| *Environmental external costs:* | | | |
| $CO_2$ low | SFr. | 0 | 120 |
| $CO_2$ medium | SFr. | 0 | 156 |
| $CO_2$ high | SFr. | 0 | 317 |

Tab. 9.7: Selected flows of commercial and ecological commodities and environmental external costs for the unit process and the life cycle of an average run of river hydroelectric power plant in Switzerland. For the complete documentation of this unit process it is referred to Frischknecht et al. (1996a, Part VIII Wasserkraft, p. 16ff.).
[1]): including 1TJ from the electricity produced in the power plant and consumed elsewhere.

The environmental external costs amount to between 0.0004 and 0.0011SFr. per $kWh_e$ depending on the $CO_2$-damage costs scenario. The environmental external costs (based on emissions only) are neglegible compared to the private costs[29].

Based on the information given in Friedrich (1997) and Mutzner (1997), interest rates of 2 and 5%, a life time of 80 years and a base load character of the power plant with a load factor of 54% (Swiss average), full costs amount to between 0.033 and 0.042SFr. per $kWh_e$. The costs are in the lower part of the range given by Mutzner (1997, p. 63). Prognos (1996b, p.64) gives no figure for existing plants (these may operate at variable costs close to zero being almost completely written-off). New plants are assumed to show higher costs of between 0.10 and 0.13SFr. per $kWh_e$.

[29] It should be stressed, however, that external effects due to direct ecosystem impairment and on flora and fauna due to changes in flow patterns, *et cetera*, are *not* included in these figures.

### 9.3.7 Hard Coal Pressurized Fludized Bed Combustion Power Plant

The data used for the representation of pressurized fluidized bed combustion technology are documented in Dones et al. (1996, p.19ff.). Pulverized coal is burned under pressure and at relatively low temperature. Limestone is directly added to the combustion chamber to reduce $SO_X$-emissions. Due to the low temperatures, the emission factor for $NO_X$ is low even compared to existing coal power plants with flue gas treatment. On the other hand, $N_2O$-emissions are higher by about a factor of between 20 and 60. Besides the air pollutants $CH_4$, $N_2O$, $SO_X$, $NO_X$, and particles, the emission factors of the average Austrian hard coal power plant are used. The net efficiency equals to 47% (Dones et al. 1996, p. 18). In the UNIPEDE forecast report about investments and planning in the European electricity supply industry (UNIPEDE 1996, p. A15), the shares of new coal power plants in European countries is indicated. Based on these information, it is assumed that 40% of PFBC plants will be operated in Italy and Spain, 15% in the Netherlands and 5% in Germany (see Tab. 9.8). The supply situation for coal for these regions is assumed to be the same as in the early nineties (Frischknecht et al. 1996a, Part VI Kohle, p. 65ff.).

| Per TJ electricity | Unit | Unit process | Life Cycle |
|---|---|---|---|
| *Input:* | | | |
| Hard coal for Italy | t | 36.2 | - |
| Hard coal for Spain | t | 36.2 | - |
| Hard coal for The Netherlands | t | 13.6 | - |
| Hard coal for Germany | t | 4.5 | - |
| *Output:* | | | |
| Electricity | TJ | 1 | 1 |
| *Emissions to air:* | | | |
| Waste heat in air and water [1]) | TJ | 1.23 | 2.68 |
| $CH_4$, Methane | kg | 7.7 | 613 |
| CO, Carbon monoxide | kg | 10.6 | 52 |
| $CO_2$, Carbon dioxide | kg | 200'000 | 215'000 |
| Non-Methane Volatile Organic Carbon (NMVOC) | kg | 4.3 | 37 |
| $SO_X$, Sulphur oxides as $SO_2$ | kg | 77 | 282 |
| $NO_X$, Nitrogen oxides as $NO_2$ | kg | 77 | 244 |
| Particulate matter | kg | 38 | 276 |
| $^{14}C$ | kBq | 0 | 70 |
| $^{85}Kr$ | kBq | 0 | 4.3á$10^6$ |
| $^{222}Rn$ | kBq | 930 | 6.2á$10^6$ |
| *Environmental external costs:* | | | |
| $CO_2$ low | SFr. | 4'600 | 14'700 |
| $CO_2$ medium | SFr. | 14'400 | 23'300 |
| $CO_2$ high | SFr. | 57'700 | 61'500 |

Tab. 9.8: Selected flows of commercial and ecological commodities and environmental external costs for the unit process and the life cycle of a future hard coal fluidized pressurized bed combustion power plant in Western Europe. For the complete documentation of this unit process it is referred to Dones et al. (1996, p.18ff.) and Frischknecht et al. (1996a, Part VI Kohle, p. 121ff.).
[1]): including 1TJ from the electricity produced in the power plant and consumed elsewhere.

The environmental external costs vary between 0.053 and 0.22SFr. per $kWh_e$ depending on the $CO_2$-damage costs scenario. In the low $CO_2$ damage costs scenario, the operation phase contributes less than one third to the total external costs.

The private costs of PFBC electricity vary between 0.049 and 0.056 SFr. per $kWh_e$ (excluding transport and distribution of electricity). They are about 15% lower than the costs for electricity generated in the average hard coal power plant.

### 9.3.8 Natural Gas Gas Combined Cycle Power Plant

The efficiency of gas turbines is increased by using the flue gas from the turbine to generate steam and to drive a steam turbine. No cogeneration is assumed and the net efficiency amounts to 57%. The provenience of the natural gas is modelled based on the European forecast for new electricity generation capacities (UNIPEDE 1996, p. A15) and the similarity in environmental performance for the different regions. That is why, the gas supply of three European nations, i.e., The Netherlands, Italy, and Spain, is used providing 45%, 35%, and 20%, respectively, of the high pressure natural gas for the power plant (see Tab. 9.9).

| Per TJ electricity | Unit | Unit process | Life Cycle |
|---|---|---|---|
| *Input:* | | | |
| Natural gas high pressure for Italy | TJ | 0.79 | - |
| Natural gas high pressure for The Netherlands | TJ | 0.61 | - |
| Natural gas high pressure for Spain | TJ | 0.35 | - |
| *Output:* | | | |
| Electricity | TJ | 1 | 1 |
| *Emissions to air:* | | | |
| Waste heat in air and water [1]) | TJ | 0.93 | 2.14 |
| $CH_4$, Methane | kg | 10.5 | 277 |
| CO, Carbon monoxide | kg | 53 | 75 |
| $CO_2$, Carbon dioxide | kg | 96'500 | 108'000 |
| Non-Methane Volatile Organic Carbon (NMVOC) | kg | 7 | 52 |
| $SO_X$, Sulphur oxides as $SO_2$ | kg | 0.9 | 26 |
| $NO_X$, Nitrogen oxides as $NO_2$ | kg | 53 | 90 |
| Particulate matter | kg | 0.53 | 5.0 |
| $^{14}C$ | kBq | 0 | 4.2 |
| $^{85}Kr$ | kBq | 0 | 2.5á10$^{5}$ |
| $^{222}Rn$ | kBq | 0 | 3.7á10$^{5}$ |
| *Environmental external costs:* | | | |
| $CO_2$ low | SFr. | 1'200 | 2'500 |
| $CO_2$ medium | SFr. | 4'900 | 6'800 |
| $CO_2$ high | SFr. | 21'200 | 26'000 |

Tab. 9.9: Selected flows of commercial and ecological commodities and environmental external costs for the unit process and the life cycle of a future natural gas gas combined cycle power plant in Western Europe. For the complete documentation of this unit process it is referred to Dones et al. (1996, p.34ff.).
[1]): including 1TJ from the electricity produced in the power plant and consumed elsewhere.

The environmental external costs vary between 0.009 and 0.094SFr. per $kWh_e$ depending on the $CO_2$-damage costs scenario. The upstream processes contribute some 20 to 50% to total environmental external costs.

The private costs of gas combined cycle electricity vary between 0.066 and 0.068 SFr. per $kWh_e$ (excluding transport and distribution of electricity). They are more than 20% lower than the costs for electricity generated in the average natural gas power plant.

### 9.3.9 Roof and Wall Integrated Photovoltaic Power Plant in Switzerland

The photovoltaic systems analysed are 3kWp standard plants that are integrated in walls and slant roofs. They consist of monocristalline solar cells with an efficiency of 16.5%, and an average electricity production of 860kWh and 610 kWh per kWp for slant roof- and wall-integrated plants, respectively. The electricity demand for the production of electronically graded silicon and of the wafers strongly influences the life cycle flows of ecological commodities for photovolatic electricity generation. Data about the production processes are mainly based on information given in Hagedorn (1992a&b). Some selected flows of ecological and commercial commodities and environmental external costs for the roof- and wall-integrated photovoltaic power plant in Switzerland are listed in Tab. 9.10.

No *in situ* emissions are considered during the operation phase, disregarding waste heat. All flows of ecological commodities stem from up- and downstream processes and are lower by one order of magnitude compared to the emissions ($CO_2$, $SO_X$, $NO_X$, *et cetera*, on the one hand, and radionuclides on the other) of fossil-fueled and nuclear power plants, respectively.

The environmental external costs amount to between 0.026 and 0.058SFr. per $kWh_e$ for wall-integrated systems, and between 0.020 and 0.043SFr. per $kWh_e$ for roof-integrated systems, depending on the $CO_2$-damage costs scenario. They are low compared to the private costs.

| Per TJ electricity | Unit | Unit process roof-integrated | Life Cycle, roof-integrated | Unit process wall-integrated | Life Cycle, wall-integrated |
|---|---|---|---|---|---|
| *Input:* | | | | | |
| Solar cells, monocristalline, 1.6Wp | units | 6'770 | - | 9'590 | - |
| *Output:* | | | | | |
| Electricity | TJ | 1 | 1 | 1 | 1 |
| *Emissions to air:* | | | | | |
| Waste heat in air and water [1]) | TJ | -1 | 0.484 | -1 | 0.666 |
| $CH_4$, Methane | kg | 0 | 65 | 0 | 85 |
| CO, Carbon monoxide | kg | 0 | 37 | 0 | 31 |
| $CO_2$, Carbon dioxide | kg | 0 | 29'200 | 0 | 39'800 |
| Non-Methane Volatile Organic Carbon (NMVOC) | kg | 0 | 30 | 0 | 41 |
| $SO_X$, Sulphur oxides as $SO_2$ | kg | 0 | 194 | 0 | 268 |
| $NO_X$, Nitrogen oxides as $NO_2$ | kg | 0 | 70 | 0 | 96 |
| Particulate matter | kg | 0 | 38 | 0 | 47 |
| $^{14}C$ | kBq | 0 | 316 | 0 | 442 |
| $^{85}Kr$ | kBq | 0 | 1.9á10$^{7}$ | 0 | 2.7á10$^{7}$ |
| $^{222}Rn$ | kBq | 0 | 2.8á10$^{7}$ | 0 | 3.9á10$^{7}$ |
| *Environmental external costs:* | | | | | |
| $CO_2$ low | SFr. | 0 | 5'400 | 0 | 7'300 |
| $CO_2$ medium | SFr. | 0 | 6'600 | 0 | 8'900 |
| $CO_2$ high | SFr. | 0 | 11'900 | 0 | 16'100 |

Tab. 9.10: Selected flows of commercial and ecological commodities and environmental external costs for the unit process and the life cycle of a roof- and a wall-integrated photovoltaic power plant in Switzerland. For the complete documentation of these unit processes it is referred to Frischknecht et al. (1996a, Part XII Photovoltaik, p. 15ff.).
[1]): including 1TJ from the electricity produced in the power plant and consumed elsewhere.

Based on the information given in SOFAS (1997), interest rates of 2 and 5%, a life time of 30 years and a load factor of about 10% and 7% (roof and wall, respectively), full costs amount to between 1.04 and 1.37SFr. per $kWh_e$ for roof-, and 1.47 and 1.93SFr. per $kWh_e$ for wall-integrated systems. Prognos (1996b, p.64) published 1.30SFr. per $kWh_e$ based on an interest rate of 2%. EWZ, Zurich's utility, buys and sells photovoltaic electricity at costs of 1.20SFr. per $kWh_e$.

### 9.3.10 Wind Power Plant on the Grenchenberg in Switzerland

Wind power is still developing in Switzerland. After two plants with a capacity of 30$kW_e$ installed in 1986 (Sool) and 1990 (Simplon), and one of 150$kW_e$ in 1994 (Grenchenberg), three 600$kW_e$ power plants have been commissioned in 1996 on Mont Crosin. They consist of a steel tower with the rotor and the generator on top. The yearly harvest of the Grenchenberg plant is about 120'000kWh$_e$, or 800kWh$_e$ per kW$_e$. The larger plants have not yet been analysed but it is assumed that their performance will profit from the upscaling. At the coast, the harvest of wind power plants may be twice as high as in inland positions. Some selected flows of ecological and commercial commodities and environmental external costs for wind power plants in Switzerland are listed in Tab. 9.11.

No *in situ* emissions are considered during the operation phase, disregarding waste heat. All flows of ecological commodities stem from up- and downstream processes and are lower by one to two orders of magnitude compared to the emissions of fossil-fueled and nuclear power plants.

The environmental external costs amount to between 0.0042 and 0.010SFr. per kWh$_e$ dependent on the $CO_2$ damage costs scenario.

Based on the information given in Buser et al. (1996), interest rates of 2 and 5%, a life time of 20 years and a load factor of about 10%, full costs amount to between 0.41 and 0.47SFr. per kWh$_e$. Prognos (1996b, p.64) published 0.12SFr. per kWh$_e$ based on an interest rate of 2% and a load factor of about 21% (1'840h). Furthermore, a range between 0.15 and 0.20SFr. per kWh$_e$ indicated by BKW for future systems is cited (Prognos 1996b, p. 58).

| Per TJ electricity | Unit | Unit process | Life Cycle |
|---|---|---|---|
| *Input:* | | | |
| Tower, foundation, *et cetera* | units | 0.057 | - |
| Generator, rotor, *et cetera* | units | 0.14 | - |
| *Output:* | | | |
| Electricity | TJ | 1 | 1 |
| *Emissions to air:* | | | |
| Waste heat in air and water [1]) | TJ | -1 | 0.097 |
| $CH_4$, Methane | kg | 0 | 25 |
| CO, Carbon monoxide | kg | 0 | 57 |
| $CO_2$, Carbon dioxide | kg | 0 | 7'200 |
| Non-Methane Volatile Organic Carbon (NMVOC) | kg | 0 | 17 |
| $SO_X$, Sulphur oxides as $SO_2$ | kg | 0 | 28 |
| $NO_X$, Nitrogen oxides as $NO_2$ | kg | 0 | 15 |
| Particulate matter | kg | 0 | 20 |
| $^{14}C$ | kBq | 0 | 16 |
| $^{85}Kr$ | kBq | 0 | 9.7á$10^{5}$ |
| $^{222}Rn$ | kBq | 0 | 1.4á$10^{6}$ |
| *Environmental external costs:* | | | |
| $CO_2$ low | SFr. | 0 | 1'200 |
| $CO_2$ medium | SFr. | 0 | 1'400 |
| $CO_2$ high | SFr. | 0 | 2'700 |

Tab. 9.11: Selected flows of commercial and ecological commodities and environmental external costs for the unit process and the life cycle of the wind power plant on the Grenchenberg in Switzerland. For the complete documentation of this unit process it is referred to Frischknecht et al. (1996a, Part XIII Windkraft, p. 6ff.).
[1]): including 1TJ from the electricity produced in the power plant and consumed elsewhere.

### 9.3.11 Energy saving Bulb

The last option introduced here is a demand side management measure, namely the replacement of an incandescent bulb (60W) by an energy saving one (11W). It is used for indicative purposes only and shall show the base line of electricity "generating" costs. The energy saving bulb has a life time of 8'000h whereas the incandescent bulb gives light during 1'000h. The replacement is based on an equivalent light capacity provided by the two options. The additional net investment consists of approximately one energy saving bulb minus eight incandescent bulbs. Besides the manufacturing activities, packing, trade and waste treatment services are included. Some selected flows of ecological and commercial commodities and environmental external costs for this energy saving measure are listed in Tab. 9.12.

No *in situ* emissions are considered during the operation phase. All flows of ecological commodities stem from up- and downstream processes and are lower by two to four orders of magnitude compared to the emissions of fossil-fueled and nuclear power plants. Certain flows are even negative which means that savings are achieved by the mere substitution of investments (the production processes for the energy saving bulb cause less emissions than the ones needed for eight incandescent bulbs). In particular, this is the case for $SO_X$, particulate matter and CO.

The environmental external costs amount to between -8á$10^{-5}$ and +3á$10^{-4}$SFr. per $kWh_e$ saved depending on the $CO_2$-damage costs scenario.

Based on information gathered by own investigations, the net investment costs amount to 7.60SFr. per 8'000 hours of use, or 390$kWh_e$ saved. Hence, the private costs per $kWh_e$ amount to about 0.001SFr..

| Per TJ electricity low voltage saved | Unit | Unit process | Life Cycle |
|---|---|---|---|
| *Input:* | | | |
| Energy saving bulbs | units | 736 | |
| Incandescent bulbs | units | -5'710 [1]) | - |
| *Output:* | | | |
| Electricity low voltage saved | TJ | 1 | 1 |
| *Emissions to air:* | | | |
| Waste heat in air and water | TJ | 0 | 0.006 |
| $CH_4$, Methane | kg | 0 | 1.1 |
| CO, Carbon monoxide | kg | 0 | -0.063 |
| $CO_2$, Carbon dioxide | kg | 0 | 500 |
| Non-Methane Volatile Organic Carbon (NMVOC) | kg | 0 | 1.5 |
| $SO_X$, Sulphur oxides as $SO_2$ | kg | 0 | -0.77 |
| $NO_X$, Nitrogen oxides as $NO_2$ | kg | 0 | 0.26 |
| Particulate matter | kg | 0 | -0.23 |
| $^{14}C$ | kBq | 0 | 0.14 |
| $^{85}Kr$ | kBq | 0 | 3'000 |
| $^{222}Rn$ | kBq | 0 | 4'000 |
| *Environmental external costs:* | | | |
| $CO_2$ low | SFr. | 0 | -22 |
| $CO_2$ medium | SFr. | 0 | -4.0 |
| $CO_2$ high | SFr. | 0 | 82 |

Tab. 9.12: Selected flows of commercial and ecological commodities and environmental external costs for the unit process and the life cycle of an energy saving bulb replacing an incandescent one. For the complete documentation of this unit process it is referred to Frischknecht et al. (1996a, Part XV Energiesparmassnahmen, p. 15ff.).
[1]): Bulbs saved.

### 9.3.12 Summary

The private costs of conventional thermal and hydroelectric power plants are relatively close together (see Tab. 9.13). Hydroelectric power plants generate most efficiently in terms of private costs whereas nuclear power is the most expensive technology in this survey due to high investment costs. Photovoltaic electricity shows costs higher by a factor of 30 to 40 compared to fossil electricity and wind power is more costly by a factor of about 8. The environmental external costs vary between 0.01 and 0.46SFr. per $kWh_e$ for fossil power plants and 0.004 and 0.056 for renewable energy systems. Nuclear energy causes external costs of less than 0.02SFr. per $kWh_e$, accidental and occupational effects not included. The energy saving measure considered here is the most profitable technology both in private and environmental external costs. The CHP plant also used in the next subchapter is introduced and described in Subchapter 10.2.

| $SFr./kWh_e$ | Private costs | | | Environmental external costs | | |
|---|---|---|---|---|---|---|
| | total costs 2% [1]) | total costs 5% [1]) | energy costs | $CO_2$, low | $CO_2$, medium | $CO_2$, high |
| Heavy fuel oil power plant, Italy | 0.177 | 0.181 | 0.052 | 0.191 | 0.223 | 0.364 |
| Lignite power plant, Germany | 0.158 | 0.165 | 0.016 | 0.190 | 0.240 | 0.461 |
| Hard coal power plant, Germany | 0.160 | 0.167 | 0.029 | 0.067 | 0.108 | 0.290 |
| Natural gas power plant, The Netherlands | 0.189 | 0.193 | 0.064 | 0.017 | 0.042 | 0.150 |
| Nuclear power plant, France | 0.185 | 0.201 | 0.015 | 0.017 | 0.018 | 0.019 |
| Run of river power plant, Switzerland | 0.137 | 0.146 | - | 0.0004 | 0.0006 | 0.0011 |
| Hard coal pressurized fluidized bed combustion p.p. | 0.153 | 0.159 | 0.021 | 0.053 | 0.084 | 0.221 |
| Natural gas gas combined cycle power plant | 0.169 | 0.172 | 0.044 | 0.009 | 0.025 | 0.094 |
| Roof-integrated photovoltaic power plant, Switzerland | 1.042 | 1.375 | - | 0.019 | 0.024 | 0.043 |
| Wall-integrated photovoltaic power plant, Switzerland | 1.465 | 1.934 | - | 0.026 | 0.032 | 0.058 |
| Wind power plant, Grenchenberg, Switzerland | 0.409 | 0.471 | - | 0.0042 | 0.0052 | 0.0099 |
| Energy saving bulb replacing an incandescent bulb | 0.020 | 0.022 | - | -0.00008 | -0.00001 | 0.00030 |

Tab. 9.13: Private and environmental external costs per kWh electricity for power plants and an energy saving measure. Private costs include investment costs, fixed and variable operation costs, energy costs, and partly transmission and distribution costs. See Appendix 3 for further details concerning private costs.
[1]): Interest rate.

## 9.4 The Choice of the Marginal Electricity Generating Technology

### 9.4.1 Introduction

In Chapter 5 it has been argued why marginal technologies shall be chosen for the analysis of changes and how the marginal technology may be determined. In this subchapter, the marginal technology for base-load electricity generation within the UCPTE grid is determined based on minimum and maximum social costs. The following consideration are based on two important assumptions[30]. First, it is assumed that existing hydroelectric power plants are used as much as possible independent of the course of electricity demand. Furthermore, the erection of new hydroelectric power plants is limited due to natural capacity constraints. This means that hydroelectric power is not a marginal technology. Second, the consideration is simplified in that no discrimination of technologies in relation to availability, determinability, and flexibility in production is made.

Investment in (marginal) electricity generating technologies due to an increased overall demand in electricity need to be separated into a part needed for substitution and a part that covers additional demand. When new power plants are substituted for old ones, the amount of yearly electricity production may change or be constant depending on the forecast of electricity demand. When the production volume increases due to a replacement, this new power plant may be considered as a marginal one. On the other side, when the production volume decreases, the old power plant decom-

[30] In Section 9.4.6, these assumptions will be discussed in the light of the UNIPEDE forecast about future investments in the European electricity supply industry.

missioned may be interpreted as a marginal one. Finally, when the production volume remains constant, the replacement has no effect on the mix of marginal power generation technologies.

### 9.4.2 The Most and Least Expensive Technology

The marginal technology is the one that enters the market next (in the case of an increase in demand) or leaves the market next (in the case of a decrease in demand). Besides of economic and environmental aspects, other constraints like supporting jobs may also be relevant in a particular case. However, the disutility function developed in Subchapter 4.2 only comprises private and environmental external costs, the latter with a variable weight in relation to the private costs. We will start our considerations with the technology leaving the market next. Fig. 9.1 to 9.3 show social costs of power plants in relation to the environmental exchange rate for the three $CO_2$-damage scenario low, medium and high, defined in Section 8.2.4.

Based on private full costs only (see Tab. 9.13), nuclear energy is currently the most expensive technology disregarding new renewable technologies like photovoltaics or wind power[31]. The main share of total costs are capital costs which, for existing plants, already occurred and cannot be reduced. In terms of variable costs only, nuclear power would be one of the cheapest options. If we start to include environmental external costs, the average Italian heavy fuel oil power plant (partially still without secondary flue gas treatment measures) becomes the most expensive technology (see Fig. 9.1). The break-even point of heavy fuel oil and nuclear power is at low environmental exchange rate, i.e., at 0.11, 0.10, and 0.06 for the low, medium and high $CO_2$-scenario, respectively.

The break-even point of the average German hard coal plant (fully equipped with desulphurisation and DeNOx technology) compared to nuclear power is reached at an environmental exchange rate of 0.68, 0.38, and 0.13 for the low, medium and high $CO_2$-scenario, respectively. Comparing the PFBC power plant with nuclear power, the break-even points are at 1.19, 0.45, and 0.21, respectively. Compared to the average natural gas power plant, hard coal power has an advantage at environmental exchange rates below 0.52, 0.39 and 0.19 for the low, medium and high $CO_2$-scenario, respectively. The average Italian heavy fuel oil power plant shows a better environmental perfomance compared to the average German lignite power plant. Lower private costs are the reason for a better enviro-economic competitiveness of the lignite power plant below an environmental exchange rate of 0.92 in the high $CO_2$-scenario. The natural gas-fired gas combined cycle power plant shows the lowest environmental external costs in the low $CO_2$-scenario[32]. This may be recognised by the lowest gradient of the respective straight line in Fig. 9.1. In the medium and high $CO_2$-scenario, Fig. 9.2 and 9.3, nuclear power shows the lowest environmental external costs.

In general, power plants fueled with coal or heavy fuel oil show higher social costs compared to nuclear power. Therefore the ranking based on private costs alone changes when environmental external costs are included. Natural gas fueled power plants, i.e., the CHP and GCC power plant, reach the social costs of nuclear power at environmental exchange rates of 2.2 and 4.3, respectively, in the medium $CO_2$-scenario, and 0.35 and 0.39, respectively, in the high $CO_2$-scenario.

Based on these results, the average lignite and heavy fuel oil power plant may be considered as the marginal technologies in a scenario where the overall electricity demand is decreasing[33]. However, it must be kept in mind that the power plants considered here are not the ones in Europe with the highest environmental external costs. The average Spanish hard coal power plant, for instance, shows similar external costs like the average German lignite power plant and the national average lignite power plant with the badest environmental performance shows external costs higher by a factor of two compared to the German one. In addition to that, the private costs of electricity generation vary from one country to another.

[31] Full costs are used because investments are assumed not to be written off yet.
[32] Disregarding hydro power, wind power, and the energy saving measure.
[33] The UNIPEDE forecast, however, prognosticates an increase in electricity generation of 31% in the European Union until 2010, see Section 9.4.6 below.

Fig. 9.2: Relation between the environmental exchange rate and the social costs of average existing power plant technologies; the costs are based on an interest rate of 5% and a medium damage costs scenario for global warming.
CHP plant: 62% of the flows of commercial and ecological commodities is allocated to electricity.

Fig. 9.3: Relation between the environmental exchange rate and the social costs of average existing power plant technologies; the costs are based on an interest rate of 5% and a high damage costs scenario for global warming. CHP plant: 62% of the flows of commercial and ecological commodities is allocated to electricity.

The opposite situation, an overall increase in electricity demand, shows similar effects of changes in the ranking. Among the large-size technologies, the PFBC hard coal power plant shows the lowest private costs. Including environmental external costs, the gas-fired gas combined cycle power plant becomes the cheapest technology option above an environmental exchange rate of about 2.55, 1.03, and 0.29 for the low, medium and high $CO_2$-damage scenario. Below, the standard gas-fueled, spark ignition engine CHP plant, where 62% of the flows of commercial and ecological commodities are allocated to the electricity produced (see Subchapters 10.1 to 10.4 for a description of the system), is the cheapest option. If the social costs for heat produced with the CHP system prove also to be below the social costs of heat produced by competing heating systems (here light fuel oil, natural gas or wood chips boiler), CHP systems may be interpreted as the marginal technology for situations where the overall electricity demand increases. Fig. 9.4 and 9.5 show the social costs of heat from a CHP plant and competing heating systems for the low and high $CO_2$-scenario, and depending on the environmental exchange rate. The CHP plant proves its enviro-economic competitiveness for an environmental exchange rate below 1.8 in the high $CO_2$-scenario[34]. Whether this conclusion is supported by the UNIPEDE forecast is discussed in Section 9.4.6.

[34] About allocation approaches and the competitiveness of the CHP plant in general, it is referred to Chapter 10.

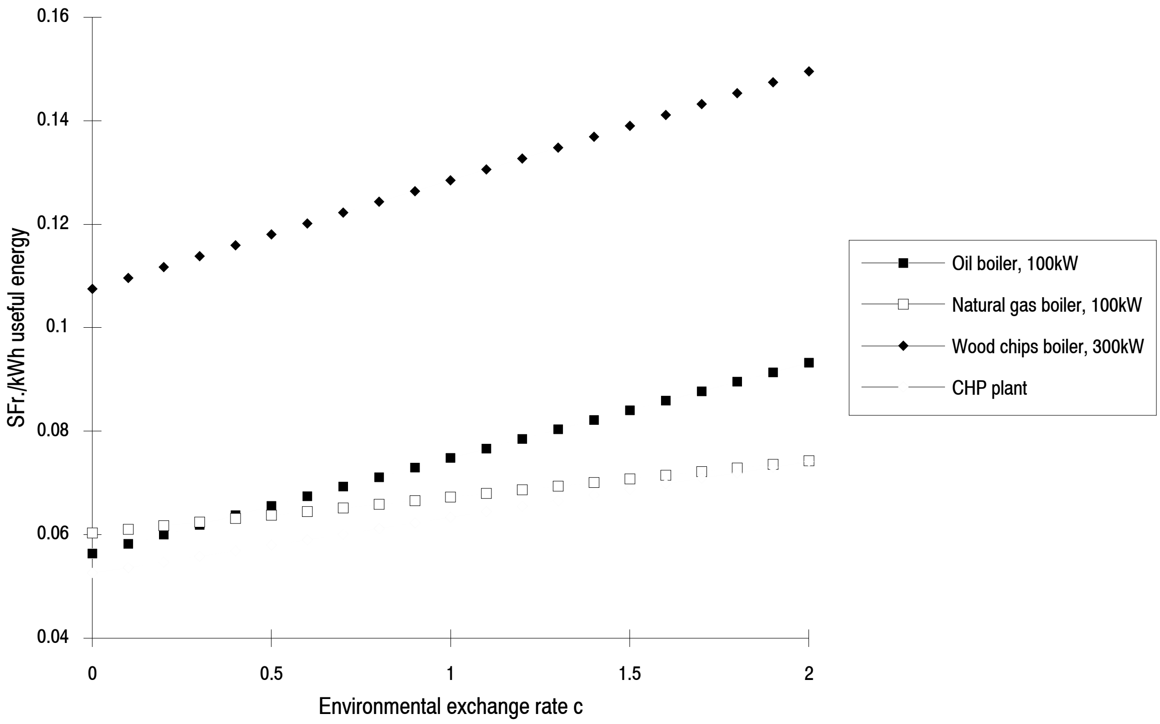


Fig. 9.4: Relation between the environmental exchange rate and the social costs of heat produced in new heating systems and in a CHP plant; 38% and 100% of the flows of commercial and ecological commodities of the CHP plant and the peak load boilers, respectively, are allocated to the heat produced; the costs are based on an interest rate of 5% and a low damage costs scenario for global warming.
CHP plant: 62% of the flows of commercial and ecological commodities is allocated to electricity.

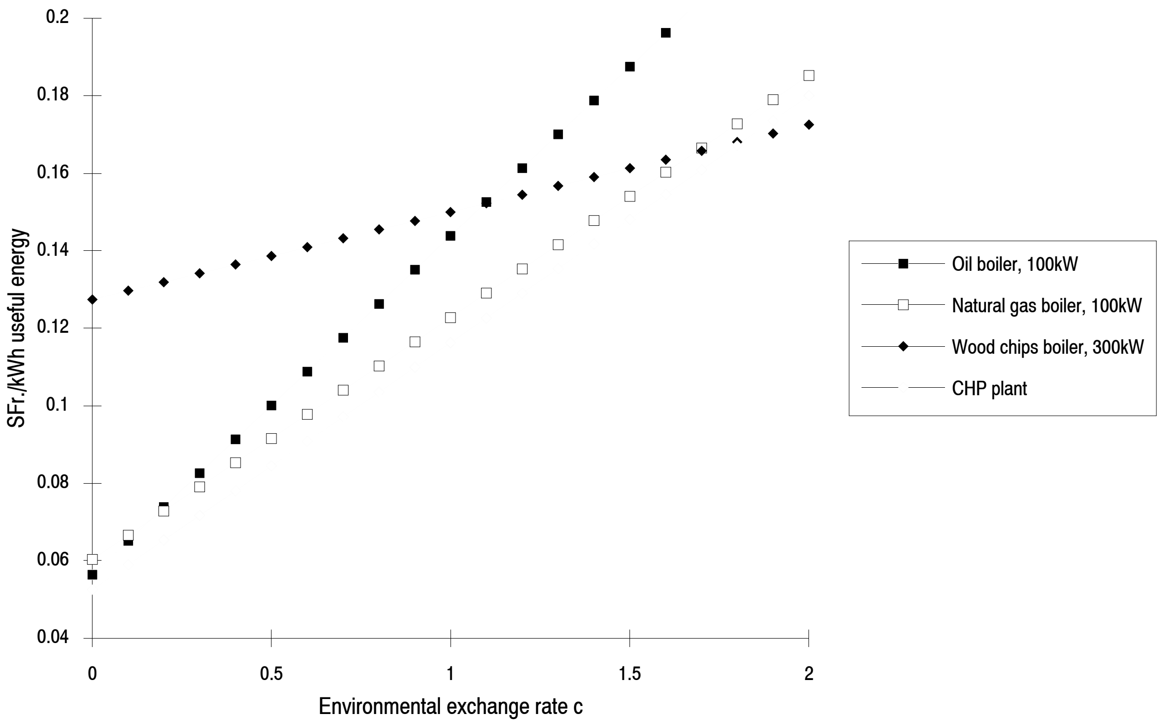


Fig. 9.5: Relation between the environmental exchange rate and the social costs of heat produced in new heating systems and in a CHP plant; 38% and 100% of the flows of commercial and ecological commodities of the CHP plant and the peak load boilers, respectively, are allocated to the heat produced; the costs are based on an interest rate of 5% and a high damage costs scenario for global warming.
CHP plant: 62% of the flows of commercial and ecological commodities is allocated to electricity.

When environmental external effects as introduced in Chapter 8 are included in the decision-making process about the shut down of power plants, a switch occurs from nuclear power to technologies based on heavy fuel oil or lignite.

And including environmental external effects in the decision-making process of commissioning new production capacities, the cheapest solutions are CHP plant (environmental exchange rate 0<c<0.29), GCC power plant (0.29<c<0.39) and nuclear power (c>0.39) in the high $CO_2$-scenario. In the low and medium $CO_2$-scenario, gas-fired power plants are the cheapest options for environmental exchange rates below 4.3 and 2.2, respectively. The low environmental external costs of new renewable technologies (i.e., photovoltaics and wind power) do not compensate for the much lower private costs of electricity from traditional thermal power plants.

### 9.4.3 Cumulative Emissions Computed with Marginal Technologies

The cumulative flows of ecological commodities and the environmental external costs of marginal technologies have up to now be determined based on a system model where all electricity needed in the process network is generated by an average electricity mix (either UCPTE or Swiss national mix). In this section, it is shown how the environmental performance of the potential marginal electricity generating technologies changes if the electricity required in the process network of a marginal electricity generating technology is provided by itself. For that purpose, the corresponding marginal power plant is entirely substituted for the power plant mixes in the process modules "electricity mix UCPTE" and "electricity mix Switzerland". Tab. 9.14 shows selected flows of ecological commodities and environmental external costs related to the production of electricity with the marginal technologies.

| Per TJ electricity | Unit | fuel oil, I | lignite, D | hard coal, D | natural gas, NL | nuclear, F | CHP plant 2) |
|---|---|---|---|---|---|---|---|
| *Output:* | | | | | | | |
| Electricity | TJ | 1 | 1 | 1 | 1 | 1 | 1 |
| Waste heat in air and water 1) | TJ | 3.34 | 3.94 | 3.14 | 2.89 | 3.36 | 2.85 |
| $CH_4$, Methane | kg | 306 | 22.8 | 1280 | 107 | 3.99 | 827 |
| CO, Carbon monoxide | kg | 76 | 45 | 49 | 68 | 5.7 | 157 |
| $CO_2$, Carbon dioxide | kg | 230'000 | 372'000 | 283'000 | 179'000 | 1560 | 145'500 |
| NMVOC | kg | 597 | 10.7 | 20 | 38.1 | 3.6 | 124 |
| $SO_X$, Sulphur oxides as $SO_2$ | kg | 2380 | 2720 | 390 | 6.29 | 16.1 | 65.2 |
| $NO_X$, Nitrogen oxides as $NO_2$ | kg | 508 | 508 | 250 | 244 | 6.25 | 109 |
| Particulate matter | kg | 96 | 209 | 212 | 6.2 | 5.0 | 9.5 |
| $^{14}C$ | kBq | 0.12 | 0.083 | 0.15 | 0.16 | 4'190 | 0.052 |
| $^{85}Kr$ | kBq | 7'130 | 5'080 | 9'340 | 10'000 | 3.1á$10^8$ | 3'180 |
| $^{222}Rn$ | kBq | 10'900 | 8'820 | 16'100 | 14'800 | 4.4á$10^8$ | 4'960 |
| *Environmental external costs:* | | | | | | | |
| $CO_2$ low | SFr. | 53'900 | 53'800 | 18'400 | 4'700 | 4'800 | 3'800 |
| $CO_2$ medium | SFr. | 62'900 | 67'900 | 30'200 | 11'500 | 4'800 | 10'000 |
| $CO_2$ high | SFr. | 102'600 | 130'400 | 82'200 | 41'800 | 5'100 | 37'300 |

Tab. 9.14: Selected flows of ecological commodities and environmental external costs for the life cycle of the electricity production with different marginal technologies, under the assumption that the electricity required in the process network is generated with the respective marginal technology.
1): including 1TJ from the electricity produced in the power plant and consumed elsewhere.
2): 62% of the flows of commercial and ecological commodities is allocated to electricity.

The differences are minor, between an analysis of marginal power plants based on a system model with average European (UCPTE) and Swiss electricity production and based on a system model, where the respective marginal power plant generates the electricity supplied within the UCPTE and the Swiss electricity grid. The figures shown in Tab. 9.14 are compared with the values given in Tab. 9.3 to 9.6, and Tab. 10.13 (CHP plant, alternative 3). In general, the fossil power plants considered as marginal technologies show slightly higher cumulative emission factors when computed with themselves as electricity-generating technologies in UCPTE and Switzerland. The only exceptions are the average Dutch natural gas power plant and the gas-fired CHP plant, which show slightly lower values. The emission of radionuclides caused by fossil power plants, however, are much lower with the marginal (fossil) power plant producing the electricity required in the process network. For the nuclear marginal power plant, the situation is just reversed. The $CO_2$-emissions are reduced from a relatively low level by about 30%. This shows the relatively high share of the average UCPTE electricity-mix contributing to the cumulative $CO_2$-emission of nuclear energy.

In terms of environmental external costs, the differences are even smaller. Heavy fuel oil, lignite, and hard coal (medium and high $CO_2$-scenario) power plants show slightly higher costs if they themselves produce the electricity they need within their process network. Natural gas, nuclear and hard coal (low $CO_2$-scenario) power plants and the CHP plant show slightly lower environmental external costs.

We conclude that the effect of using the "right", marginal technology in the up- and downstream processes instead of the existing average power plant mixes is negligible for the determination of environmental external costs of the respective marginal power plant. This shows the relatively minor importance of the flows of ecological commodities caused by the electricity needed for up- and downstream processes. The accuracy of the computation with a system model using average electricity mixes (e.g., UCPTE or Swiss mix) is sufficient to discriminate the potential marginal technologies in terms of social costs. Hence, no second iteration is necessary for its determination.

### 9.4.4 Marginal Technologies Applied on Earth Coupled Electric Heat Pumps

We will now apply the various marginal technologies on the example of an earth coupled electric heat pump and see how these potential marginal power plants will influence the cumulative flows of ecological commodities and the environmental external costs. The earth coupled electric heat pump with a heating capacity of about $10kW_{th}$ works with 3kg of the refrigerant H-CFC 22 in total of which 0.7kg are emitted per TJ useful energy due to leakage (5%), incautious work (10%) and escape during dismantling of the system (10% of the remaining 85%). The yearly average coefficient of performance is 3.5, a value achieved by good systems with low forward flow temperatures (i.e., 35¡C). The total electricity demand per TJ useful energy amounts to $0.295TJ_e$ including distribution losses in the house as well as the electricity consumption of circulating pumps. In Tab. 9.15 some selected flows of commercial and ecological commodities and environmental external costs are listed for different electricity producing marginal technologies. For comparative purposes, the cumulative flows of the system using Swiss electricity mix including electricity trade are shown.

The life cycle flows of the emissions shown in Tab. 9.15 vary by a factor of 10 ($NO_X$) up to a factor of nearly 55 ($^{222}Rn$). Depending on the electricity generation technology applied, the life cycle emissions surmount the ones of other heating systems for which data are shown and used in Chapter 10. Except the refrigerant's emissions, all emissions occur during up- and downstream processes. The environmental external costs as introduced in Chapter 8, amount to between 0.006 and 0.045SFr. per $kWh_{th}$ when the electricity is generated with a CHP plant, and between 0.06 and 0.14SFr. per $kWh_{th}$ using electricity generated in the average German lignite power plant.

| Per TJ useful energy | Unit | Unit | Life cycle, electricity generated by | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | proces s | CH mix, incl. trade | nuclear , F | lignite, D | fuel oil, I | hard coal, D | natural gas, NL | CHP plant 3) |
| *Input:* | | | | | | | | | |
| Electricity, low voltage | TJ | 0295 | - | - | - | - | - | - | - |
| *Output:* | | | | | | | | | |
| Useful energy | TJ | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Waste heat in air | TJ | 1.03 | 1.55 | 1.88 | 1.92 | 1.58 | 1.61 | 1.65 | 1.91 |
| $CH_4$, Methane | kg | 0 | 33 | 12 | 20 | 100 | 370 | 41 | 250 |
| CO, Carbon monoxide | kg | 0 | 16 | 14 | 27 | 34 | 26 | 32 | 54 |
| $CO_2$, Carbon dioxide | kg | 950 1) | 15'600 2) | 4690 2) | 126'000 2) | 71'000 2) | 85'700 2) | 56'600 2) | 46'200 2) |
| NMVOC | kg | 0 | 16 | 11 | 14 | 180 | 16 | 21 | 45 |
| $SO_X$, Sulphur oxides as $SO_2$ | kg | 0 | 85 | 33 | 920 | 720 | 150 | 28 | 35 |
| $NO_X$, Nitrogen oxides as $NO_2$ | kg | 0 | 33 | 15 | 180 | 160 | 86 | 84 | 43 |
| Particulate matter | kg | 0 | 15.2 | 8.8 | 76 | 35 | 68 | 8.8 | 8.2 |
| $^{14}C$ | kBq | 0 | 970 | 1'420 | 32 | 30 | 38 | 15 | 14 |
| $^{85}Kr$ | kBq | 0 | 5.1á$10^7$ | 1.0á$10^8$ | 2.1á$10^6$ | 1.8á$10^6$ | 2.3á$10^6$ | 9.1á$10^5$ | 9.2á$10^5$ |
| $^{222}Rn$ | kBq | 0 | 7.3á$10^7$ | 1.5á$10^8$ | 2.8á$10^6$ | 2.7á$10^6$ | 3.5á$10^6$ | 1.5á$10^6$ | 1.1á$10^6$ |
| *Environmental external costs:* | | | | | | | | | |
| $CO_2$ low | SFr. | 9 | 3'100 | 2'400 | 16'600 | 16'600 | 6'500 | 2'400 | 1'800 |
| $CO_2$ medium | SFr. | 44 | 3'800 | 2'700 | 20'900 | 19'500 | 10'100 | 4'600 | 3'800 |
| $CO_2$ high | SFr. | 202 | 6'800 | 3'800 | 40'000 | 32'100 | 26'000 | 14'600 | 12'600 |

Tab. 9.15: Selected flows of commercial and ecological commodities and environmental external costs for the unit process and the life cycle of the earth coupled electric heat pump, $10kW_{th}$. For the complete documentation of this unit process it is referred to Frischknecht et al. (1996a, Part X WŠrmepumpe mit ErdwŠrmenutzung, p. 9ff.).
1): H-CFC 22 emissions, expressed in $CO_2$-equivalents.
2): only $CO_2$-emissions.
3): 62% of the flows of commercial and ecological commodities is allocated to electricity.

The private costs vary between 0.141 and 0.171 SFr. per kWh useful heat, based on interest rates of 2 and 5% and a life time of 20 years (see Tab. 10.6, and Appendix 3).

### 9.4.5 Self-Fulfilling Prophecies?

The environmental performance of useful heat generated with an earth coupled electric heat pump is very much dependent on the technology used to provide the electricity. The environmental external costs vary by one order of magnitude even within one particular $CO_2$ damage costs scenario. The question is however, how the social costs behave in relation to other competing small-sized heating energy systems. For that purpose, their social costs are computed in relation to the environmental exchange rate and are shown in Fig. 9.6 and 9.7 for the low and the high $CO_2$-scenario.

While the earth coupled electric heat pump is the cheapest solution in terms of private costs only, it becomes the most expensive technology at environmental exchange rate of 0.46 and 0.16 (low and high $CO_2$-scenario), when the electricity for the operation of the heat pump is produced in the average German lignite power plant. On the other hand, a heat pump driven with electricity generated in a CHP plant is the cheapest options for an environmental exchange rate below 0.83 for the high $CO_2$-scenario[35]. The following question arises: Which one is the "right" system model to represent the installation of additional heat pumps? Is it the one with the lignite power plant because overall electricity

[35] In the low $CO_2$-scenario, it is the cheapest option independent of the environmental exchange rate.

demand is expected to decrease in the future or is it the CHP plant because a rise in electricity demand is anticipated? No clear answer may be given to this question on the basis of this electricity application alone.

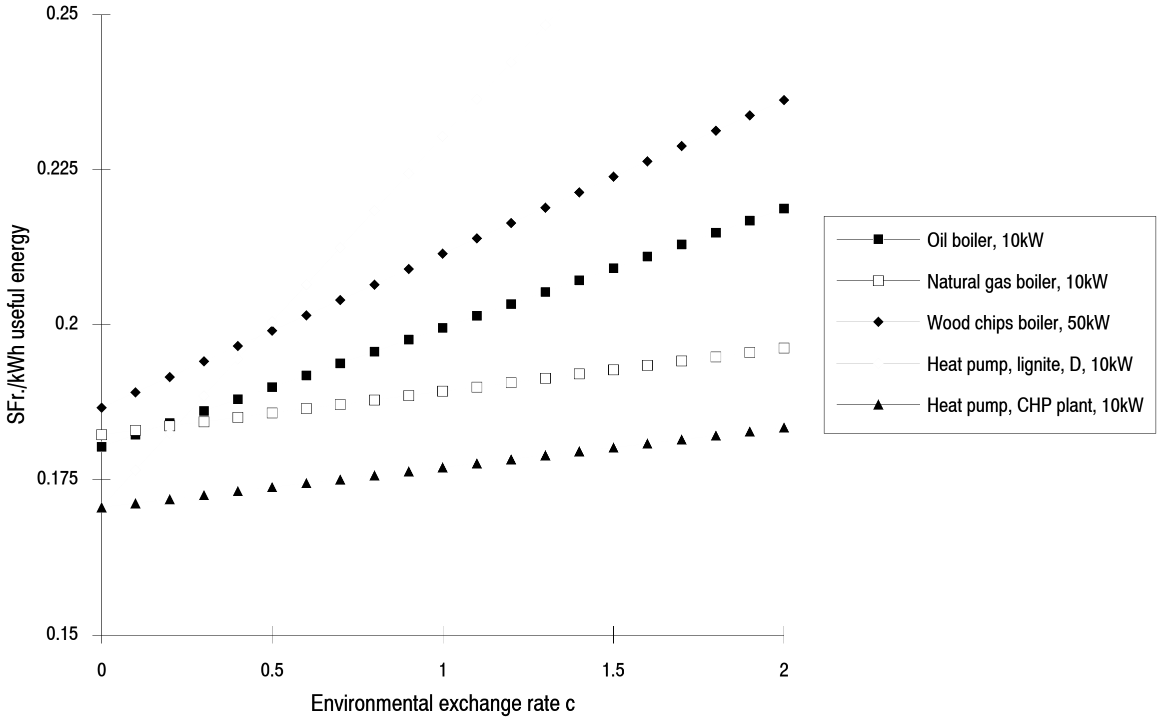


Fig. 9.6: Relation between the environmental exchange rate and the social costs of heat produced in small-sized new heating systems; 62% of the flows of commercial and ecological commodities of the CHP plant are allocated to the electricity produced to be used by the heat pump; the costs are based on an interest rate of 5% and a low damage costs scenario for global warming.
CHP plant: 62% of the flows of commercial and ecological commodities is allocated to electricity.

If it is assumed that the electricity demand will increase in the future, cheap and environmentally benign technologies (i.e., new natural gas-fired power plants) will be used for electricity generation and therefore the heat pump shows favorable social costs. If decision-makers act according to the least social cost principle, as it is assumed in this thesis, the electricity demand would in fact increase and thereby comply with the assumption made. If, on the other hand, it is assumed that the electricity demand will decrease, other marginal technologies, i.e., economically and ecologically "expensive" ones (here an average German lignite power plant), will be used and the heat pump shows relatively high social costs. In this case the heat pump option would not be chosen, and, moreover, other actors would also tend to optimise (i.e., reduce) their electricity demand in order to improve the enviro-economic performance of their goods. The electricity demand would in this case tend to decrease, and by that also comply with the assumption made.

When environmental external costs are included in the decision about a new heating system to be installed, we are confronted with two stable and consistent models because of positive feedbacks. The problem is, however, that the two models tell us two entirely different stories. Of course, these two solutions are influenced by the assumptions made in Section 5.3.3. It is hard to conclusively establish a link between an increase or decrease in demand of, e.g., electricity caused by a change in demand patterns (change from one brand to another one to satisfy a certain demand) and the development of the electricity sector as a whole. That is why, the question about the adequate marginal technology may be left to political discussions about energy scenario which most probably will be influenced by the respective position of the opponents involved (affecting versus affected parties, see, e.g., Linneweber (1997) and Section 3.4.1).

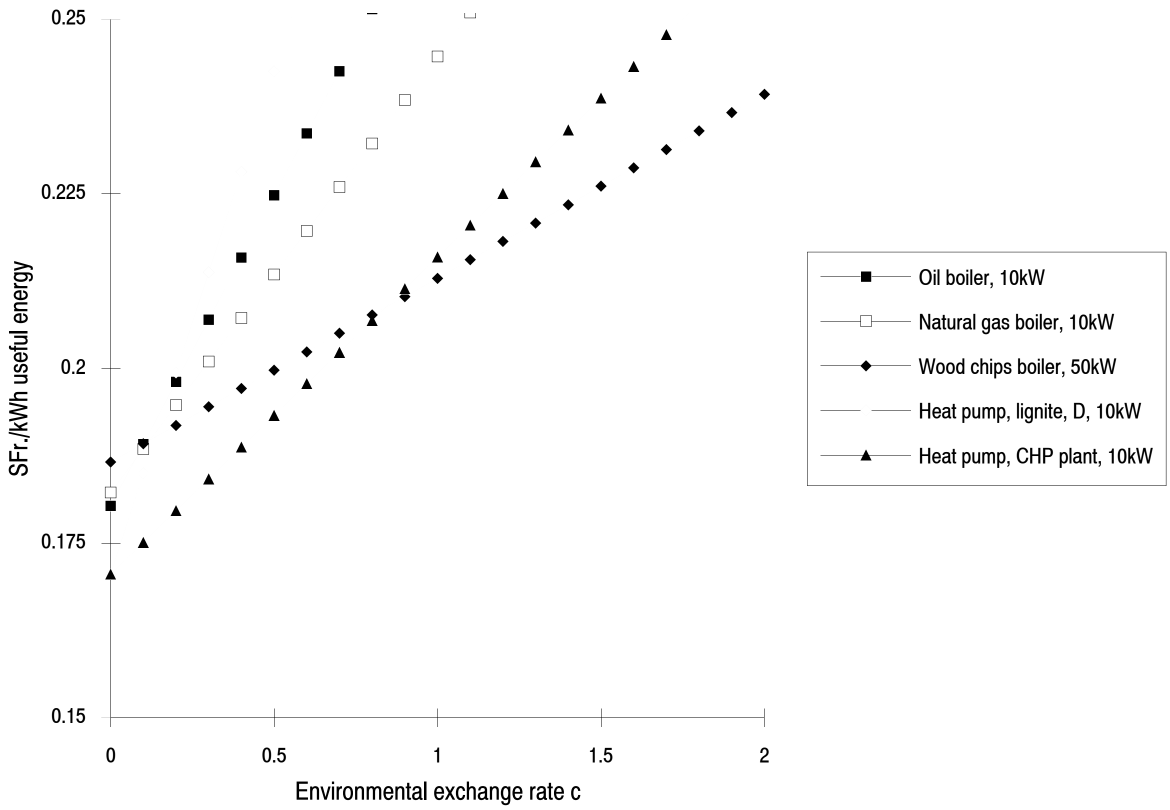


Fig. 9.7: Relation between the environmental currency exchange rate and the social costs of heat produced in small-sized new heating systems; 62% of the flows of commercial and ecological commodities of the CHP plant are allocated to the electricity produced for the heat pump; the costs are based on an interest rate of 5% and a high damage costs scenario for global warming.
CHP plant: 62% of the flows of commercial and ecological commodities is allocated to electricity.

### 9.4.6 The UNIPEDE Forecast, a "Moose Test" for the Disutility Function

In 1996, UNIPEDE published the forth progress report about investments and planning in the European electricity supply industry (UNIPEDE 1996). In this report, an increase in electricity consumption of about 720TWh from 2'310TWh in 1994 to 3'030TWh in 2010 is prognosticated for the 15 EU countries plus Norway and Switzerland[36]. In the same time, population increases from 382 million to 394.5 million. Hence, nearly 90% of the increase in electricity demand is caused by an increase of the (direct and indirect) per capita consumption[37]. Furthermore, a discrimination of the electricity generating technologies used to cover this additional demand is shown. Coal, lignite and oil power show a substantial reduction in production volume between 1994 and 2005, a tendency that changes for coal and lignite for the period between 1994 and 2010. Due to high anticipated costs for oil, oil power reduces its production even on the longer run. Natural gas, nuclear, miscellaneous, derived gas, and hydro and other renewable power are the technologies used for additional production in this descending order (see Tab. 9.16). The volume of net exchanges contributes only little to the total[38]. The major part (more than 90%) of the increase in electricity production until 2010 is covered by thermal power plants. Thereby, fossil power and in particular natural gas and derived gas play the dominant role. The leading position of natural gas is reasoned as follows:

> Already the effect of environmental pressures is being seen with emission targets being further tightened each year leading to premature closures of old coal and oil-fired plants. This, coupled with relaxation of restrictions on the use of natural gas, has led to the large-scale development of gas-fired plants. The relatively lower capital

[36] Underlying an economic growth rate of 2.3% per year.
[37] Neglecting an increase in the specific electricity consumption due to an increase in production of goods for export.
[38] This, however, does not imply that electricity trade is of low importance.

costs, higher thermal efficiency and shorter construction lead times of this type of plant would suggest that gas-fired plant will play a significantly greater role in the near future.[39]

The tendency of the reasoning about the marginal technology for the production of additional electricity given in this subchapter is confirmed, except for CHP plants, which play a minor role in respect to the new capacity installed until 2010 (3.4% of the total, UNIPEDE (1996, p. 25)). According to this report, environmental aspects seem to be included qualitatively. Natural gas, derived gas, and miscellaneous fuels (not specified by the member countries involved in the UNIPEDE survey) may be interpreted as the main marginal energy carriers for electricity generating technologies in the future. This holds for the whole European Union (including Norway and Switzerland) as well as for the 11 countries that are connected to the UCPTE network.

| | 1994 | | 1994-2005 | 1994-2010 | | Marginal electricity mix | |
|---|---|---|---|---|---|---|---|
| | [TWh] | [%] | [TWh] | [TWh] | [%] | [TWh] | [%] |
| Hydro and other renewable | 476.9 | 20.5 | 21.3 | 47.5 | 6.6 | 40.2 | 5.7 |
| pumping storage | - | - | - | - | - | 7.3 | 1.0 |
| Nuclear | 770.7 | 33.1 | 86.5 | 102.2 | 14.1 | 102.2 | 14.4 |
| *Thermal* | *1'083.8* | *46.5* | *180.2* | *560.3* | *77.4* | *560.3* | *78.9* |
| Coal | 496 | 21.3 | -34.1 | 92.4 | 12.8 | 102.7 | 14.5 |
| Lignite | 182.5 | 7.8 | -0.1 | 16.8 | 2.3 | 18.7 | 2.6 |
| Oil products | 162.6 | 7.0 | -18.5 | -15.6 | -2.2 | - | - |
| Natural gas | 191.1 | 8.2 | 193.9 | 326.9 | 45.2 | 363.4 | 51.2 |
| Derived gas | 16.3 | 0.7 | 7.6 | 67.8 | 9.4 | 75.4 | 10.6 |
| Miscellaneous | 35.3 | 1.5 | 31.4 | 71.9 | 9.9 | - | - |
| Net exchange | 2.6 | - | -1.8 | 8.8 | 1.2 | - | - |
| Pumping [1]) | -22.6 | - | 2.4 | 5.1 | -0.7 | - | - |
| Total | 2'311.4 | 100.0 | 283.8 | 713.7 | 100 | 710.0 | 100.0 |

Tab. 9.16: Electricity production per technology in 1994 in the 15 EU countries and Norway and Switzerland, change in electricity production between 1994 and 2005 and between 1994 and 2010, UNIPEDE (1996); and marginal electricity mix derived from the changes in production between 1994 and 2010.
[1]): To be subtracted from total production.

Based on the figures in Tab. 9.16, a marginal electricity mix is derived[40]. The electricity generation classified as "other renewable" allocated to hydro power has a share of about 50% in terms of additional capacity installed (UNIPEDE 1996, p. 25). Assuming a pumping efficiency of 70% (Frischknecht et al. Part VIII Wasserkraft, p. 11), the share of pumping storage on hydropower is 15% or 7.3TWh. Furthermore, it is assumed that the decrease in oil power generation is compensated equally by fossil power plants. The production of miscellaneous power plants is assumed to show the same shares as the remaining fossil power plants and net trade the same shares as the entire marginal electricity production mix. Compared to the average electricity mix of all the European countries, the share of nuclear power and hydro power decreases from one third to less than 15%, and from 20% to about 6%, respectively. This is compensated by fossil power plants which enlarge their total share from nearly half to more than three quarters of the whole marginal production. Within fossil power plants, plants fired with natural and derived gas contribute more than 60% to the total additional electricity generation[41].

The marginal power plant may therefore be characterised as a power plant predominantly fired with fossil fuels, using a minor share of uranium and a nearly negligible contribution from hydro. Due to the tightened emission targets and higher efficiencies, the technologies to be commissioned will show a better environmental performance compared to the

[39] UNIPEDE (1996, p. 14)
[40] A characterisation of the marginal power plant mix of a country's additional electricity supply can not be made based on UNIPEDE (1996), because relevant economic information about investments in foreign countries is missing.
[41] Nearly identical shares result for the 11 countries connected to the UCPTE grid (former Yugoslavia, Croatia, Bosnia-Herzegovina and Slovenia are not included in the UNIPEDE survey).

environmental performance of the average national power plants reported in Frischknecht et al. (1996a). Therefore we may proceed from the assumption that the marginal electricity mix shown in Tab. 9.16 will cause substantially less environmental external effects compared to the widely used average UCPTE electricity mix. First estimates indicate reduction factors of about 4, 3, and 2 in terms of environmental external costs compared to the UCPTE electricity mix 1990-1994 for the low, medium and high $CO_2$-damage costs scenario[42].

The assumptions made in the UNIPEDE forecast differ from the ones made in the beginning of this subchapter. First, hydro-electric power proves to be a marginal technology and it may still enlarge its capacity, however, at rates much below the one of fossil power plants. Second, the consideration of other aspects such as the market structure (energy developments driven by market forces or energy and other policies, UNIPEDE (1996, p. 14)), leads to a diversified marginal power plant portfolio. However, the dominant role of natural gas is immense and in that, the messages from the UNIPEDE forecast and obtained with the disutility function coincide fairly well.

## 9.5 Conclusions

In the last four subchapters, several questions related to the electricity mix have been treated. First, it has been shown that the use of a system model based on mere physical information (measured physical flows) results in relatively moderate deviations from the results received with a model based on economic (contractual) flows. This however may not be taken as a guarantee that physical flows may in any case be used as the substitute flows to establish the system model in cases where economic information is not available. Second, the marginal electricity generating technology (the marginal power plant) has been determined based on the concept of enviro-economic competitiveness. Dependent on whether the overall electricity consumption of the relevant region is assumed to in- or decrease, gas-fired combined heat and average Italian heavy fuel oil power plants have proven to be the cheapest and most expensive technologies, respectively[43].

Furthermore it has been shown, that the assumptions to be made are consistent with the results received. If it is assumed that the electricity demand would decrease and the most expensive power plant is used in the system model, electricity becomes an important issue in terms of cumulative environmental impacts, and measures will be taken to reduce the amount of electricity needed in the respective life cycle. On the other side, if it is assumed that electricity consumption would further increase, the comprehensively cheapest technology will be applied and the effect of electricity consumption within the life cycle of a product becomes minor. In this case, the incentive to reduce electricity consumption is less pronounced or even not given compared to other measures that help to reduce the environmental external costs of the good or service under study.

However, these conclusions have to be seen in relation to the assumptions made:

- First, marginal technology is determined based on social costs. In today's economy, this is hardly the case.
- Second, only one single technology (i.e., the cheapest and the most expensive one, respectively) is assumed to be the marginal one. But reality is more complex. Beside the two parameters private and environmental external costs, other aspects like job supporting measures, diversification for the sake of an increased safety of supply, *et cetera*, may lead to a portfolio of various, cheap and more expensive electricity generating technologies.

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[42] Assuming that PFBC technology is used for new coal power plants, and GCC technology for new natural and derived gas power plants.
[43] Within the restricted set of possible alternatives given in this work.

- Third, the assumption that predictions about the course of electricity demand on a macro-economic level influence decisions on a micro-economic level (positive feedbacks) is both crucial and weakly based. Such a relation cannot be verified in reality and hence the results may only be interpreted as the outcome of a game of thoughts.

However, the forecast of future electricity generating options in Western Europe, confirms one part of the outcome received in this chapter, that natural gas-fired power plants are assumed to play a predominant role to cover an increasing electricity demand in Europe.

The following conclusions are drawn from the national electricity mix case study:

- The difference between the environmental external costs of the Swiss national electricity mix modelled according to economic and physical information, respectively, is between 1 and 9% of total environmental external costs.
- On the Long Run, the marginal technology may be different depending on whether only private costs or social costs are considered, and whether an increase or decrease in the overall electricity demand (of regions, nations or economic areas) is anticipated.
- Similar to standard economics, self-fulfilling prophecies may be encountered. The prediction on the development of electricity consumption determines the marginal technology(ies) and by that the environmental performance and the enviro-economic competitiveness of predominantly electricity consuming goods and services.
- Marginal technologies used for the Long Run and the Very Long Run LCA need to be determined based on political and social information. Consistent predictions and scenario about the development of consumption of goods and services produced with the respective Long Run marginal technologies are needed.
- The UNIPEDE forecast of Western European countries predicts that gas-fired power plants will generate more than half of the predicted additional electricity demand. Nuclear and hydro power together contribute about 20%. Due to tightened air emission standards, the environmental performance of the marginal electricity mix is likely to be improved substantially compared to today's average power plant portfolio. The model applied in this chapter shows a similar result.

# PART III:

# CASE STUDIES

# 10.Allocation in Combined Heat and Power Production

## 10.1Introduction

In Chapter 7 it is stated that if environmental information is used in addition to mere economic information in a decision-making process, the motivation for allocation should also be based on economic *and* environmental information. That is why, a combination of information about private and environmental external costs of competing systems will be used in the allocation procedure of the following case study. In order to show the consequences of such a procedure, a standard combined heat and power (CHP) plant will be analysed and several allocation procedures will be applied on it.

After a short description of the CHP plant and competing heating systems (Subchapters 10.2 and 10.3), commonly used allocation approaches (Subchapter 10.4) as well as the context-specific allocation (Subchapter 10.5) will be applied on the CHP plant case. After a discussion of the main results and the corresponding limitations, conclusions are drawn in respect of the new allocation approaches introduced.

## 10.2Description of the Combined Heat and Power (CHP) Plant

### 10.2.1The Standardized 360 kWth Spark Ignition CHP Plant

To show the characteristics of the allocation approaches described in Part II, a particular plant of a thirty year old district near Basel/ Switzerland is used. The district comprises 220 units, 54 single family houses and 9 multiple family housings, an old people's home and a kindergarden. The CHP plants covers the base load heating energy demand whereas a 600 kW oil boiler is used for peak loads. Additionally, a 1'200 kW oil boiler is installed for the case of CHP revision. Warm water is generated with decentralised electric boilers and two gas condensation units. The CHP plant runs mainly in winter time, with full load in day time and with an average of 60% partial load during night time. During 5 months in summer time (mid of may until mid of october) it is out of use.

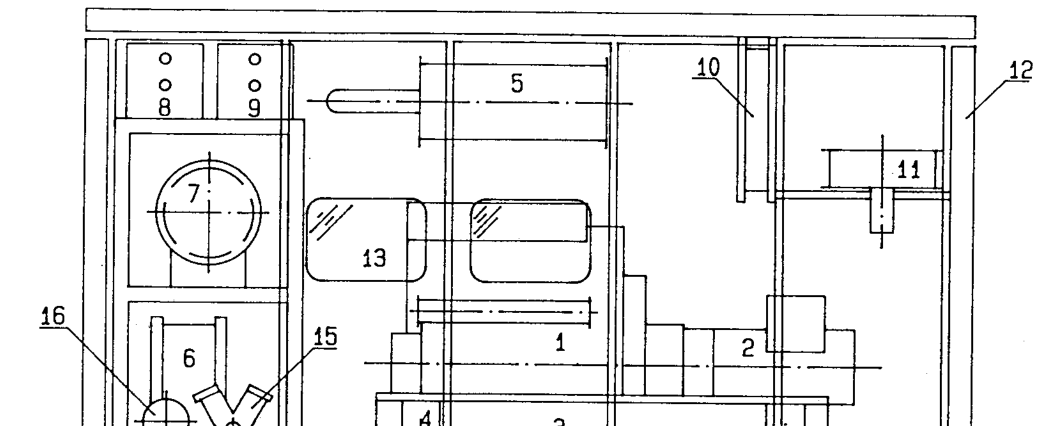


Fig. 10.1: Scheme of a CHP plant, DIMAG (1993).
1: gas-fueled spark-ignition engine; 2: synchrogenerator; 3: steel base frame; 4: vibration damper; 5: catalyst; 6: cooling water heat exchanger; 7: Flue gas cooler; 8: oil container; 9: cooling water container; 10: cooler unit for circulated air; 11: ventilator for air circulation; 12: sound-absorbing case; 13: inspection window; 15: compressor; 16: condenser.

The CHP plant is equipped with a gas-fueled spark-ignition engine (MWM G234 V12). The motor drives a synchrogenerator and both are mounted on a vibration damped steel base frame (see Fig. 10.1). A heat exchanger transfers the heat from the primary circulation (motor cooling water) to the secondary circulation (district heating water). Furthermore the heat of the flue gases is recovered and transferred to the secondary heating circulation. A heat pump is installed to utilise the low temperature waste heat emitted by the motor and captured in the sound-absorbing case. The flue gas is purified by passing a 3-way catalyst which is controlled by a lambda-probe. Although the plant analysed is equipped with a catalyst with a ceramic matrix, a metallic matrix is assumed here as used in most of the CHP plants in Switzerland.

The motor may be operated at partial load. There will be of course a loss of both electric and thermal efficiency. The share between electricity and heat changes from 0.6 at full load to 0.45 at 50% partial load, because the efficiencies do not alter with the same rate (see Fig. 10.2). The effect on the allocation factors is however of minor importance.

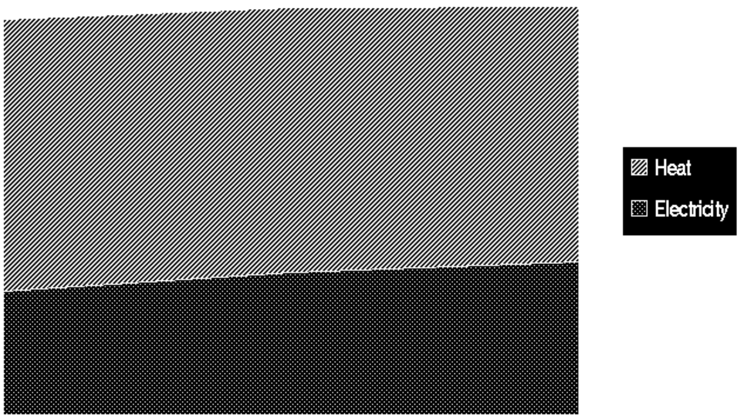


Fig. 10.2: Electric and thermal efficiency of a gas-fueled spark ignition engine (heat pump not included) dependent on the load factor, according to Zacharias (1992).

The forward flow temperature of the secondary heating circulation reaches 85°C, whereas the return flow temperature is 65°C. Two 10 $m^3$ hot water tanks are used as buffers in the hot water circulation system which helps to extend the periods of operation for the CHP plant and to minimise inefficient start-up phases. With 56 liters per kW heating power, the storage units are between 30 and 50% larger than hot water tanks used for similar installations.

Data concerning the plant are extensively documented in Frischknecht et al. (1996a, Part XIV Wärme-Kraft-Kopplung), based on a students thesis (Bollens 1995). Data about the operation and emission performance of CHP plants were mainly provided by Rapp (1994) and Graf (1988, 1996).

### 10.2.2 The Environmental Performance of the CHP Plant

For the production of 2.4TJ electricity delivered to the local grid and 6.32TJ of district heat, 10TJ of natural gas are required yearly. Furthermore it is assumed that the infrastructure may be used during 100'000 operating hours (except catalysts, which have a operation lifetime of 15'000h only). The emissions of the spark ignition engine, the heart of the CHP plant, as well as its requirement of low pressure natural gas are listed in Tab. 10.1. Its annual average energy efficiency is 76%.

However, due to the heat pump, the overall annual energy efficiency of the CHP module reaches 87%. On a yearly average, the peak load oil boilers contribute 40% of the heat delivered to the district heating grid. From the remaining 60%, more than 75% is generated directly by the engine whereas 22% are produced by the heat pump[1] which is driven with electricity produced by the CHP plant. The oil boilers are assumed to have an emission performance similar to the 100kW light fuel oil boiler described in section 10.3.2. but the energy efficiency is lower by 7%-points (non-condensing technology).

| per TJ Output (district heat and electricity) | unit | Unit process | Life Cycle |
|---|---|---|---|
| *Input:* | | | |
| Natural gas, low pressure used in Switzerland | TJ | 1.32 | - |
| *Output:* | | | |
| Heat from the engine | TJ | 0.64 | 0.64 |
| Electricity from the generator | TJ | 0.36 [1]) | 0.36 [1]) |
| Waste heat in air | TJ | 1.45 | 1.63 |
| $CH_4$, Methane | kg | 3.3 | 477 |
| CO, Carbon monoxide | kg | 65 | 89 |
| $CO_2$, Carbon dioxide | kg | 72'400 | 84'300 |
| Non-Methane Volatile Organic Carbon (NMVOC) | kg | 3.3 | 40 |
| $SO_X$, Sulphur oxides as $SO_2$ | kg | 0.72 | 39 |
| $NO_X$, Nitrogen oxides as $NO_2$ | kg | 25.5 | 63 |
| Particulate matter | kg | 0 | 5.6 |
| $^{14}C$ | kBq | 0 | 6.1 |
| $^{85}Kr$ | kBq | 0 | $3.3 \cdot 10^5$ |
| $^{222}Rn$ | kBq | 0 | $4.8 \cdot 10^5$ |
| *Environmental external costs:* | | | |
| $CO_2$ low | SFr. | 700 | 2'200 |
| $CO_2$ medium | SFr. | 3'500 | 5'800 |
| $CO_2$ high | SFr. | 15'800 | 21'600 |

Tab. 10.1: Selected flows of commercial and ecological commodities and environmental external costs of a gas-fueled spark ignition engine per TJ low pressure natural gas.
[1]): thereof 0.04TJ used by the heat pump

While the main share of hydrocarbon (methane and NMVOC), of $SO_X$, $NO_X$, particulate matter emissions, and radionuclides stems from upstream processes, the operation of the spark ignition engine determines the cumulative emission score of $CO_2$ and CO. Due to the lower efficiency of the engine compared to a natural gas boiler, the specific cumulative emissions per kWh produced are higher[2]. The environmental external costs amount to 0.0025, 0.012, and 0.057SFr. per kWh energy generated (heat and electricity). The contribution of the operation phase varies between 32% and 73%.

Fig. 10.3 shows the system model for the CHP plant and gives an survey of components needed in the CHP system and of their allocation to one or both of the two joint products heat and electricity. Some of the equipment is only needed for the generation of heat or of electricity, respectively. In order to enable the carrying out of the allocation procedure described in ISO 14041 (first, separate processes that are only needed by one of the jointly produced products), such processes and components are analysed and documented separately.

[1] Yearly average coefficient of performance: 4.5.
[2] However the emissions of the CHP plant are not yet allocated to electricity and heat.

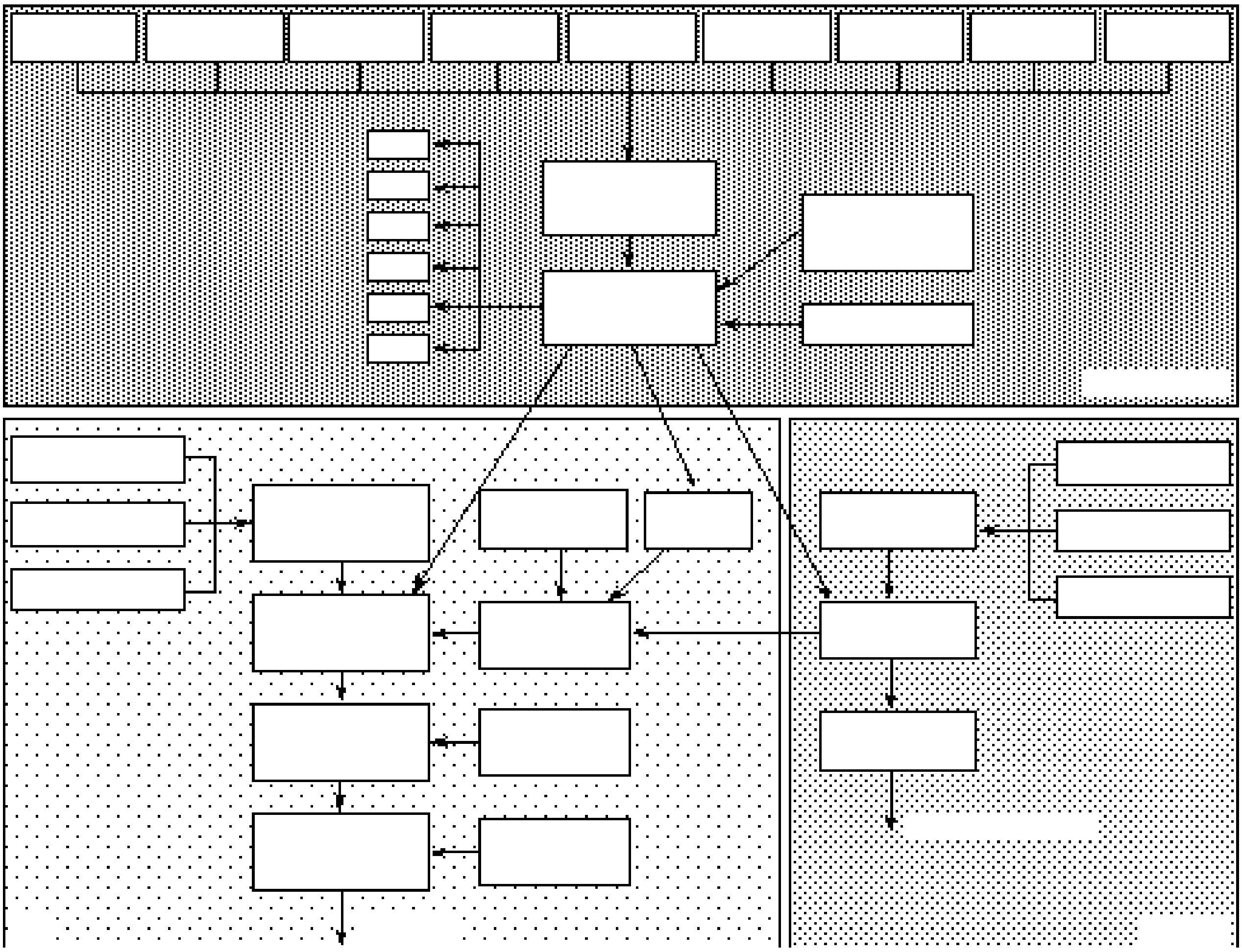

Fig. 10.3: Simplified process flow chart of the gas-fueled spark ignition engine with electric heat pump and peak load light fuel oil boilers for district heating purposes as well as a synchro-generator for the generation of electricity.

While it is possible to determine the flows of ecological commodities on a detailed level, detailed economic information for the components is not available. Furthermore, the products sold are district heat and electricity and neither mechanical energy on the shaft nor heat directly taken from the spark ignition engine, the joint production process itself. Both products are further treated before they are sold. Hence, no prices are available for the joint products at the split-off point.

### 10.2.3The Economic Performance of the CHP Plant

The range given in the literature for total specific costs varies between 0.08 to 0.2 SFr. per $kWh_e$ (Prognos 1996b, p. 51) and 0.12 and 0.24 SFr. per $kWh_e$ (Mutzner 1997, p. 63). The specific costs per $kWh_e$ for several systems in operation in Switzerland show a variation between 0.09 and 0.155SFr. (WKK 1996)[3].

It is shown in Chapter 7, that it is not necessary to allocate costs when preparing an investment decision. Therefore, no *a priori* allocation of investment and operation costs is needed in principle and the costs are given for the whole CHP plant. In this case study, costs of about 0.09SFr. per kWh total output (heat and electricity) are used (see Appendix 3).

[3] The proceeds for the heat sold are subtracted.

## 10.3 Description of Competing Systems

### 10.3.1 Introduction

For the question of allocating environmental impacts caused by a CHP plant, data about competing systems producing either electricity or heat are needed. In Part II, new allocation approaches have been introduced based on the principles of the "enviro-economic competitiveness" and "fairness", respectively (cf. Subchapter 7.5). Hence, economic data on the private costs of production and on the environmental external costs are needed. The systems used in this case study are

*a)* heating systems[4]

- oil boiler, 10kW/100kW, LowNO$_X$, condensing,
- gas boiler, <100kW, LowNO$_X$, condensing,
- wood chips boiler (saw mill), 50kW/300kW,

*b)* power plants

- average fuel oil power plant in Italy,
- average gas-fired power plant in The Netherlands,
- average hard coal power plant in Germany,
- average nuclear power plant in France,
- average run of river hydroelectric power plant in Switzerland,
- pressurized fluidized bed combustion (PFBC), hard coal power plant,
- gas combined cycle (GCC), natural gas power plant,
- roof integrated photovoltaic power plant, monocristalline, 3kWp,
- wall integrated photovoltaic power plant, monocristalline, 3kWp,
- wind power plant on the Grenchenberg, Switzerland,
- energy saving measure, replacement of an incandescent bulb by a energy saving bulb.

In the following sections, the heating systems are shortly described in technical, and ecological terms. A description of the power plant systems is given in Subchapter 9.3. The private costs are described in detail in Appendix 3.

### 10.3.2 Light Fuel Oil Boiler

The oil boilers are condensing LowNO$_X$ boilers for heating purposes only (no warm water production). The annual, overall energy efficiency is 94% (including in-house distribution) in relation to the lower heating value of the light fuel oil. In the case of the small unit, an ion exchanger box is used for the neutralisation of the condensate. The boiler has a weight of 140kg and 570kg, respectively and is mainly made of steel and mineral wool. It produces about 1.5TJ and 15TJ useful energy during its twenty years operating time (10 and 100kW, respectively). The auxiliary energy (electricity) needed during the operation (circulation pump, control system) amounts to 3.5 and 1.7%, respectively, of the useful energy delivered. Some selected flows of ecological and

[4] The small units are used in Section 9.4.4.

commercial commodities and the environmental external costs for the light fuel oil boilers are listed in Tab. 10.2.

The life cycle flows of $SO_X$ are doubled by upstream processes and the $NO_X$ emissions are nearly augmented by a factor of four. Hydrocarbon emissions mainly stem from upstream activities (i.e., oil extraction and refineries), whereas the operation of the boiler is responsible for the largest share of $CO_2$ emissions. The upstream activities contribute some additional 25%. The emissions of radionuclides (here, $^{14}C$, $^{85}Kr$ and $^{222}Rn$ are shown) are caused by the electricity demand within the process network. The environmental external costs as introduced in Chapter 8 amount to about 0.029, 0.03 and 0.09SFr. per kWh useful heat for the low, medium and high $CO_2$-scenario, respectively. The contribution of the operation phase increases from one third for the low $CO_2$-scenario to more than 70% of total environmental external costs for the high $CO_2$-scenario.

| Per TJ useful energy | Unit | Unit process 10kW | Life Cycle 10kW | Unit process 100kW | Life Cycle 100kW |
|---|---|---|---|---|---|
| *Input:* | | | | | |
| Light fuel oil | t | 24.9 | - | 24.9 | - |
| Electricity, low voltage | TJ | 0.035 | - | 0.017 | - |
| *Output:* | | | | | |
| Useful energy | TJ | 1 | 1 | 1 | 1 |
| *Emissions to air:* | | | | | |
| Waste heat to air | TJ | 1.17 | 1.40 | 1.15 | 1.36 |
| $CH_4$, Methane | kg | 0.85 | 115 | 0.85 | 112 |
| CO, Carbon monoxide | kg | 5.3 | 31 | 5.3 | 31 |
| $CO_2$, Carbon dioxide | kg | 78'700 | 92'600 | 78'700 | 91'100 |
| Non-Methane Volatile Organic Carbon (NMVOC) | kg | 3.4 | 225 | 3.4 | 223 |
| $SO_X$, Sulphur oxides as $SO_2$ | kg | 69 | 131 | 69 | 126 |
| $NO_X$, Nitrogen oxides as $NO_2$ | kg | 26.5 | 94 | 26.5 | 92 |
| Particulate matter | kg | 0.11 | 9.9 | 0.11 | 9.9 |
| $^{14}C$ | kBq | 0 | 140 | 0 | 77 |
| $^{85}Kr$ | kBq | 0 | $6.1 \cdot 10^6$ | 0 | $3.5 \cdot 10^6$ |
| $^{222}Rn$ | kBq | 0 | $8.7 \cdot 10^6$ | 0 | $5.0 \cdot 10^6$ |
| *Environmental external costs:* | | | | | |
| $CO_2$ low | SFr. | 1'800 | 5'300 | 1'800 | 5'100 |
| $CO_2$ medium | SFr. | 4'800 | 8'900 | 4'800 | 8'600 |
| $CO_2$ high | SFr. | 18'000 | 24'700 | 18'000 | 24'300 |

Tab. 10.2: Selected flows of commercial and ecological commodities and environmental external costs for the unit process and the life cycle of the light fuel oil condensing boiler, 10 and 100kW. For the complete documentation of these unit processes it is referred to Frischknecht et al. (1996a, Part IV Erdöl, p. 159ff.).

The private costs amount to 0.155 and 0.180SFr. per kWh for the 10kW boiler, and 0.052 and 0.056SFr. for the 100kW boiler, based on interest rates of 2 and 5% and a life time of 20 years (see Appendix 3).

### 10.3.3Natural Gas Boiler

The small-scale natural gas boiler is equiped with an atmospheric burner and condenses the water damp of the flue gases. The annual overall energy efficiency reaches 97% (including in-house distribution) in relation to the lower heating value of the low pressure natural gas. No neutralisation of the condensate is required. The boiler is similar in weight and composition to the oil boiler (see previous section). The auxiliary electricity demand amounts to 2.1% of the useful energy delivered. Some selected flows of ecological and commercial commodities and the environmental external costs for the natural gas boiler are listed in Tab. 10.3.

The life cycle flows of NMVOC, particulate matter, methane, and $SO_X$ increase by one to two orders of magnitude due to the upstream processes. The $NO_X$ emissions are augmented by a factor of 2.5. Similar to the oil boiler, the operation of the gas boiler is responsible for the largest share of $CO_2$ emissions. The upstream activities contribute some additional 13%. The environmental external costs as introduced in Chapter 8 amount to 0.007, 0.017 and 0.06SFr. per kWh useful heat for the low, medium and high $CO_2$-scenario, respectively. The operation phase contributes 30 and 70% to the total environmental external costs.

| Per TJ useful energy | Unit | Unit process | Life Cycle |
|---|---|---|---|
| *Input:* | | | |
| Natural gas, low pressure, in CH | $Nm^3$ | 28'300 | - |
| Electricity, low voltage | TJ | 0.021 | - |
| *Output:* | | | |
| Useful energy | TJ | 1 | 1 |
| Waste heat to air | TJ | 1.14 | 1.31 |
| $CH_4$, Methane | kg | 2.1 | 412 |
| CO, Carbon monoxide | kg | 30.9 | 53 |
| $CO_2$, Carbon dioxide | kg | 57'700 | 65'500 |
| Non-Methane Volatile Organic Carbon (NMVOC) | kg | 2.1 | 59.5 |
| $SO_X$, Sulphur oxides as $SO_2$ | kg | 0.52 | 33.2 |
| $NO_X$, Nitrogen oxides as $NO_2$ | kg | 20.6 | 50.9 |
| Particulate matter | kg | 0.1 | 5.8 |
| $^{14}C$ | kBq | 0 | 74 |
| $^{85}Kr$ | kBq | 0 | $3.1 \cdot 10^6$ |
| $^{222}Rn$ | kBq | 0 | $4.4 \cdot 10^6$ |
| *Environmental external costs:* | | | |
| $CO_2$ low | SFr. | 600 | 1'900 |
| $CO_2$ medium | SFr. | 2'700 | 4'800 |
| $CO_2$ high | SFr. | 12'100 | 17'400 |

Tab. 10.3: Selected flows of commercial and ecological commodities and environmental external costs for the unit process and the life cycle of the natural gas condensing boiler, <100kW. For the complete documentation of this unit process it is referred to Frischknecht et al. (1996a, Part V Erdgas, p. 59ff.).

The private costs are very close to the costs of the oil boiler. They vary between 0.157 and 0.182SFr. per kWh for the 10kW boiler and 0.056 and 0.06 for the 100kW boiler, based on interest rates of 2 and 5% and a life time of 20 years (see Appendix 3).

### 10.3.4 Wood Chips Boiler

The wood chips boilers are made of steel, fire-clay and mineral wool insulation. They are equiped with a ventilator to regulate the air supply. The boiler is fed automatically with wood chips by a screw conveyor. The wood chips are a by-product from saw mills and therefore no flows of ecological commodities from upstream processes like cutting trees, *et cetera*, are related to the chips, except the carbon bound in the wood. The extraction of $CO_2$ during tree growing, expressed in negative $CO_2$-emissions (see section 3.3.2), is considered and associated with the by-product of the saw mill[5]. The annual overall energy efficiency of the boiler is 65% and 75% (50 and 300kW, respectively) and the auxiliary electricity demand amounts to 2.3 and 1.7% of the useful energy delivered. The emission of particulate matter improved in the recent years compared to the data reported in Frischknecht et al. (1996a, Part IX Holz). According to measurements on 16 wood chips

[5] While the extraction of $CO_2$ is allocated based on physical causality, the upstream activities (harvesting, *et cetera*) are allocated according to the value of the products from the saw mill.

boilers (average capacity 295kW) installed between 1994 and 1996, the emission factor is reduced by about 40% from 117kg/$TJ_{In}$ to 71kg/$TJ_{In}$ including start-up phases (VHe 1997). Some selected flows of ecological and commercial commodities and the environmental external costs for the wood chips boilers are listed in Tab. 10.4.

The life cycle flows of all ecological commodities are mainly caused by the operation of the boiler. There are two exceptions. The $CO_2$ emissions from burning wood are compensated by the extraction of $CO_2$ during the growing phase of trees. Second, similar to the other systems, the release of radionuclides is entirely caused by mainly upstream processes and related to electricity consumption. The environmental external costs as introduced in Chapter 8 amount to between 0.021 and 0.026SFr. per kWh useful heat delivered by the 50kW and 300kW boiler, depending on the $CO_2$-scenario applied.

| Per TJ useful energy | Unit | Unit process 50kW | Life Cycle 50kW | Unit process 300kW | Life Cycle 300kW |
|---|---|---|---|---|---|
| *Input:* | | | | | |
| Wood chips from saw mills | t | 83.2 | - | 72.1 | - |
| Electricity, low voltage | TJ | 0.023 | - | 0.017 | - |
| *Output:* | | | | | |
| Useful energy | TJ | 1 | 1 | 1 | 1 |
| Waste heat to air | TJ | 1.71 | 0.06 | 1.48 | 0.06 |
| $CH_4$, Methane | kg | 23.8 | 28.6 | 5.1 | 8.7 |
| CO, Carbon monoxide | kg | 1483 | 1'495 | 830 | 836 |
| $CO_2$, Carbon dioxide | kg | 150'300 | 1'170 | 130'600 | 1'670 |
| Non-Methane Volatile Organic Carbon (NMVOC) | kg | 36 | 38.8 | 8.6 | 10.8 |
| $SO_X$, Sulphur oxides as $SO_2$ | kg | 31.8 | 37.5 | 27.6 | 32.2 |
| $NO_X$, Nitrogen oxides as $NO_2$ | kg | 160 | 167 | 139 | 144 |
| Particulate matter | kg | 109 [1]) | 113 | 95 [1]) | 98 |
| $^{14}C$ | kBq | 0 | 105 | 0 | 98 |
| $^{85}Kr$ | kBq | 0 | $4.4 \cdot 10^6$ | 0 | $4.0 \cdot 10^6$ |
| $^{222}Rn$ | kBq | 0 | $6.2 \cdot 10^6$ | 0 | $5.7 \cdot 10^6$ |
| *Environmental external costs:* | | | | | |
| $CO_2$ low | SFr. | 6'600 | 6'900 | 5'600 | 5'800 |
| $CO_2$ medium | SFr. | 6'600 | 7'000 | 5'600 | 5'900 |
| $CO_2$ high | SFr. | 6'700 | 7'300 | 5'600 | 6'300 |

Tab. 10.4: Selected flows of commercial and ecological commodities and environmental external costs for the unit process and the life cycle of the wood chips (saw mill) boilers, 50 and 300kW. For the complete documentation of these unit processes it is referred to Frischknecht et al. (1996a, Part IX Holz, p. 35ff.).
[1]): Emission factor according to measurements on new boilers (VHe 1997).

The private costs vary between 0.163 and 0.187 SFr. per kWh for the 50kW boiler and 0.108 and 0.127 for the 300kW boiler, based on interest rates of 2 and 5% and a life time of 20 years (see Appendix 3).

### 10.3.5District Heating Grid

For larger energy supply options, a small-sized district heating grid is needed. Although the discussion of the systems is based on the heat delivered to the district heating grid (i.e., excluding the flows of ecological commodities caused by the construction and operation of the grid), the figures for the district heating grid are shown nevertheless. If the useful heat delivered to the clients are of interest, e.g., if small, decentralised units with large centralised alternatives are compared, the share of flows of ecological commodities to be added is readily available. According to Frischknecht et al. (1996a, Appendix E Fernwärmenetz, p. 4), the electricity demand amounts to 1% of the useful heat delivered, and about 6% of the useful heat delivered is lost on the way to the clients (see Tab. 10.5).

The life cycle flows of all ecological commodities are all caused by up- and downstream processes except the waste heat emitted to the soil. They are lower by a factor of 20 and more compared to the useful heat produced with conventional oil and gas boilers. The environmental external costs as introduced in Chapter 8 amount to between 0.0002 and 0.0004SFr. per kWh useful heat delivered depending on the $CO_2$-scenario applied.

| Per TJ useful energy delivered | Unit | Unit process | Life cycle |
|---|---|---|---|
| *Input:* | | | |
| Electricity, medium voltage | kg | 0.01 | - |
| *Output:* | | | |
| Useful energy delivered | TJ | 1 | - |
| Waste heat to air, water and soil | TJ | 0.01 (0.06) [1]) | 0.082 |
| $CH_4$, Methane | kg | 0 | 0.81 |
| CO, Carbon monoxide | kg | 0 | 1.9 |
| $CO_2$, Carbon dioxide | kg | 0 | 220 |
| Non-Methane Volatile Organic Carbon (NMVOC) | kg | 0 | 0.68 |
| $SO_X$, Sulphur oxides as $SO_2$ | kg | 0 | 1.0 |
| $NO_X$, Nitrogen oxides as $NO_2$ | kg | 0 | 0.43 |
| Particulate matter | kg | 0 | 0.75 |
| $^{14}C$ | kBq | 0 | 30 |
| $^{85}Kr$ | kBq | 0 | $1.2 \cdot 10^6$ |
| $^{222}Rn$ | kBq | 0 | $1.8 \cdot 10^6$ |
| *Environmental external costs:* | | | |
| $CO_2$ low | SFr. | 0 | 57 |
| $CO_2$ medium | SFr. | 0 | 67 |
| $CO_2$ high | SFr. | 0 | 113 |

Tab. 10.5: Selected flows of commercial and ecological commodities and environmental external costs for the unit process and the life cycle of a small-sized district heating grid. For the complete documentation of this unit process it is referred to Frischknecht et al. (1996a, Appendix E Fernwärmenetz, p. 1ff.).
[1]): In brackets: waste heat emission to soil (distribution losses).

### 10.3.6Summary

The systems analysed may only be considered as partly competing ones. They show rather large differences in environmental external and private costs. However, there is no general rule for a correlation between private and external costs. Especially, it cannot be said that the cheapest systems (according to traditional economic considerations) are the ones with the highest environmental external costs and *vice versa*. In Tab. 10.6 key figures of the systems used in the next subchapters are listed. Furthermore, the figures for several electric heat pump systems which are used in Section 9.4.4 are shown.

Within the small-scale systems, the electric heat pump shows the lowest private costs per kWh useful heat delivered. Compared to larger units, the costs of small systems are higher by a factor of about three. In the low $CO_2$-scenario the environmental external costs are low compared to the private costs. Only for heat pumps driven with electricity from the average German lignite or the average Italian heavy fuel oil power plant, the environmental external costs surpass the energy costs of less than 0.05SFr. per kWh useful heat. In the other $CO_2$-scenario, the environmental external costs are similar or substantially higher compared to the energy costs.

| Per kWh useful energy | Private costs | | | Environmental external costs | | |
|---|---|---|---|---|---|---|
| | total costs 2% [1]) | total costs 5% [1]) | energy costs | $CO_2$, low | $CO_2$, medium | $CO_2$, high |
| Spark ignition engine, gas-fueled CHP plant, 360kW$_{th}$ [2]) | 0.087 | 0.093 | 0.040 | 0.0076 | 0.0193 | 0.0712 |
| Light fuel oil boiler, condensing, 10kW | 0.155 | 0.180 | 0.032 | 0.0192 | 0.0320 | 0.0890 |
| Light fuel oil boiler, condensing, 100kW | 0.052 | 0.056 | 0.032 | 0.0184 | 0.0311 | 0.0875 |
| Natural gas boiler, condensing, ca. 10kW | 0.157 | 0.182 | 0.036 | 0.0070 | 0.0172 | 0.0625 |
| Natural gas boiler, condensing, ca. 100kW | 0.056 | 0.060 | 0.036 | 0.0070 | 0.0172 | 0.0625 |
| Wood chips boiler, 50kW | 0.163 | 0.187 | 0.031 | 0.0248 | 0.0251 | 0.0263 |
| Wood chips boiler, 300kW | 0.108 | 0.127 | 0.027 | 0.0210 | 0.0213 | 0.0226 |
| Electric heat pump, CH incl. trade, 10kW$_{th}$ | 0.141 | 0.171 | 0.044 | 0.0113 | 0.0137 | 0.0245 |
| Electric heat pump, fuel oil, I, 10kW$_{th}$ | " | " | " | 0.0599 | 0.0701 | 0.1156 |
| Electric heat pump, lignite, D, 10kW$_{th}$ | " | " | " | 0.0598 | 0.0753 | 0.1441 |
| Electric heat pump, hard coal, D, 10kW$_{th}$ | " | " | " | 0.0233 | 0.0363 | 0.0937 |
| Electric heat pump, nuclear, F, 10kW$_{th}$ | " | " | " | 0.0087 | 0.0097 | 0.0137 |
| Electric heat pump, natural gas, NL, 10kW$_{th}$ | " | " | " | 0.0087 | 0.0167 | 0.0525 |
| Electric heat pump, CHP plant, 10kW$_{th}$ [3]) | " | " | " | 0.0064 | 0.0136 | 0.0454 |

Tab. 10.6: Private and environmental external costs per kWh useful energy for heating systems.
[1]): Interest rate.
[2]): Total costs of the entire plant (excluding peak load boilers).
[3]): 62% of the flows of commercial and ecological commodities are allocated to the electricity.

## 10.4 Classical Allocation Approaches Applied on the CHP Plant

### 10.4.1 Introduction

This subchapter is intended to show the variation in results achieved by applying different allocation approaches and parameters in the long run system model. Thereby, the procedure of the actual ISO proposal for allocation is followed and commented.

First, the "avoided burden"- or "system expansion"-approach is applied. Because both joint products are further treated after the split-off point (which is just after the spark ignition engine), no separation of separately used processes is possible, except the peak load oil boilers. Neither the mechanical energy at the shaft, nor the heat content of the cooling water is saleable. Furthermore some of the electricity produced by the synchrogenerator is used to produce additional heat with a heat pump. For these reasons, system expansion is applied on the level of a black box model including all system components needed to generate the saleable products district heat and electricity.

Second, the three step procedure stated by Anonymous (1997b) will be applied for the allocation of flows of ecological commodities, based on the detailed information available about the CHP plant. Single components will be allocated to the joint products, and allocation will be performed according to parameters such as energy, exergy, and (private) costs as well as motivation.

Third, the two context-specific allocation approaches "enviro-economic competitiveness" and "enviro-economic fairness" developed in Chapter 7 are applied, and the consequences and differences especially compared to the approaches shown before will be highlighted.

### 10.4.2The "Avoided Burden"-Approach for Heat

When running a CHP plant to produce electricity and heat, other opportunities available are foregone. The private, the environmental external, and the social costs of electricity may be used for the determination of accurate costs for the heat produced. For that purpose, a black box model of the CHP system is established. In this model, natural gas enters the black box system, whereas the joint products electricity and heat as well as emissions leave it. Together with heat produced by the peak load boilers, the heat from the CHP plant is fed into the district heating grid.

When analysing changes, particularly with the Long Run system model (see Section 5.3.5), the concept of avoided burdens may also be characterised as a "reality"-oriented system representation. If an additional demand for heat is covered, without an overall increase in demand of electricity, some other electricity generating facility needs to reduce its production and is displaced. However, this approach may also be applied independent from such considerations. It indicates the environmental burdens avoided by operating the multi-function option at issue.

The total expenses required, and the entire flows of ecological commodities due to the construction and operation of the CHP plant are considered and allocated to the heat delivered. Per TJ heat delivered to the district heating grid and produced by the co-generation plant, 1.59TJ natural gas and 0.76% of the capital equipment are needed. On the other hand, 0.38TJ low voltage electricity are replaced which is expressed in Tab. 10.7 by a negative value.

| per TJ useful heat | | unit |
|---|---|---|
| *Energy carriers:* | | |
| Electricity low voltage | -0.38 | TJ |
| *CHP plant:* | | |
| CHP plant Black Box | 0.008 | Units |
| Natural gas in CHP plant 160 $kW_e$ Black Box | 1.59 | TJ |

Tab. 10.7: Flows of commercial commodities for the production of 1TJ heat produced by the CHP system and delivered to the district heating grid; system representation based on the "avoided burden"-approach.

The central question with this approach is, which electricity generating technology is the opportunity foregone on the Long Run? Is it a French nuclear, a German hard coal or lignite, an Italian heavy fuel oil, or even a Dutch gas-fired power plant? Should a mix of marginal technologies be applied? In Chapter 9 it has been shown that the technology in operation with the highest social costs is the average French nuclear power plant, the average Italian heavy fuel oil power plant, and the average German lignite power plant, dependent on the environmental exchange rate used. Here, nuclear and lignite power are used.

The capital equipment needed comprise all components of the CHP system (i.e., spark ignition engine, synchrogenerator, heat exchanger, hot water tanks, *et cetera*, but excluding the peak load oil boilers). The flows of commercial and ecological commodities related to the "black box" production process are summarized in Tab. 10.8.

| per 1 Unit CHP plant Black Box | | unit |
|---|---|---|
| *Non-energetic Resources:* | | |
| Water | 19960 | kg |
| Tin | 2.617 | kg |
| *Energy carriers:* | | |
| Electricity medium voltage - purchased in CH | 0.02325 | TJ |
| Electricity medium voltage - purchased in UCPTE | 0.013781 | TJ |
| Electricity low voltage - purchased in CH | 0.12784 | TJ |
| *Basic materials:* | | |
| Varnish | 8.4 | kg |
| Aluminium 0% Rec. | 174.65 | kg |
| Concrete (without reinforcing steel) | 3520 | kg |
| Lead | 1.23 | kg |
| Rubber EPDM | 40 | kg |
| Cast iron | 1595 | kg |
| Wood | 2 | kg |
| Refrigerant HFC 134a | 20 | kg |
| Cardboard | 3.85 | kg |
| Copper | 336.3 | kg |
| Mineral wool | 655 | kg |
| Nickel from refining | 0.55 | kg |
| Palladium from refining | 0.0021 | kg |
| PE (LD) | 126 | kg |
| Platinum from refining | 0.0146 | kg |
| PVC | 14.6 | kg |
| Rhodium from refining | 0.0021 | kg |
| Steel high alloy | 570 | kg |
| Steel low alloy | 846 | kg |
| Steel no alloy | 13'400 | kg |
| Zeolite | 26.6 | kg |
| Zinc for galvanization | 0.404 | kg |
| *Transports:* | | |
| Transport lorry 28t brutto | 602 | tkm |
| Transport lorry 40t brutto | 163 | tkm |
| Transport private car, Western Europe | 25'800 | km |
| Transport Railway | 6750 | tkm |
| *Oil:* | | |
| Light fuel oil in boiler 1 MW | 0.45 | TJ |
| Petrochemical oil from refinery | 8.0 | t |
| *Natural gas:* | | |
| Natural gas in industrial boiler >100 kW Euro | 0.11 | TJ |
| *Untreated wastes:* | | |
| Concrete in landfill for inert materials | 3520 | kg |
| Untreated wood in waste incinerator | 2 | kg |
| Cardboard in waste incinerator | 3.85 | kg |
| Polymers in waste incinerator | 138 | kg |
| Polymers in landfill for reactive materials | 42.6 | kg |
| Mineral wool in landfill for inert materials | 655 | kg |
| Steel in landfill for inert materials | 128 | kg |
| *Emissions to air:* | | |
| Waste heat to air | 0.165 | TJ |
| $CO_2$ Carbon dioxide | 4.7 | kg |
| Particulate matter | 0.03 | kg |
| HFC 134a | 4.7 | kg |

Tab. 10.8: Flows of commercial and ecological flows for the production of a standard CHP-plant system (CHP plant Black Box, including gas spark ignition engine, heat pump, catalyst, hot water tanks, maintenance, *et cetera*).

Some selected cumulative flows of ecological commodities as well as the environmental external costs for heat co-produced in a CHP plant applying the "avoided burden"-approach are listed in Tab. 10.9. The cumulative flows of ecological commodities are partially negative. In particular, the release of radionuclides may partially be avoided if the joint electricity production in a CHP plant replaces a nuclear power plant. Assuming a replacement of the German lignite power plant, emissions of $SO_X$, $NO_X$ and particulate matter may be avoided, and the $CO_2$ emissions are reduced markedly. They amount to less than 10% of the emissions with a conventional, condensing gas boiler. In terms of environmental external costs, negative values result for all $CO_2$-scenario in the lignite case. For the high $CO_2$-scenario in the nuclear case, however, the environmental external costs of useful heat from the CHP plant are higher than the value of a natural gas condensing boiler.

| Per TJ useful heat | Unit | Replacing nuclear power, F | Replacing lignite power, Ger |
|---|---|---|---|
| *Output:* | | | |
| Useful heat | TJ | 1 | 1 |
| *Emissions to air:* | | | |
| Waste heat in air and water | TJ | 1.13 | 0.99 |
| $CH_4$, Methane | kg | 388 | 382 |
| CO, Carbon monoxide | kg | 81 | 70 |
| $CO_2$, Carbon dioxide | kg | 99'500 | 6'190 |
| Non-Methane Volatile Organic Carbon (NMVOC) | kg | 147 | 145 |
| $SO_X$, Sulphur oxides as $SO_2$ | kg | 71 | -610 |
| $NO_X$, Nitrogen oxides as $NO_2$ | kg | 83 | -44 |
| Particulate matter | kg | 7.1 | -41 |
| $^{14}C$ | kBq | -1'070 | 55 |
| $^{85}Kr$ | kBq | $-8.1 \cdot 10^{7}$ | $2.1 \cdot 10^{6}$ |
| $^{222}Rn$ | kBq | $-1.1 \cdot 10^{8}$ | $3.0 \cdot 10^{6}$ |
| *Environmental external costs:* | | | |
| $CO_2$ low | SFr. | 320 | -20'400 |
| $CO_2$ medium | SFr. | 4'500 | -22'200 |
| $CO_2$ high | SFr. | 23'200 | -29'800 |

Tab. 10.9: Selected flows of ecological commodities and environmental external costs for the life cycle of heat from a gas-fired CHP plant applying the avoided burden approach for the heat produced. For the complete documentation of these unit processes it is referred to Frischknecht et al. (1996a, Part XIV Wärme-Kraft-Kopplung, p. 10ff.).

One important aspect of the "avoided burden"-approach applied here for the heat produced in a CHP system has to be kept in mind when using these results. In order to fulfill the "100% additivity"-rule, the environmental performance of the electricity produced in the CHP plant shows exactly the same environmental performance as if produced by the technology avoided. Hence, in the case of avoiding the electricity generation in a nuclear power plant, CHP electricity "releases" the same amount of radionuclides, and produces the same amount of low, medium and high radioactive wastes as the nuclear power plant (see Tab. 9.6). For the other avoided option, the lignite power plant, the considerations are analogous. The $CO_2$ emissions are as high as the ones of the lignite power plant it displaces (see Tab. 9.4).

### 10.4.3The "Avoided Burden"-Approach for Electricity

In the case of electricity being the functional unit under consideration, all flows of commercial and ecological commodities are entirely allocated to the electricity delivered to the grid. Similar to the district heat case above, the flows of ecological commodities of other options to produce (district) heat are subtracted from the flows' total in relation to the amount of heat produced per kWh electricity delivered to the grid.

| per TJ electricity low voltage | | unit |
|---|---|---|
| ***Natural gas:*** | | |
| Useful heat from heating system A, B, C, ... | -2.48 | TJ |
| ***CHP plant:*** | | |
| CHP plant Black Box | 0.02 | Units |
| Natural gas in CHP plant 160 $kW_e$ Black Box | 4.18 | TJ |

Tab. 10.10: Flows of commercial commodities for the production of 1TJ electricity produced by the CHP system and delivered to the electricity grid of the local utility; system representation based on the "avoided burden"-approach.

Per TJ electricity delivered, 4.18TJ natural gas and about 2% of the capital equipment are needed. On the other hand, about 2.63TJ heat are delivered to the district heating grid replacing 2.48TJ useful heat produced by an alternative energy system (6% losses in the district heating net considered, see Frischknecht et al. (1996a, Appendix E Fernwärmenetz, p. 4). This is expressed by a negative value in Tab. 10.10. Similar to above, the question about the marginal technology displaced by an additional amount of heating energy produced needs to be determined. The displaced technologies may be, e.g., a LowNOx atmospheric gas boiler, a light fuel oil boiler, a heat pump, single room coal ovens, *et cetera*. We choose an oil and a gas boiler. The capital equipment needed are the same as for the heating energy case (see Tab. 10.8 above).

| Per TJ electricity | Unit | Replacing an oil boiler | Replacing a natural gas boiler |
|---|---|---|---|
| *Output:* | | | |
| electricity, low voltage | TJ | 1 | 1 |
| *Emissions to air:* | | | |
| Waste heat to air and water [1]) | TJ | 1.57 | 1.57 |
| $CH_4$, Methane | kg | 1'210 | 374 |
| CO, Carbon monoxide | kg | 208 | 172 |
| $CO_2$, Carbon dioxide | kg | 24'600 | 87'500 |
| Non-Methane Volatile Organic Carbon (NMVOC) | kg | -372 | 62 |
| $SO_X$, Sulphur oxides as $SO_2$ | kg | -214 | 34 |
| $NO_X$, Nitrogen oxides as $NO_2$ | kg | -45 | 76 |
| Particulate matter | kg | -17 | 2.9 |
| $^{14}C$ | kBq | -177 | -272 |
| $^{85}Kr$ | kBq | $-7.8 \cdot 10^6$ | $-1.1 \cdot 10^7$ |
| $^{222}Rn$ | kBq | $-1.1 \cdot 10^7$ | $-1.6 \cdot 10^7$ |
| *Environmental external costs:* | | | |
| $CO_2$ low | SFr. | -6'600 | 2'000 |
| $CO_2$ medium | SFr. | -4'700 | 5'400 |
| $CO_2$ high | SFr. | 3'600 | 20'800 |

Tab. 10.11: Selected flows of ecological commodities and environmental external costs for the life cycle of electricity from a gas-fired CHP plant applying the "avoided burden"-approach for the electricity produced. For the complete documentation of these unit processes it is referred to Frischknecht et al. (1996a, Part XIV Wärme-Kraft-Kopplung, p. 10ff.).
[1]): including 1TJ from the electricity produced in the power plant and consumed elsewhere.

In Tab. 10.11, some selected cumulative flows of ecological commodities as well as environmental external costs for electricity co-produced in a CHP plant applying the "avoided burden"-approach are listed. If we assume that an oil boiler is replaced by the additional heat produced, emissions of $SO_X$, NMVOC, $NO_X$, particulate matter and radionuclides may be avoided. The $CO_2$-emissions are reduced to a level comparable to the one of photovoltaic electricity (see Tab. 9.10). The environmental external costs are negative, except for the high $CO_2$-scenario, which means that external benefits are achieved (compared to the situation before the installation of the CHP system). In the case of displacing natural gas boilers, the benefits are less distinct. The emissions are rather low compared to conventional, average fossil-fired power plants, but no negative figures occur. Again it must be emphasized that the environmental performance of the heat produced by the CHP plant will equal the one of a standard oil- and gas-fired boiler, respectively. Hence the whole benefit of co-production is allocated to the electricity in this case.

### 10.4.4 The Three Step Allocation Procedure

In contrast to the "avoided burden"-approach, the allocation which follows the three step procedure relies on a detailed analysis of the unit process by subdividing it and establishing causal relationships. In a *first step*, all processes used by only one of the outputs will be separated (Fig. 10.3). The hot water tanks are allocated to the delivered heat[6] whereas the electricity generating unit is dedicated to the electricity. In addition to that, all processes delivering quantifiable contributions to either output would be separated in this first step. However, in our case no such processes exist.

In a *second step*, physical, chemical or biological causalities should be used if available and suitable to allocate the requirements and environmental interventions of the remaining multiple processes to the co-products. Chemical properties are not applicable in our case because the goods produced stem from one main single input, namely natural gas. On the other side, physical causalities are more disputable. One might argue that electricity is always produced while it is physically not imperative to make also and always use of the waste heat. However, the same line of reasoning is also applicable in the opposite direction. One might only make use of the heat produced in a spark ignition engine and dissipate the mechanical energy co-produced. Although both considerations are theoretically right, they fail because they are economically inefficient. Single-function processes (power plants only generating electricity and boilers only generating heat) are able to produce at less costs than a multi-function process (a CHP plant) that would only be operated either for its heat or electricity generation. CHP plants are built to produce both heat *and* electricity which renders them economically competitive.

Furthermore, it must be emphasized that neither the energy nor the exergy content of the outputs influence the emission characteristics of a CHP-plant[7]. That is why no parameters exist which reflect physical causalities (the requirement for parameters to be used in the second step of the ISO procedure) and by that would allocate flows of commercial and ecological commodities of the CHP plant in a non-arbitrary way. Therefore we need to move to the *third step*, namely the identification of other kinds of causalities or relationships. Among these, economic parameters are the ones, that are named most frequently. In the context of CHP plants, energy and exergy content of the products are other relationships often applied.

The physical properties of the joint outputs may be used as a short-cut indicator for the relative value of the two products. In this case either the energy or the exergy content of heat and electricity may be applied, resulting in quite different cumulative flows of ecological commodities. With the latter concept, the second principle of thermodynamics is included in that the energy's capacity to generate mechanical work is considered. Because of the high exergy content of electricity (100% of the energy content), the environmental performance of 1kWh electricity is much worse compared to the environmental performance of 1kWh heat. However, if the electricity is used for heating

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[6] Although the performance of the spark ignition engine, and therefore the performance of both heat and electricity production is improved by this measure.

[7] Heat and electricity as outputs cannot cause inputs, physically speaking.

purposes in combination with a heat pump, the environmental performance of this heat is comparable to the environmental performance of the heat directly generated with the CHP plant.

As already mentioned, the gross or relative sales value may be used as the allocation parameter. With such a parameter, the integral value of the two products is indicated[8]. Hence, the main physical property, the exergy content of the outputs is included in the realisable prices of the two products.

Besides these three parameters, the motivation of the commissioner of the plant is translated into allocation factors. The motivations to run a CHP plant may differ markedly, and the decision for an investment may either be motivated more in order to generate heat or more in order to generate electricity. For communities, the heating aspect of CHP is mentally in the foreground whereas the revenues of the electricity sold to the utility is used to keep the heating costs on a level that is competitive with conventional fossil-fueled heating systems. Industrial use of CHP is mainly motivated by lowering energy demand and/or energy costs by producing steam and heat at various levels as well as electricity used in the plant. Banking institutes are able to lower their costs for electricity by using CHP plants and therefore focus more on the electricity generating aspect.

As a consequence, the electricity and the heat, respectively, is assumed to bear no flows of commercial and ecological commodities. These approaches define the extremes of all possible allocation approaches (except, of course, some of the "avoided burden"-approaches, where negative figures are realised). The allocation factors calculated on the basis of the characteristics of the spark ignition engine are shown in Tab. 10.12.

| Step in ISO 14041 | Criterion | Parameter | Case Nr. | Weighting factor | | Allocation factor 4) | |
|---|---|---|---|---|---|---|---|
| | | | | Electricity | District heat | Electricity | District heat |
| 1. step | subdivision | - | - | - | - | - | - |
| 2. step | physical causality | no parameter available | - | - | - | - | - |
| 3. step | physical value | energy content, [kWh/kWh] 5) | 1 | 1 | 1 | 0.36 | 0.64 |
| | | exergy content, [kWh/kWh] | 2 | 1 | 0.182 2) | 0.75 | 0.25 |
| | economic value 1) | relative sales value, [SFr./kWh] | 3 | 0.178 3) | 0.062 3) | 0.62 | 0.38 |
| | | net realisable value | - | n.d. | n.d. | n.d. | n.d. |
| | | constant gross margin value | - | n.d. | n.d. | n.d. | n.d. |
| | | sales to production ratio | - | n.d. | n.d. | n.d. | n.d. |
| | motivation | district heat is a by-product, [-] | 4 | 1 | 0 | 1 | 0 |
| | | electricity is a by-product, [-] | 5 | 0 | 1 | 0 | 1 |

Tab. 10.12: The allocation factors used, and the relation between the criterion applied, and the parameters used to allocate flows of commercial and ecological commodities to district heat and electricity.
n.d.: not determined.
1)): see Appendix 1 for a description of the approaches.
2)): Upper temperature: 85°C, lower temperature: 20°C.
3)): Specific average proceeds in SFr. per kWh heat and electricity sold, respectively, according to Graf (1996).
4)): Based on an average production volume of the spark ignition engine of 1'373MWh heat and 761MWh electricity (Frischknecht et al. 1996a, Part XIV Wärme-Kraft-Kopplung, p. 23).
5)): In brackets: unit of the weighting factors.

Because the CHP plant analysed here is either used at full load, definite partial load, or taken out of operation, allocation parameters based on an intentional and short-term *change* from partial load to full load (and backwards) will not be considered[9]. Furthermore, in Frischknecht et al. (1996a, Part

[8] As reflected by today's economy, of course.
[9] This would comply with the representation of short-term changes, see Section 5.3.4.

XIV Wärme-Kraft-Kopplung, p. 31ff.) it could be shown on the basis of information given by the producer of the spark ignition engines (Zacharias 1992), that the results based on partial load characteristics are very similar to the results when allocating on the basis of full load characteristics.

It can be seen that criteria based on the exergy content and the economic value lead to similar values whereas the purely energetic criterion leads to different shares. This does not mean that the former two are the adequate ones but simply tells us, that the economic value of energy carriers coincides fairly well with its physical value to perform mechanical work. In Tab. 10.13 and 10.14, selected flows of ecological commodities are listed for the five allocation factors.

| Life cycle, per TJ useful energy delivered | Unit | energy content | exergy content | relative sales value | motivation electricity | motivation heat |
|---|---|---|---|---|---|---|
| alternative | | 1 | 2 | 3 | 4 | 5 |
| *Output:* | | | | | | |
| Useful energy delivered | TJ | 1 | 1 | 1 | 1 | 1 |
| Waste heat in air and water | TJ | 1.30 | 0.89 | 1.03 | 0.628 | 1.67 |
| $CH_4$, Methane | kg | 283 | 162 | 205 | 88 | 391 |
| CO, Carbon monoxide | kg | 59 | 36 | 44 | 22 | 79 |
| $CO_2$, Carbon dioxide | kg | 81'400 | 60'000 | 67'500 | 46'700 | 101'000 |
| Non-Methane Volatile Organic Carbon (NMVOC) | kg | 133 | 115 | 121 | 104 | 149 |
| $SO_X$, Sulphur oxides as $SO_2$ | kg | 75 | 65 | 69 | 59 | 84 |
| $NO_X$, Nitrogen oxides as $NO_2$ | kg | 72 | 56 | 61 | 46 | 86 |
| Particulate matter | kg | 7.4 | 5.9 | 6.4 | 5.1 | 8.6 |
| $^{14}C$ | kBq | 38 | 36 | 37 | 35 | 40 |
| $^{85}Kr$ | kBq | $1.8 \cdot 10^6$ | $1.7 \cdot 10^6$ | $1.7 \cdot 10^6$ | $1.6 \cdot 10^6$ | $1.9 \cdot 10^6$ |
| $^{222}Rn$ | kBq | $2.5 \cdot 10^6$ | $2.4 \cdot 10^6$ | $2.4 \cdot 10^6$ | $2.2 \cdot 10^6$ | $2.7 \cdot 10^6$ |
| *Environmental external costs:* | | | | | | |
| $CO_2$ low | SFr. | 3'400 | 2'800 | 3'000 | 2'400 | 3'900 |
| $CO_2$ medium | SFr. | 6'700 | 5'200 | 5'700 | 4'300 | 8'000 |
| $CO_2$ high | SFr. | 21'300 | 15'800 | 17'700 | 12'400 | 26'100 |

Tab. 10.13: Selected flows of commercial and ecological commodities and environmental external costs for the life cycle of heat produced in a gas-fueled CHP plant including a peak load oil boiler. For the complete documentation of these unit processes it is referred to Frischknecht et al. (1996a, Part XIV Wärme-Kraft-Kopplung, p. 10ff.).

The variation of the results for the heat produced is not very distinct compared to the results for electricity. This is due to the fact that 13% of the heat delivered to the district heating grid stems from the electric heat pump which uses the electricity generated by the CHP plant. In addition to that, about 40% stems from the peak load oil boilers. With the parameter "exergy content" the environmental external costs reach about 55 to 65% of the costs of a conventional oil boiler. For the low $CO_2$-scenario, the environmental external costs for the heat from the CHP plant are always higher than for the conventional, condensing gas boiler. In the high $CO_2$-scenario, the parameter "relative sales value" leads to costs comparable with the natural gas boiler.

The cumulative flows of ecological commodities related to electricity from the CHP plant is strongly dependent on the allocation factor used. While alternative Nr. 5 ("motivation heat") leads to values close to zero (all flows of commercial and ecological commodities are allocated to the heat from the spark ignition engine, hence just the capital equipment dedicated to the electricity production is considered), whereas alternative Nr. 4 leads to values similar to the average Dutch natural gas-fueled power plant (see Tab. 9.5).

| Per TJ electricity, low voltage | Unit | energy content | exergy content | relative sales value | motivation electricity | motivation heat |
|---|---|---|---|---|---|---|

| alternative | | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| *Output:* | | | | | | |
| Electricity, low voltage | TJ | 1 | 1 | 1 | 1 | 1 |
| Waste heat in air and water [1]) | TJ | 1.66 | 3.48 | 2.84 | 4.63 | 0.017 |
| $CH_4$, Methane | kg | 479 | 1'010 | 823 | 1'340 | 0.50 |
| CO, Carbon monoxide | kg | 92 | 191 | 156 | 254 | 1.6 |
| $CO_2$, Carbon dioxide | kg | 85'000 | 179'000 | 146'000 | 237'000 | 204 |
| Non-Methane Volatile Organic Carbon (NMVOC) | kg | 72 | 151 | 123 | 200 | 0.57 |
| $SO_X$, Sulphur oxides as $SO_2$ | kg | 41 | 84 | 69 | 112 | 1.3 |
| $NO_X$, Nitrogen oxides as $NO_2$ | kg | 64 | 135 | 110 | 179 | 0.47 |
| Particulate matter | kg | 5.9 | 12 | 9.9 | 16 | 0.29 |
| $^{14}C$ | kBq | 9.6 | 19 | 15 | 24 | 1.5 |
| $^{85}Kr$ | kBq | $5.1 \cdot 10^5$ | $9.9 \cdot 10^5$ | $8.2 \cdot 10^5$ | $1.3 \cdot 10^6$ | $6.7 \cdot 10^4$ |
| $^{222}Rn$ | kBq | $7.3 \cdot 10^5$ | $1.4 \cdot 10^6$ | $1.2 \cdot 10^6$ | $1.9 \cdot 10^6$ | $9.5 \cdot 10^4$ |
| *Environmental external costs:* | | | | | | |
| $CO_2$ low | SFr. | 2'300 | 4'800 | 3'900 | 6'300 | 36 |
| $CO_2$ medium | SFr. | 5'900 | 12'300 | 10'100 | 16'300 | 44 |
| $CO_2$ high | SFr. | 21'800 | 45'600 | 37'400 | 60'800 | 80 |

Tab. 10.14: Selected flows of commercial and ecological commodities and environmental external costs for the life cycle of electricity produced in a gas-fueled CHP plant. For the complete documentation of these unit processes it is referred to Frischknecht et al. (1996a, Part XIV Wärme-Kraft-Kopplung, p. 10ff.).
[1]): Waste heat including 1TJ from electricity generated in the CHP plant and used elsewhere.

The five alternatives of both heat and electricity production need to be considered pairwise together because the relatively low scores for heat when applying the allocation factors of alternative 4 (motivation "electricity") are mirrored by rather high cumulative values for electricity and *vice versa*. To show this interdependency, heat-electricity diagrams are used where the cumulative environmental external costs are plotted (see illustrative example in Fig. 10.4).

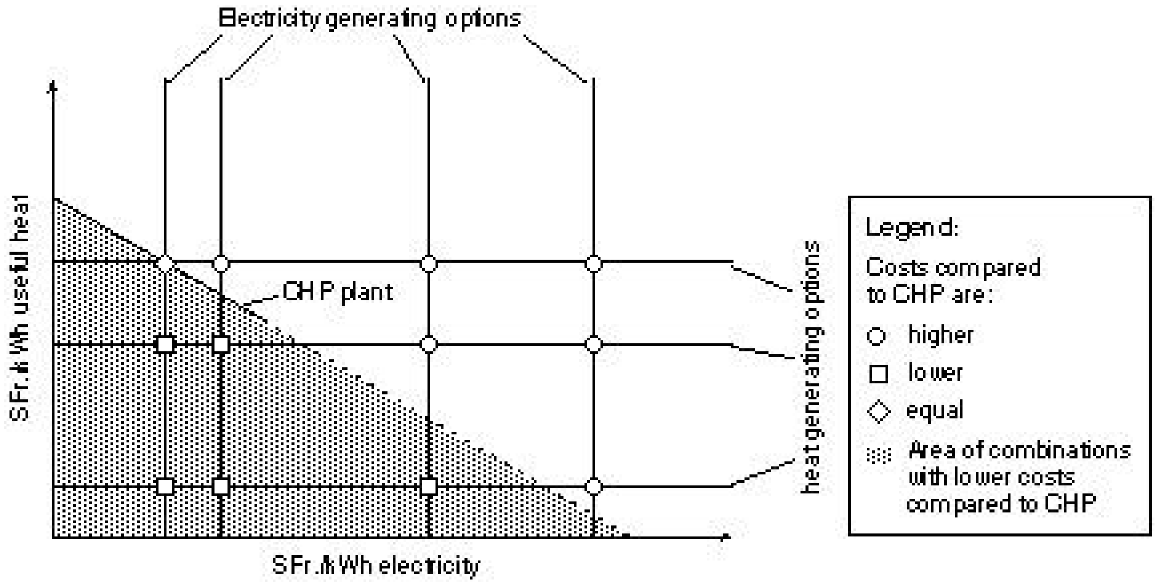


Fig. 10.4: Principle scheme for specific costs of a natural gas spark ignition engine CHP plant (including heat pump and peak load boilers) depending on the allocation factor applied compared to the specific costs of various competing energy systems.

In addition to the CHP plant, competing single-function options as described above and in Chapter 9 are also included. The cumulative environmental external costs of electricity and of the heating generating technologies are shown on the horizontal and vertical axis, respectively. The vertical and horizontal lines help to find the points of intersection. These points indicate possible combinations of purely single-function heat and electricity generating systems. These combinations may compete with the combined heat and electricity production. The points of intersection above and to the right of the CHP line (and its elongation) produce at higher costs per kWh heat and electricity (private, environmental external, or social costs) compared to CHP; the points of intersection below and to the left (the shaded area in Fig. 10.4) produce at lower costs.

The CHP line is obtained by varying the allocation factor for electricity between zero (upper left end) and one (lower right end). In the following examples, the five allocation factors derived from five different allocation parameters introduced in Tab. 10.12 are shown and indicated accordingly. In Fig. 10.5 to 10.7, the situation for the three different $CO_2$-damage costs scenario are shown.

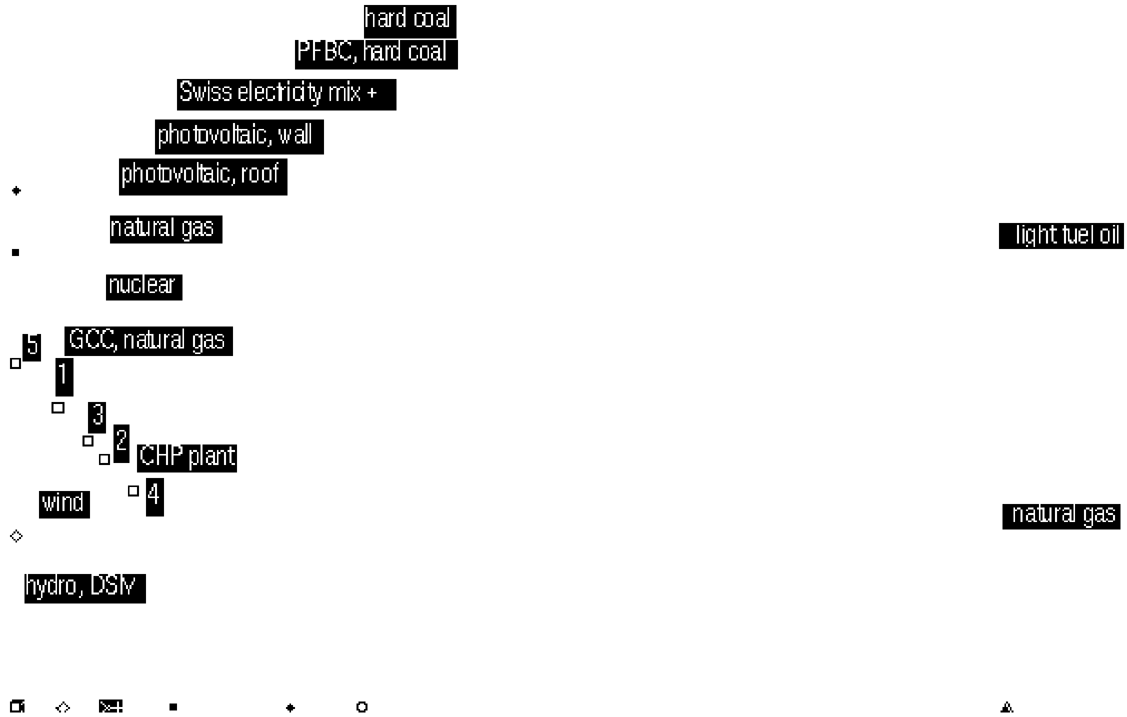


Fig. 10.5: Specific environmental external costs determined on the basis of a low $CO_2$-scenario and a variable allocation factor for a natural gas spark ignition engine CHP plant (including heat pump and peak load boilers) and various competing energy systems. The numbers close to the CHP curve correspond to the five allocation parameters introduced in Tab. 10.12.
Swiss electricity mix +: Electricity mix including trade, see Subchapter 9.2 for more details.

In the low $CO_2$-scenario, the environmental external costs of the electricity produced in a CHP plant are always lower than the costs for fossil thermal power plants except natural gas. The environmental external costs of the heat produced in a CHP plant are lower compared to these of the oil and the wood chips boiler, even if all flows of commercial and ecological commodities are allocated to the heat (allocation parameter Nr. 5 "motivation heat").

Furthermore, the maximum (and minimum) values for the allocation factors where both heat and electricity from the CHP plant show lower costs may be determined (see Section 7.5.1 for its mathematical derivation). Underlying higher damage costs for greenhouse gases (medium $CO_2$-scenario, see Fig. 10.6), the allocation factor for electricity needs to be below 0.41 and 0.30 (achieved by allocation parameters Nr. 1 and 5, "energy" and "motivation heat"), respectively, in order to show a better environmental performance than the best thermal (natural gas GCC and nuclear) power plants. With these maximum allocation factors for electricity, the environmental performance for the jointly produced heat is better only compared to the oil boiler. In the high $CO_2$-scenario, the maximum allocation factors for electricity when comparing CHP electricity with GCC and nuclear electricity are 0.43 and 0.09, respectively. The natural gas and the wood chips boiler produce at lower environmental external costs applying these or lower allocation factors. The combination nuclear power and light fuel oil boiler also shows slightly lower costs compared to CHP electricity and heat.

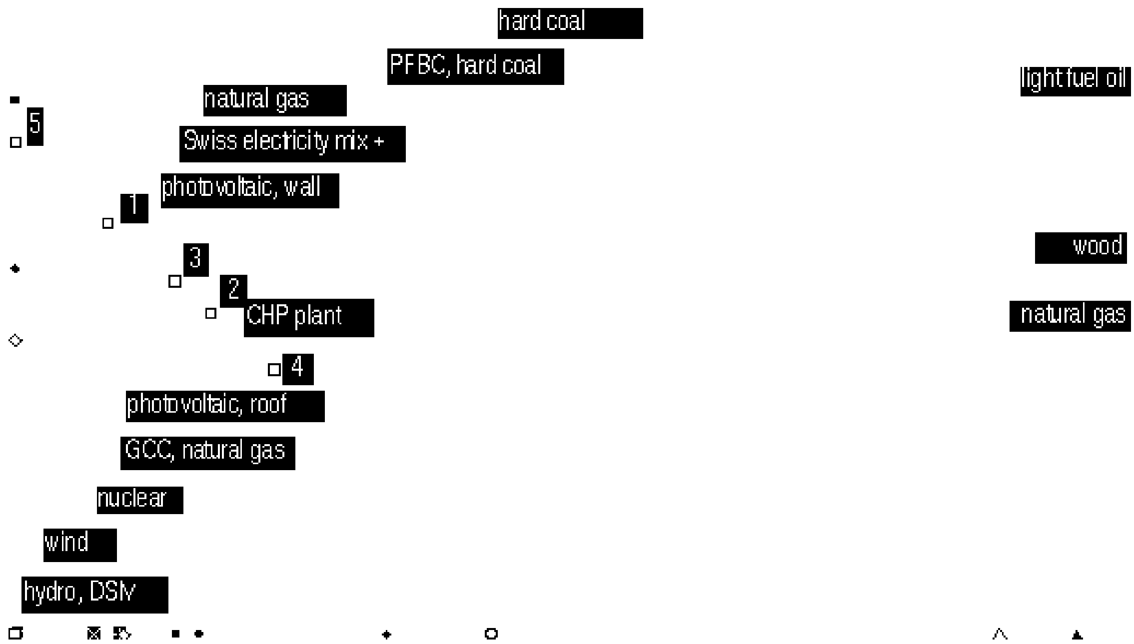


Fig. 10.6: Specific environmental external costs determined on the basis of a medium $CO_2$-scenario and a variable allocation factor for a natural gas spark ignition engine CHP plant (including heat pump and peak load boilers) and various competing energy systems. The numbers close to the CHP curve correspond to the five allocation parameters introduced in Tab. 10.12.
Swiss electricity mix +: Electricity mix including trade, see Subchapter 9.2 for more details.

If the environmental external costs of heat produced by the CHP system should be lower compared to the environmental external costs of heat produced by the gas boiler, the allocation factor for electricity should not be lower than 0.64 in the high $CO_2$-scenario. This is only achieved by the "motivation electricity" and the "exergy content" allocation parameters (Nr. 4 and 2). In that case, only average natural gas, liquid and solid fossil-fueled power plants show higher environmental external costs than CHP plant electricity. For instance, the environmental external costs of electricity and heat produced by the CHP system are higher compared to the environmental external costs of electricity generated in the natural gas GCC power plant and heat produced in the gas boiler, respectively. No allocation factors exist which would lead to lower environmental external costs for both heat and electricity from the CHP plant in comparison to this combination of single function technologies (gas boiler and GCC power plant).

In all $CO_2$-scenario, other technologies, especially roof-integrated photovoltaics, wind and hydroelectric power plants show lower environmental external costs if combined with a gas boiler. Combined with a light fuel oil boiler, CHP heat and electricity are always less expensive. Combined with a wood chips boiler, CHP heat and electricity is more expensive in the medium and high $CO_2$-scenario. In the medium and high $CO_2$-scenario, nuclear power gets environmentally competitive when combined with the gas boiler or the wood chips boiler. The Swiss electricity mix (including electricity trade) is shown for indicative purposes only. If it is combined with a gas boiler, lower environmental external costs result in the medium and high $CO_2$-scenario compared to the CHP system.

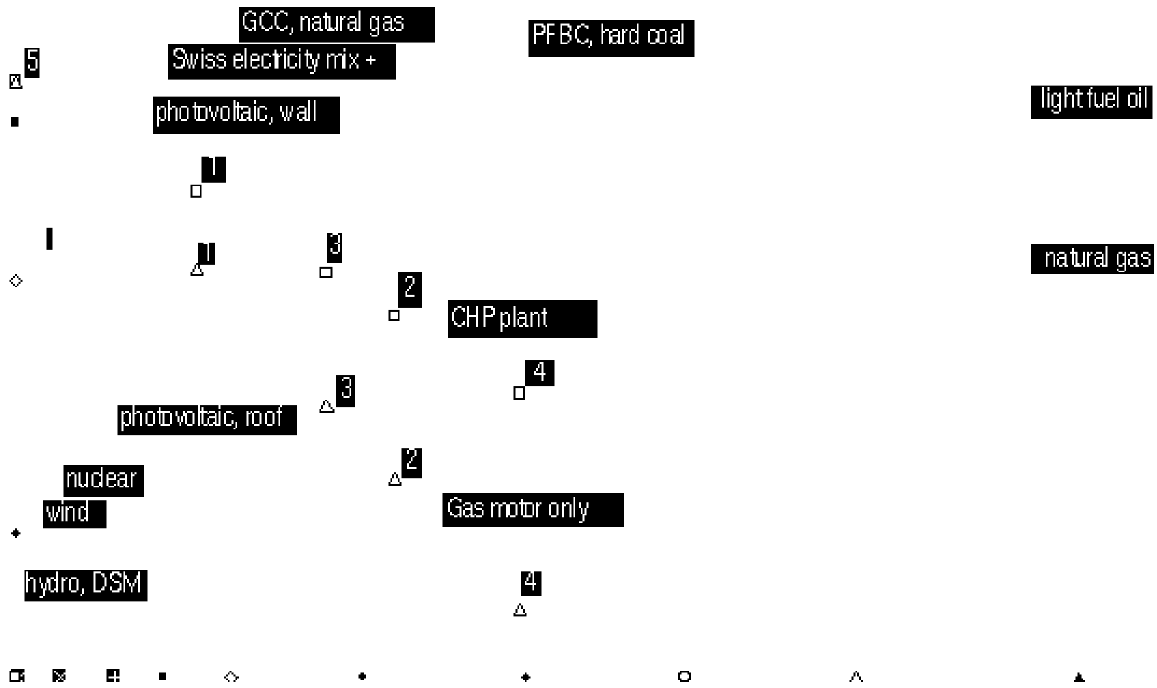


Fig. 10.7: Specific environmental external costs determined on the basis of a high $CO_2$-scenario and a variable allocation factor for a natural gas spark ignition engine CHP plant (including heat pump and with and without peak load boilers) and various competing energy systems. The numbers close to the CHP curve correspond to the five allocation parameters introduced in Tab. 10.12.
Swiss electricity mix +: Electricity mix including trade, see Subchapter 9.2 for more details.

In Fig. 10.7 the influence of the light fuel oil peak load boilers and the heat pump within the CHP system is shown in addition (the line "Gas motor only"). The peak load boilers, which generate about 40% of the total heat delivered by the CHP system to the district heating network, increases the environmental external costs of the CHP system substantially. Its influence is larger the more environmental impacts are allocated to the jointly produced electricity (allocation parameters Nr. 3, 2, and 4, "relative sales value", "exergy content", and "motivation electricity"). The heat and electricity produced with the spark ignition engine show a similar environmental performance like electricity generated with the gas-fired GCC power plant and heat from the natural gas boiler. It indicates, that an efficiency gain in terms of emissions compared to other fossil fuel technologies is mainly due to a switch in fuel (from coal and oil to gas) and not so much due to the joint production. Baehr et al. have answered the question, whether a reduction in $CO_2$-emissions is due to either the technology applied (CHP plants) or the energy carrier used, in a similar way:

> Not the energy savings due to CHP plants play the dominant role [for the reduction in $CO_2$-emissions] but the substitution of energy carriers caused by CHP plants.[10]

[10] Baehr et al. (1995, p.469), (originally in German: *"Nicht die durch KWK [Kraftwärmekopplung] erzielte Energieeinsparung spielt die Hauptrolle [bezüglich Minderung der $CO_2$-Emissionen], sondern die durch KWK bewirkte Substitution von Energieträgern."*)

### 10.4.5 Summary and Conclusions

In this subchapter it has been shown that the environmental competitiveness of CHP plants is very much dependent on the damage costs assumed for greenhouse gases, and on the competing technologies[11]. The CHP plant with a gas-fired spark ignition engine and peak load oil boilers shows to be competitive in terms of environmental external costs (as defined in Chapter 8) in comparison with condensing oil boilers in combination with lignite, heavy fuel oil, hard coal, and nuclear power plants. When assuming high damage costs related to greenhouse gas emissions (high $CO_2$-scenario), the wood chips boiler becomes competitive if combined with any electricity generating technology except lignite, and heavy fuel oil.

If the installed electricity generating capacity of CHP plants and its electricity production rises steeper than the electricity demand, CHP plants may be used to displace power plants in operation. In this case, it would be best in terms of environmental improvements to shut down fossil ones (heavy fuel oil, lignite and hard coal)[12].

The "avoided burden"-approach may lead to negative environmental external costs (environmental benefits). This effect mirrors situations where a change from, e.g., a conventional light fuel oil boiler to a gas-fueled CHP plant is made and the electricity generation in a conventional thermal power plant is displaced and *vice versa*. When a CHP system is in operation, this approach represents a fictive scenario which shows the effects that *would* occur *if*, e.g., the heat *were* produced with a conventional light fuel oil boiler. It shows the environmental inopportunity escaped for one of the joint products. But with this approach, the second joint product generated in the CHP plant system, i.e., electricity, necessarily shows the same environmental performance like the technology displaced, for instance, the average German lignite or French nuclear power plant.

Furthermore, the "avoided burden"-approach may be interpreted as one special case of allocation, where the allocation factors are not determined directly, but by chosing adequate technologies that are or would be displaced. With this procedure, negative environmental external costs may result, which is represented by negative allocation factors for one joint product, and allocation factors above 1 for the other one. The line in heavy type showing possible combinations of environmental external costs for heat and electricity in Fig. 10.5 to 10.7 would then be lengthened to the left (e.g., displacing a light fuel oil boiler) and to the right (displacing a lignite power plant) as indicated in Fig. 10.4. Allocation factors above one (and consequently below zero) may be interpreted as subsidising one product (the one where negative factors are applied) by the other one. It may be motivated by one joint product's ability to bear more environmental impacts than would be allocated to it with an allocation factor equal to 1.

The allocation of environmental impacts only tells one part of the whole story. Based on Hypothesis 2 that firms optimise their activities based on social costs, joint product allocation shall also be performed based on social cost parameters. That is why, the next subchapter deals with the concept of "enviro-economic competitiveness" and "fairness", respectively. It is examined, whether the allo-

[11] Furthermore, the conclusions are influenced by other boundary conditions which could not be considered in our general comparison, mainly because they are highly case specific. Questions about the concrete energy demand and its course in time, about the requirements in relation to the district heating grid, the situation with regard to the gas distribution grid (already available or not) as well as the availability and the degree of determinability of the electricity production are left out in our considerations.

[12] Always under the premise that one follows the weighting scheme derived and described in Chapter 8.

cation factors will change and whether the conclusions to be drawn will change when using social costs as an allocation parameter.

## 10.5 Context-specific Allocation

### 10.5.1 Introduction

So far, we have focused on the allocation problem only considering environmental aspects of competing technologies. Now, information about private *and* environmental external costs will be combined. For that purpose, the private cost data derived in Appendix 3 and the environmental external costs determined in the last subchapter are used. In the following sections, results are presented for the case with one decision-maker producing for competitive markets ("enviro-economic competitiveness") and for the case where two decision-makers may join for a voluntary coalition ("enviro-economic fairness"). The case with one decision-maker producing in imperfect markets where the price-output optimum is to be determined, is not treated here because of lack of adequate data (particularly about the demand functions).

### 10.5.2 The "Enviro-Economic Competitiveness"-Approach

For the discussion of the allocation problem in relation to electricity and heat produced in a CHP plant, only some of the scenario (interest rate, environmental exchange rate, $CO_2$ damage costs) defined earlier are chosen. The private costs of the alternatives discussed here are calculated based on an interest rate of 5%, and the environmental exchange rate is assumed to be 1 and 2, respectively[13]. Furthermore the two extreme $CO_2$-scenario (low and high) are considered. Let us start with the low $CO_2$-scenario and an environmental exchange rate of 1 (see Fig. 10.8).

Due to the inclusion of environmental external costs, the small spectrum of private costs of traditional thermal power plants (between 0.17 and 0.20SFr. per $kWh_e$, see Fig. A3.1) is spreaded markedly. Two groups may be identified. On the one hand, the fossil power plants not (yet) equipped with flue gas treatment facilities (i.e., heavy fuel oil and lignite power plant) with social costs of more than 0.35SFr. per $kWh_e$, and, on the other hand, natural gas, hard coal and nuclear power plants with social costs between 0.18 and 0.23SFr. per $kWh_e$. Due to the higher costs of peak load electricity, and - to a minor extent - due to a small share of fossil power plants in the Swiss electricity mix[14], the average social costs of the electricity mix are higher than the costs for nuclear power and hydroelectric run of river power plants. On the side of boilers, the sequence and the relations between fossil and renewable options remains about the same as with private costs only. The gas boiler gets slightly cheaper than the oil boiler.

The specific environmental external costs of the heating systems are much lower than the environmental external costs for some of the electricity generating systems. This is mainly due to better fuel properties (e.g., low sulphur and trace element content) and improved burning technologies. Summing up, the joint products from the CHP plant show a better or equal enviro-economic performance compared to its respective competitors considered here, except the energy saving measure and the run of river hydro power plant (see Fig. 10.8).

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[13] 1SFr. environmental external costs is valued 1 and 2SFr. private costs, respectively.
[14] Including a share of foreign fossil power plants (German and French ones).

The picture changes when the environmental external costs are weighted twice compared to the private costs (see Fig. 10.9). Now the natural gas boiler combined with the gas-fired gas combined cycle (GCC) power plant show equal social costs for heat and electricity compared to the CHP system. The same specific costs for heat and electricity are obtained with allocation parameter Nr. 3 ("relative sales value"). The oil and the wood chips boiler combined with any electricity generating technology are still more expensive than the CHP plant. Some technologies which today are expensive in terms of private costs (e.g. wind power with about 0.47SFr. per $kWh_e$) come close to existing technologies that are competitive in today's economy (i.e., heavy fuel oil, lignite). But with social costs of between 0.48 and 0.56SFr. per $kWh_e$, these technologies would not be competitive in a social costs sense.

In the case of a high $CO_2$-scenario, and an environmental exchange rate of 1 (see Fig. 10.10), the picture changes in relation to the competitiveness of the CHP plant with other heating systems. The ranking between the three heating systems remains the same although the difference between them is now smaller. Some other changes are observable in relation to the electricity generating systems. The social costs of the average natural gas power plant are now higher compared to the social costs of nuclear power. The competitiveness of CHP plants, however, is still about the same. Lower social costs for heat and electricity result for the CHP system compared to all heating systems and all electricity generating options, except the hydroelectric run of river and nuclear power plant combined with a gas boiler. For an environmental exchange rate of 1 and 2 (see Fig. 10.10 and 10.11), the natural gas-fired GCC plant and the gas boiler show similar costs for electricity and heat like the CHP plant[15]. In all cases discussed here, the lowest costs per unit electricity are achieved by saving electricity with an energy saving bulb replacing an incandescent one.

From low to high $CO_2$-damage cost scenario as well as from low to high environmental exchange rate, the environmental performance of the CHP system impairs compared to non-fossil electricity generating technologies in combination with wood chips and natural gas boilers. This is mainly due to the relatively inferior environmental performance of the light fuel oil peak load boilers used within the CHP system. The use of gas-fired peak-load boilers might substantially improve the environmental performance and with that reduce the specific social costs of CHP heat and electricity (see also Fig. 10.7).

[15] Applying an allocation factor slightly below the one of the allocation parameter Nr. 3, "relative sales value".

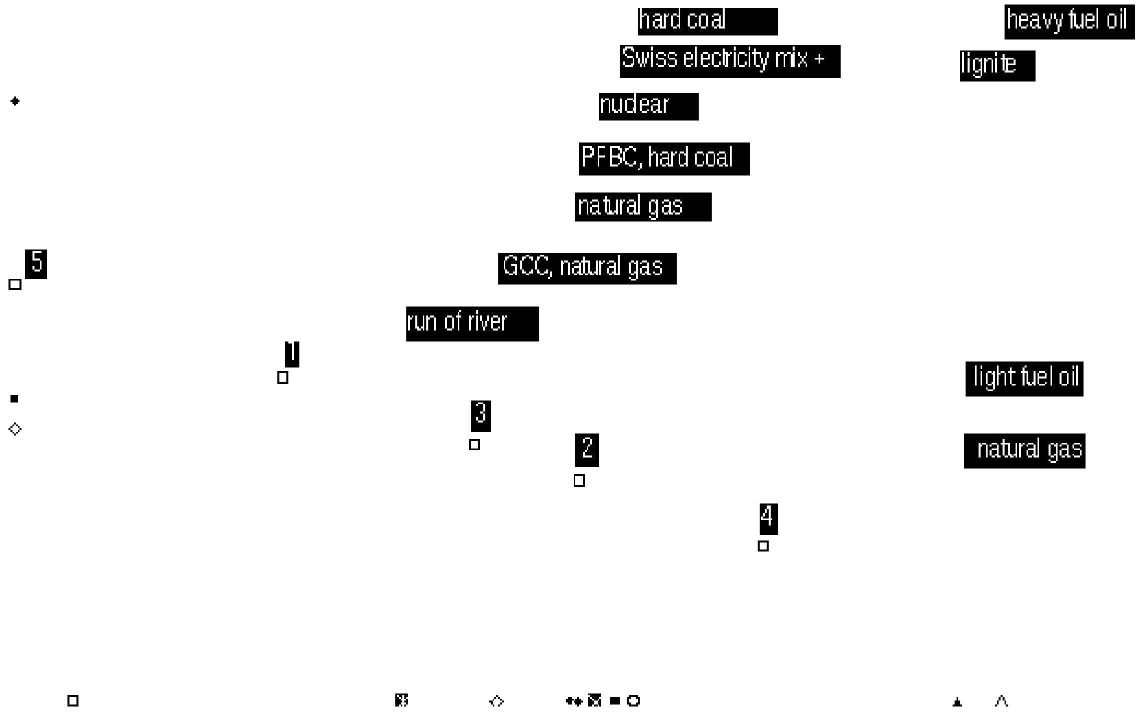


Fig. 10.8: Specific social costs determined on the basis of a low $CO_2$-scenario, an environmental exchange rate of 1 and a variable allocation factor for a gas spark ignition engine CHP plant (including heat pump and peak load boilers) and various competing energy systems. The numbers close to the CHP curve correspond to the five allocation parameters introduced in Tab. 10.12.
Swiss electricity mix +: Electricity mix including trade, see Subchapter 9.2 for more details.

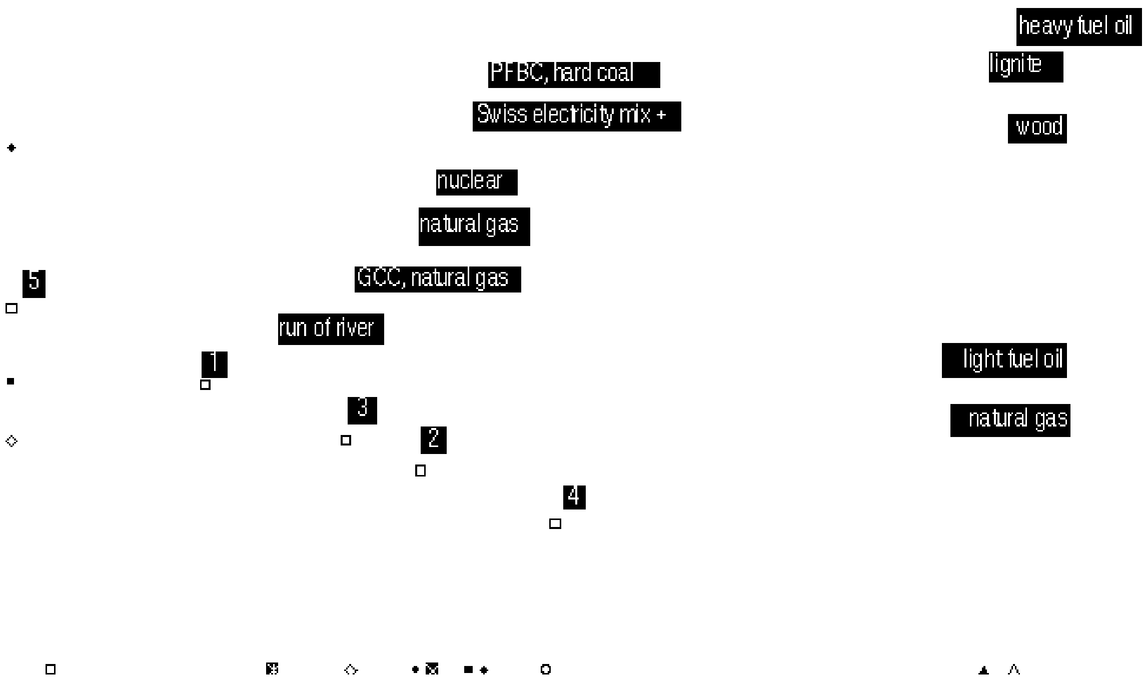


Fig. 10.9: Specific social costs determined on the basis of a low $CO_2$-scenario, an environmental exchange rate of 2 and a variable allocation factor for a gas spark ignition engine CHP plant (including heat pump and peak load boilers) and various competing energy systems. The numbers close to the CHP curve correspond to the five allocation parameters introduced in Tab. 10.12.
Swiss electricity mix +: Electricity mix including trade, see Subchapter 9.2 for more details.

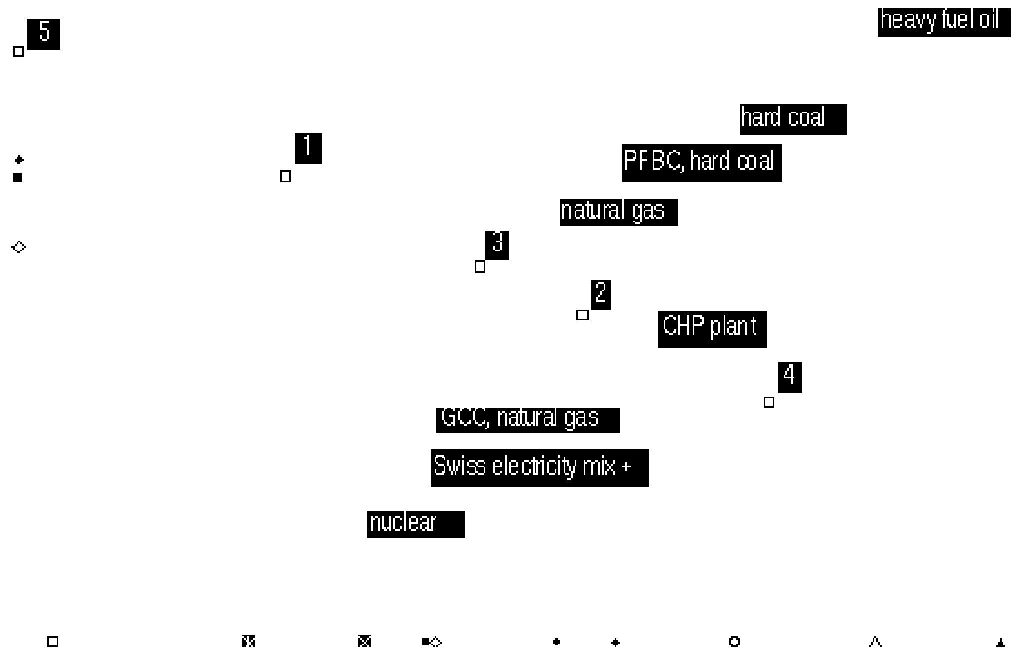


Fig. 10.10: Specific social costs determined on the basis of a high $CO_2$-scenario, an environmental exchange rate of 1 and a variable allocation factor for a gas spark ignition engine CHP plant (including heat pump and peak load boilers) and various competing energy systems. The numbers close to the CHP curve correspond to the five allocation parameters introduced in Tab. 10.12.
Swiss electricity mix +: Electricity mix including trade, see Subchapter 9.2 for more details.

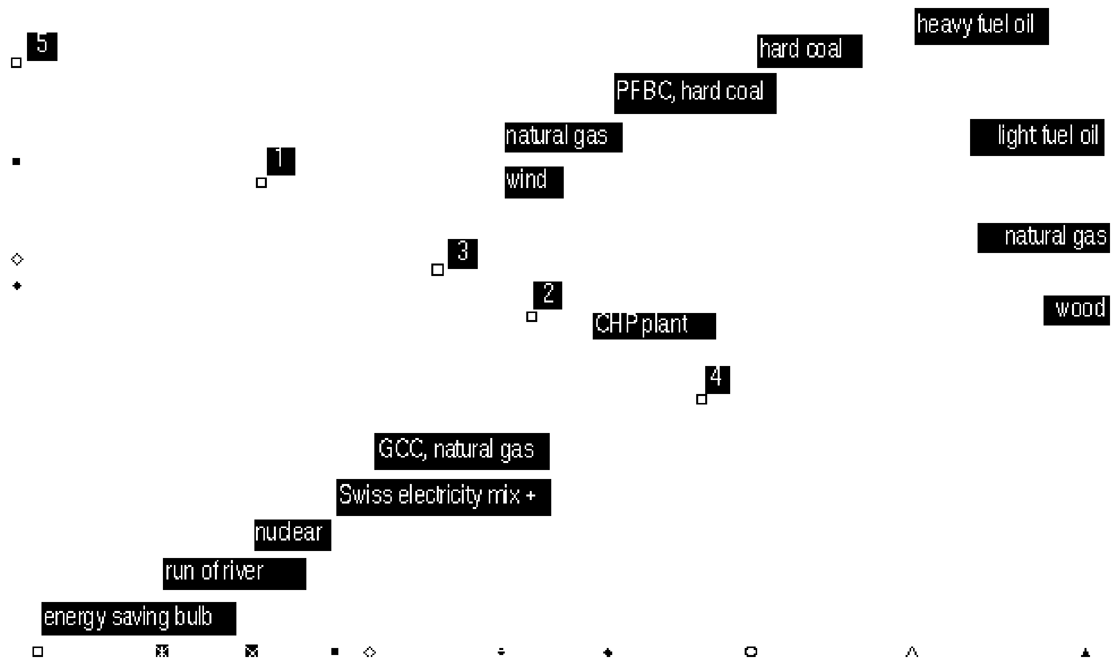


Fig. 10.11: Specific social costs determined on the basis of a high $CO_2$-scenario, an environmental exchange rate of 2 and a variable allocation factor for a gas spark ignition engine CHP plant (including heat pump and peak load boilers) and various competing energy systems. The numbers close to the CHP curve correspond to the five allocation parameters introduced in Tab. 10.12.
Swiss electricity mix +: Electricity mix including trade, see Subchapter 9.2 for more details.

We will now examine how the maximum and minimum allocation factors change dependent on the various parameters (private, environmental external, and social costs). The relevant competing technologies are the marginal ones which would enter or leave the market. We assume that the decision to be made with the help of LCA data is the choice of how to provide heating energy, either by replacing an existing, written-off system (i.e., covering an existing demand) or by an additional installation (i.e., covering an additional demand). Furthermore, we assume that the overall demand for electricity is *constant* and that electricity additionally produced with a CHP system would displace existing capacity. Depending on the disutility function which we assume to be identical with the allocation parameter, the marginal technology differs. Considering private costs only, the most expensive, existing technology is nuclear power (see Fig. A3.1). Looking at environmental external and social costs, the most "expensive" existing technologies are the average Italian heavy fuel oil and the average German lignite power plant, respectively, depending on the $CO_2$-damage scenario. All heating systems described in Subchapter 10.3 (natural gas and light fuel oil condensing boilers, as well as wood chips boiler) are available as competing technologies. These technologies provide the framework within which feasable allocation factors may be determined. First the private cost case will be treated (see also Fig. A3.1 in Appendix 3).

Here, the allocation factor for electricity should be below 0.77[16] for the costs of CHP electricity to be below the private costs of electricity from nuclear power, and above 0.56[17], 0.49[18], and 0 (-0.64)[19] for the costs of CHP heat to be below the specific private costs of the light fuel oil, the natural gas, and the wood chips boiler, respectively. The CHP plant is therefore more competitive compared to any of the combinations considered here. The allocation factors may be varied between 0.56 and 0.77 to be below the private costs for both heat and electricity compared to the combination of nuclear power and a light fuel oil boiler, between 0.49 and 0.77 to be below the private costs for heat from a natural gas boiler and for electricity from a nuclear power plant, and between 0 and 0.77 for the wood chips boiler option. Nevertheless, it is difficult for CHP plants today to be economically competitive compared to conventional solutions based on natural gas or light fuel oil boilers. One reason is that utilities pay less for electricity delivered to the grid by the CHP plant compared to the average Swiss electricity wintertime tariff for private clients (about 0.12SFr. per $kWh_e$ in winter time compared to an average of 0.187SFr. per $kWh_e$ see Appendix 3). How allocation factors change when environmental external costs are used as the guiding quantity is shown in the next paragraph (cf. Fig. 10.5 to 10.7).

Based on the low $CO_2$-scenario, the environmental external costs for heat generated with the CHP system are in any case, i.e., for any allocation factor between 0 and 1, higher than the ones for heat produced with the natural gas boiler option. But because the environmental external costs for electricity produced in the marginal power plant (average German lignite power plant) are that high, an "overcosting" of the electricity may be accepted. For that purpose, the allocation factor for electricity is set higher than one (about 1.35) and the one for heat gets negative (-0.35). The negative figure means, that the CHP heat production is subsidised by the electricity production. Compared to

16 $\frac{1-0}{0.260-0.0}\cdot(0.0201-0.0)=0.77$, see Appendix 3 and equation (7.6) in Section 7.5.1.

17 $\frac{1-0}{0.089-0.030}\cdot(0.056-0.030)=0.44$, dito.

18 $\frac{1-0}{0.089-0.030}\cdot(0.060-0.030)=0.51$, dito.

19 $\frac{1-0}{0.089-0.030}\cdot(0.127-0.030)=1.64$, dito.

competing technologies, electricity from the CHP system has a high "ability to bear" environmental external costs. Opposite to that, the heat from the CHP plant is able to bear only little environmental external costs because of its relatively environmentally benign competing technology, the natural gas boiler. The other two competing heating systems show higher environmental external costs so that the allocation factors may be varied unrestrictedly between 0 and 1. Based on the medium $CO_2$-scenario, the allocation factors for electricity may be chosen between 0.86 and 1 (or more), 0.56 and 1 (or more) and between 0 (even -0.18) and 1 (or more), if compared to natural gas, wood chips and light fuel oil boilers, respectively. Based on the high $CO_2$-scenario, the spread of the allocation factor for electricity is 0.86 and 1 (or more), 0.54 and 1 (or more), and between 0 (even -0.19) and 1 (or more) for the same boilers. Again, the environmental costs of the lignite power plant are much higher. This technology does not pose any real restrictions on the allocation factors for the CHP plant.

In the last step, private and external costs are combined to see how such a combination influences the possibilities to chose the allocation factor in competition with the heating systems and the marginal power plants mentioned above (see Fig. 10.8 to 10.11). The upper limits for the allocation factor for electricity are 1.32 and 1.84, for the low $CO_2$-scenario and an exchange rate of 1 and 2, respectively. Hereby, the heavy fuel oil power plant is the most expensive one. For the high $CO_2$-scenario and an environmental exchange rate of 1 and 2, the upper limit for the allocation factor for electricity are 1.31 and 1.56 respectively, with the lignite power plant as the most expensive one. The lower limit for the allocation factor is given by the natural gas boiler. The values are, in the same sequence as before: 0.55, 0.61, 0.55, and 0.58. Compared to the private cost allocation parameter, the upwards range within which the allocation factor may be chosen is wider (between about 0.55 and more than 1 compared to 0.49 and 0.77 in the private cost case). Compared to the environmental external cost allocation parameter, on the other side, the range of the social costs allocation parameter is cut off at lower lower limits (0.55 to 0.61 compared to about 0.86 and more). But similar to the environmental external cost case, allocation factors above 1 may be chosen for the social costs case with the effect that CHP electricity "subsidises" CHP heat.

### 10.5.3The "Enviro-Economic Fairness"-Approach

The concept of "enviro-economic fairness" may be applied in cases where voluntary coalitions are formed. In this case, negotiations will lead to allocation factors satisfactory to all parties to the respective deal. CHP plants may be used to generate energy for two (or more) distinct decision units. This case will be analysed in this section. It is supposed that one division of the company needs electricity and the other one needs heat. The two divisions want to negotiate about a joint production option. The demand patterns of the two divisions have been simplified in order to be able to concentrate on the relevant aspects. For the two parties A and B, three options exist for which the following technologies are feasible (for heating systems) and required (average Swiss electricity mix and marginal technologies for electricity production). The incremental social costs for the coalition vary between SFr. 30'000.- for the combination of natural gas boiler and nuclear power plant to SFr. 290'000.- for the combination of wood chips boiler and the average heavy fuel oil power plant (see Tab. 10.15).

| | Unit | {A} | {B} | {A,B} |
|---|---|---|---|---|
| *Energy demand:* | | | | |
| Heating energy | MWh/a | 0 | 2'250 | 2'250 |
| Electricity | MWh/a | 500 | 0 | 500 |
| *Technology options:* | | | | |
| Light fuel oil boiler | SFr./a | - | 168'000 | - |
| Natural gas boiler | SFr./a | - | 151'000 | - |
| Wood chips boiler | SFr./a | - | 334'000 | - |
| Swiss electricity mix + [1]) | SFr./a | 113'000 | - | - |
| Lignite power plant | SFr./a | 178'000 | - | - |
| Heavy fuel oil power plant | SFr./a | 186'000 | - | - |
| Nuclear power plant | SFr./a | 109'000 | - | - |
| CHP plant incl. peak load boilers | SFr./a | - | - | 229'000 |

Tab. 10.15: Heating energy and electricity demand of the two parties, and social costs (based on the low $CO_2$-scenario and an environmental exchange rate of 1) for different technological options.
[1]): Average of the years 1990-1994, including electricity trade.

Let us therefore assume that in our case, the alternative option consists of electricity being produced in the average Italian heavy fuel oil power plant (the marginal technology) and the heat being provided by a condensing natural gas boiler. Hence, the social costs saved by forming a coalition amount to SFr. 108'000.- which will be attributed equally among the two partners. The social costs allocated to the two divisions are reduced to SFr. 132'000.- per year for division A, and SFr. 97'000.- per year for division B[20].

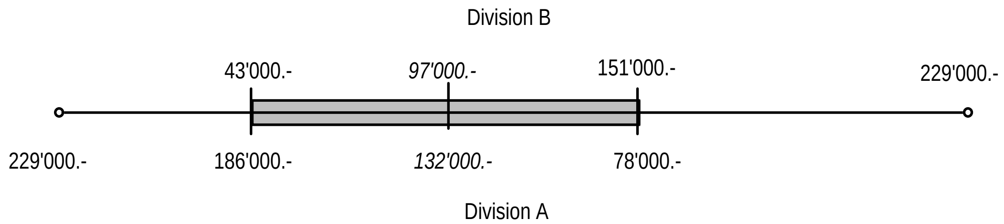


Fig. 10.12: The core (shaded) of the social cost function for the coalition of two divisions to jointly produce electricity and heat. The cost figures are in SFr. per year and based on the demand listed in Tab. 10.15, a low $CO_2$-scenario and an environmental exchange rate of 1.
The technologies are: natural gas condensing boiler for heat, average Italian heavy fuel oil power plant for electricity production, and a gas spark ignition engine CHP plant including light fuel oil peak load oil boilers for joint production of heat and electricity.

The specific social costs for electricity and heat for the "fair" allocation situation amount to 0.26SFr. per $kWh_e$, and 0.043SFr. per $kWh_{th}$. How the profits have been shared between the coalition partners may as well be seen in Fig. 10.13, which shows the same situation as Fig. 10.8. The vertical and horizontal arrow indicate the social costs saved. At the point "x" on the "CHP-plant" line, the "fair" allocation factor for electricity amounts to about 0.93, whereas the range of the allocation factor for electricity resulting in lower or equal social costs for both electricity and heat varies between 0.55 and 1.26.

[20] 229'000-151'000+108'000/2=132'000; 229'000-186'000+108'000/2=97'000. See Appendix 1 for the mathematical derivation.

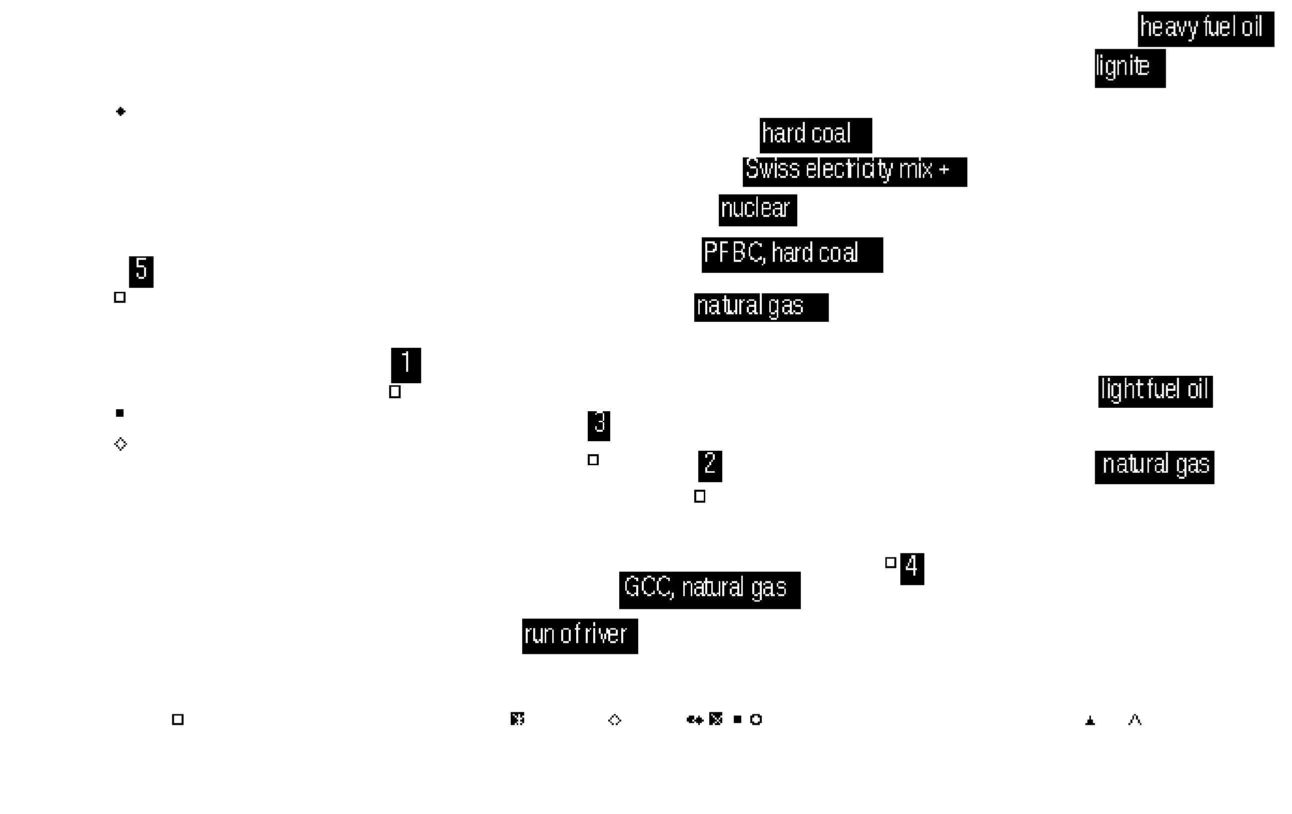


Fig. 10.13: Social cost reductions for the firm's division A (horizontal arrow) and the firm's division B (vertical arrow) based on the game theory solution shown in Fig. 10.12 (here point "X"). Social costs are determined based on a low $CO_2$-scenario and an environmental exchange rate of 1.

Compared to an "avoided burden"-approach, where the stand alone costs of the coalition partner would be subtracted from the total costs of the joint production option, the social costs of the enviro-economic fairness approach are higher by about 70% for division A, and by more than 125% for division B[21]. If however, division A would apply its lowest possible social costs (78'000.-), division B would encounter the social costs of the stand alone option and *vice versa*. The division that still has to face its stand alone social costs would in this case see no profit and therefore no motivation in forming a coalition.

## 10.6Conclusions

In this chapter, co-generation of heat and power in small-size standardised units (CHP systems) has been analysed with a focus on allocation aspects. Hereby, the CHP plant has been considered as a purely joint process. The CHP system and some competing systems have been described and compared on the basis of private, environmental external and social costs.

First, the "avoided burden"-approach has been applied on the environmental external costs. It has been shown that in some cases negative environmental external costs (i.e., environmental benefits) for electricity or heat may occur. But in all these cases the environmental performance of the other jointly produced good (heat and electricity, respectively) equals the environmental performance of the technology displaced. Furthermore, negative figures may also be achieved by chosing an allocation factor below zero, and above one, respectively. Hence, the "avoided burden"-approach is

[21] 229'000-151'000=78'000 compared to 133'000 for division A, and 229'000-186'000=43'000 compared to 98'000 for division B.

only one special case of pure allocation in cases where the disutility function is uni-dimensional (e.g., private costs, environmental external costs and social costs).

Second, the second and third step of the ISO procedure has been applied on environmental external costs. Five pairs of arbitrary (i.e., not generally defensible) allocation factors have been applied which show the entire spread of solutions. The CHP system proves not to be competitive compared to some of the heating systems considered. On the other side, its environmental performance is much better compared to average, existing fossil fueled power plants. Hence, allocation factors above 1 for electricity and accordingly below zero for the heat produced lead to results where the environmental external costs for both CHP heat and CHP electricity are below the values of their competing technologies.

Third, the position specific allocation has been applied using the principle of "enviro-economic competitiveness" and "fairness", respectively. The competitiveness of the CHP system has been compared with various heat and electricity generating systems. It proves to be about equal compared to gas boilers in combination with a hydroelectric run of river and natural gas gas combined cycle (GCC) power plant. Compared to existing fossil power plants, the CHP system is in most cases competitive independent from the heating system these power plants are combined with.

The change in competitiveness between the three options private, environmental external and social costs shows the following particularities. While heating systems show relatively high specific private costs compared to the environmental external costs, certain power plants show environmental external costs that are higher by a factor of two and more compared to private costs. That is why the social costs of power plants are influenced more by their environmental performance whereas heating systems are more dominated by their (traditional) economic performance. The clear advantage of CHP systems in terms of environmental external costs compared to heavy fuel oil, lignite and hard coal power plants is reduced when private costs are included. Due to the relatively similar environmental performance of the CHP system compared to the oil or gas boilers[22], this effect is much smaller in relation to heating systems. In general, the inclusion of environmental external costs in the consideration about the investment in a CHP system increases its competitiveness at least if compared with marginal electricity generating technologies. The benefit, however, lies more in a change of the energy carrier (from oil and coal to gas) than in the joint production of heat and electricity. Higher damage costs for global warming impair the enviro-economic competitiveness of CHP heat compared to heat from natural gas and wood chips boilers, whereas it leads to an improvement compared to heat from light fuel oil boilers.

Forth, a coalition situation has been used to show the determination of a "just" allocation factor to give equal benefits for the parties involved ("enviro-economic fairness"). It is the opposite case to the "avoided burden"-approach where benefits are allocated to just one of the two joint products, sometimes in view of a benefit as high as possible. Similar to the "enviro-economic competitiveness"-approach, where an investment is only made if the costs are below the ones of alternative options, coalitions only take place if a core exists, i.e., if both parties can make profit of a joint production situation.

The concept of social costs proves to be manageable and useful for allocation decisions in cases where environmental issues should be considered. The benefit of the concept lies in the aggregated

[22] The peak load light fuel oil boiler substantially influence the environmental performance of the CHP system (see Section 10.4.4).

consideration of private costs and environmental performance. It emphasizes the main purpose of allocation, namely, the identification of competitive production options. Because of a full aggregating concept, the "avoided burden"-approach may here be interpreted as just one possibility to determine the allocation factors. The case study underlines the procedure to choose allocation factors according to the competitiveness (or "ability to bear") of the jointly produced outputs and not so much acording to an arbitrary allocation parameter such as "energy" or "exergy". Where competing technologies show much higher social costs (i.e., in electricity generation), more joint social costs of the CHP system may be allocated to the respective good (i.e., CHP electricity). By that the other joint product (i.e., CHP heat) gets competitive compared to technological options with low social costs. One major disadvantage of the concept introduced in Chapter 4 lies in the aggregation of uncertain figures, and especially in the fact that the uncertainties in private cost figures are - at least partly - very different in nature from the uncertainties in environmental external costs. The variation in the results is therefore assumed to be rather large and may lead to ranges that defy a definite ranking of some of the options shown here.

The following conclusions can be drawn from the CHP system case study:

- The inclusion of environmental external costs improves the competitiveness of the CHP system, predominantly due to the worse environmental performance of marginal existing electricity generating technologies.
- The uncertainty in $CO_2$-damage costs strongly influences the enviro-economic competitiveness of CHP plants. Furthermore, the particularities of concrete projects will substantially influence their competitiveness.
- The use of gas-fired peak-load boilers instead of oil boilers would improve the environmental performance and therefore lower the social costs of the CHP system.
- Compared to the proceeds received when selling electricity to the utility (average redelivery tariff), the profitability of the CHP system is critical. In this case, internalising environmental externalities would improve the competitiveness of the CHP system.
- The "avoided burden"-approach may lead to negative environmental external costs, i.e. environmental benefits for one of the joint products (subsidising effect). However, the second joint product shows the same environmental performance as if produced by the technology displaced.
- Coalitions are only attractive if all parties may profit from the joint production situation. Hence, the necessary condition is the same as for an investment decision, where the joint production must be profitable compared to a combination of single production options.
- The variation in load factors, interest rates, life time, and costs of energy carriers show a large influence on the private and the social costs of energy systems. A similar range in uncertainty is to be expected in the determination of environmental external costs. This has to be kept in mind when interpreting the figures presented in this chapter.

# PART IV:

# CONCLUSIONS

# 11.Hypotheses Revisited and Conclusions

## 11.1The Issues

This *Ph.D.*-thesis deals with the set-up of system models capable of representing changes within the economic system. For that purpose, three hypotheses concerning the representation of economic processes in Life Cycle Inventory Analysis have been introduced in Chapter 1. Hypothesis 1 deals with the principle of how to set up a Life Cycle Inventory system model. Hypothesis 2 deals with the principle how the decisions of firms relevant for the Life Cycle Inventory Analysis, i.e., default decisions[1] about the choice of a technique and particular value choices in joint product allocation, can be represented. Hypothesis 3 concerns the principle of how to represent changes occuring within the economic system. Based on these hypotheses, the following aspects have been treated:

- *Modelling principle:* The principle how economic processes are connected to form a process network delivering a good or service has been introduced in Chapter 3. Hereby it has been discussed whether economic or physical information should be used to establish the relation between single economic processes.
- *Disutility function:* A disutility function which amalgamates environmental information with private costs has been introduced in Chapter 4. This "social costs"-parameter helps to reduce inconsistencies encountered in the system model and tries, although in a rough way, to represent decisions in relation to default choices of a technique, that are made all over the process network.
- *Scope-dependent system models:* Three time horizons for decisions, namely short-, long-, and very long-term, have been discerned in Chapter 5 in view of distinct Life Cycle Inventory system models. In relation to this, questions about the inclusion of capital equipment (short-, and long-term decisions), about the choice of a technique based on the disutility function developed in Chapter 4 (long-term decisions), and about the need for quasi-dynamic analyses (very long-term decisions) are treated.
- *Salaries, taxes and subsidies:* The constantly recurrent question about the environmental relevance of private consumption in LCA has been treated in Chapter 6. Furthermore, considerations about the inclusion of other activities induced by financial flows such as paid-out profits and subsidies have been made.
- *Context-specific joint product allocation:* Finally, the special case of allocation in fully joint production processes has been treated in Chapter 7. It is proposed to use the aggregate of private costs and environmental external costs (i.e., social costs) as the allocation parameter. Three allocation contexts are discerned. In the first and the second situation, only one single decision-maker is involved in the allocation decision. Hereby, the decision-maker (the firm) may produce for reasonably working and for monopolistic markets, respectively. In the former situation, no allocation is needed for making an investment decision. Allocation may nevertheless be useful for reporting to the authorities, environmental reporting or for environmental "transfer pricing"[2].

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[1] Such decisions are not explicitely known to the commissioner(s) of an LCA but are required for an adequate representation of changes in the economic system.

[2] Charging of flows of commercial and ecological commodities within the divisions of one single company or between different firms within a process network.

In the latter situation, the firm allocates social costs in order to optimise the price-output relation of the joint products. In the third situation, joint production is established on a voluntary basis between several decision-makers (e.g., firms or divisions within one firm). That is why, a consensus must be established concerning the allocation of private costs and environmental impacts. A game theoretic approach has been introduced as one possibility to model such negotiations.

- *Case studies:* Case studies from the power generating sector have been described in Part III. The impact assessment method Eco-indicator 95$^{RF}$ has been introduced in Chapter 8 and is applied on the case studies. Two distinct system models applied for the Swiss national electricity mix have been discussed in Chapter 9. The environmental performance of the models that consider electricity trade based on physical flows and economic information, respectively, have been evaluated. Furthermore, the choice of the electricity generating technology (or technology mix) that is put in or out of operation next in the Long Run has been modelled based on the "social cost"-parameter (disutility function). Thereby, the LCA analyst may vary the environmental exchange rate in order to adjust the minimum costs criterion according to the environmental policy of the countries where processes take place and decisions are to be anticipated. By that, empirical knowledge about decisions may be reflected accordingly in the process network. Joint product allocation and the effects of applying the "social cost"-parameter have been illustrated by means of the combined production of heat and power in a small-scale gas-fired spark ignition engine in Chapter 10. This case study is limited to the production for reasonably working markets and to a coalition situation.

## 11.2The Conclusions

### 11.2.1The Set-up of the System Model

In this thesis, Life Cycle Assessment is perceived as an instrument that helps to coherently complement economic information. It provides decision-makers with information about the environmental consequences, caused by the production or consumption of a certain good or service. This perception substantiates Hypothesis 1 to use economic information for setting up the inventory system model. Following this principle, all activities induced by money flows are *in principle* included, be it by the sale of goods and services, the purchase of working materials and energy, the payment of workers, the distribution of dividends, or subsidies received. Furthermore, the link between different actors (unit processes or firms) is established according to the "real", market- or contract-based relations. This guarantees that only actors are included which have to decide on actions to be taken (being important or nearly negligible for themselves) because of their involvement in the production of the good or service under analysis.

The Swiss national average electricity mix is used to illustrate the differences between a physically- and an economically-based system model. The electricity models show substantially different shares of power generating technologies depending on whether economic (contractual) or physical information is applied for the representation of the electricity trade. While physical flows not only reflect the situation of demand and supply but also of physical particularities of the electricity grid such as bottlenecks, contractual information allows to draw the system boundaries along the responsibilities of the utilities for the operation of power plants. The economic boundaries for the supply of electricity in Switzerland do not match with the Swiss national boundaries because some of the power plants operated in Switzerland produce for Italian and German utilities as well as some of the power plants in France, Austria and Germany, but also in the Czech Republic generate for Swiss utilities. While the difference in terms of individual pollutants and resources is rather large for the different electricity models, the difference in terms of environmental external costs is minor. Although Switzerland shows one of the largest shares in electricity trade in relation to its domestic production, the difference is below 10%, with the electricity mix based on contractual information showing higher values. Nevertheless, economically-based models should always be the first choice.

### 11.2.2The Disutility Function

A disutility function based on social costs has been introduced and applied in order to anticipate decisions made in the course of changes in the economic system. An environmental exchange rate is used to adjust the extent to which environmental issues influence the decision-making in a certain region (nation, continent). The disutility function is applied for

*a)* the default choice of a technique, and

*b)* joint product allocation.

*Ad a)* Due to a change in demand, firms need to adjust its production and, maybe, its economic relations. However, it is not possible to duplicate or predict the decisions of all economic processes and firms within the process network of the good under analysis. The hypothesis that such adjustments needed are guided by the objective to reduce private costs *and* environmental impacts, expressed in social costs, is partly confirmed in the example of the determination of marginal power plants. In practice, the choice of a technique is not only based on economic and ecological considerations. Political and legal conditions may play an equally important role. That is why technology mixes will occur in most cases (see also Section 11.2.5). A refinement of the disutility function is due.

*Ad b)* In joint production neither physical nor chemical causalities are available that might found the choice of a certain allocation parameter, not to speak of a particular allocation factor. The choice of the allocation parameter and factor can therefore be justified by the context within which allocation takes place. The choice of the "social costs"-parameter for allocation is derived epistemologically. The assumption that the decision-maker allocates based on "social" costs implies a situation where environmental aspects play a role in decision-making.

Both the determination of private and environmental external costs entail several uncertainties. Beside the investment costs and the energy costs, the capacity load, the life time, and the interest rate are the major sources of uncertainty of private cost figures[3]. The environmental external costs show uncertainties in connection with the monetisation of damages, with the relation between changes in immission concentrations and damages, with the number of people affected, with the relation between emissions and immission concentrations, *et cetera*. By adding them up to social costs, two sets of data with rather large and different uncertainties are further aggregated. Because of that, the results presented in the case studies need to be applied with care and adaptations to particular situations are indispensible.

However, it is not always necessary to aggregate economic and environmental information to one single indicator. The two main allocation concepts introduced ("enviro-economic competitiveness" and "enviro-economic fairness") may as well be performed on the basis of several, individual economic and environmental parameters. The default choice of a technique, however, needs to be made

[3] The interest rate is even more important for the determination of environmental external costs.

on the basis of an aggregated indicator, because the decision-making processes of numerous firms need to be anticipated by the LCA commissioner and the LCA analyst.

### 11.2.3The Short, Long, and Very Long Run System Model

The system model of a process network that is established in view of the production of a good or service is an omnium-gatherum of several hundred individual decision-makers. In general, one of them is the commissioner of the LCA at stake which means that for just one among hundreds the strategies and the decisions derived therefrom are well known[4]. The decisions made by all other decision-makers may either be ascertained by direct contacts, or need to be guessed, if the corresponding economic process is too remote. That is why assumptions and generalisations are used in order to anticipate decisions made in the course of changes in the economic system (see Section 11.2.2). The following conclusions can be drawn:

*Short Run system model:* In the short-term, the capital equipment used in the processes is fixed. Hence, capital equipment should not be included in an LCA of the Short Run type. Furthermore, continuous short-term optimisation of combined production[5] forms the basis for the determination of allocation factors useful for an LCA for documenting purposes (e.g., environmental report). The allocation factors may be determined by integrating past optimisations over a certain time period (e.g., one calendar year).

*Long Run system model:* In the long-term, all production factors are variable, the technical possibilities are fixed but may be choosen freely. Hence, investment decisions based on product and service comparisons are made based on a long-term perspective. The investment and the production phases should be recorded separately[6] and capital equipment should be considered in expanding and saturated markets only. In shrinking markets, capital equipment should be omitted as long as no replacement investments need to be made[7].

*Very Long Run system model:* In the very long-term, everything is variable. The technical possibilities may change dramatically either due to improvements of existing technologies or due to the invention of completely new methods of production. The predictive power of an LCA based on such a system model is very much dependent on the certainty in prediction of what will be at the end of the planning (and transition) period and not so much on the course how this future state is reached. Hence it suffices to perform a static analysis of the future state, where all important technical developments are considered.

### 11.2.4Private Consumption, Dividends and Taxes

In economic and LCA models, private consumption is usually perceived as the motivation, the final end of economic activities. That is why, private consumption is not allocated to the reproduction of labour. If private consumption were allocated completely to the reproduction of labour, the whole

[4] In LCAs for consumer choices and public policies, the decision-makers may even be completely outside of the process network.

[5] In combined production the relation between the intended outputs is variable.

[6] A separate recording facilitates the adjustment to changes in lifetime output of the capital equipment.

[7] This implies that the decrease in demand equals or surpasses the decrease in capacity available due to the putting out of operation of facilities which reached their life-time.

economic system would produce no physical output. The only "output" would then be, on a global perspective, "6 billion life-years lived" per year[8]. Whether the reproduction of labour may contribute substantially to the cumulative flows of ecological commodities of a certain product depends on the environmental performance of the processes involved and on the share of private consumption that is attributed to the reproduction of labour. In our examples, the contribution in terms of primary energy requirements varies between 1% for the energy sector and 100% for the banking sector[9]. The inclusion of the energy consumption caused by private consumption leads to reduced differences in the energy intensity of different products.

In recent years, the shareholder value of firms became more and more important. That is why, the question about the motivation of a firm's activities needs to be revisited. It is concluded that the two main aims of firms, namely, to satisfy both the shareholders and the purchasers of their goods and services, should be strictly separated. Paid-out profits may be interpreted as the functional unit of an LCA of investments. In this case, the goal of an LCA would be to identify the most environmentally benign way to invest money among different alternatives with comparable profits.

A last point investigated in Chapter 6 concerns subsidies received from and taxes paid to the authorities. They are considered as artificial products which implies that the flows of commercial and ecological commodities of a subsidised product need to be allocated between the goods and services sold and the subsidies received. Hence, the government's support does not only affect the economic but also the environmental situation of the subsidised firm. If subsidies are paid for unpaid services to the commons such as the conservation of rare ecosystems by farmers, the allocation of environmental impacts to the diverse functions fulfilled reflects these payments. On the other side, firms receive certain flows of ecological commodities by paying taxes because the authorities' activities such as health care, education, *et cetera*, and the corresponding environmental impacts are referred to their tax yield.

### 11.2.5 Case Studies

**Swiss National Electricity Model**

Among base-load electricity generating technologies, nuclear power shows to be the most expensive one in terms of private total costs. When environmental external costs are included, existing heavy fuel oil and lignite power plants without or with only minor flue gas treatment become the most expensive ones. The cheapest technologies are gas-fired small-scale CHP plants and gas-fired gas combined cycle power plants. Hard coal power plants (existing average as well as advanced technologies) show rather high environmental external costs which are predominantly due to upstream activities (such as mining and long distance transportation). Renewable energy systems, e.g., wind power or photovoltaics, show substantially lower environmental impacts compared to non-renewable technologies. However, the private costs of energy carriers oil, gas, coal and uranium are still too low (between 0.005 to 0.025SFr. per kWh) in order to give a chance for renewables to become economically competitive.

The UNIPEDE (1996) forecast on investments in European countries reflects a similar order of precedence for future electricity generating technologies for the European Union. Gas-fired power

[8] Or, from a more holistic point of view "1 year of world operation" per year.

[9] When 50% of the household's consumption is allocated to the reproduction of labour (assuming 1 worker per household).

plants contribute more than 60% to the additional electricity production predicted for 2010, which is about 80% of the additional fossil power production[10]. A first estimation of the environmental external costs of such a marginal technology mix shows that they are substantially lower compared to an average[11] UCPTE electricity mix.

However, if an overall decrease in electricity production were anticipated, expensive and environmentally worse power generating technologies would be put out of operation. Hence, the social costs of electricity would be worse compared to the marginal technology mix based on the UNIPEDE forecast and electricity applications would show a worse environmental performance. Goods whose LCA is dominated by electricity consumption would in that case loose their competitive advantage (e.g., heat pumps). Hence, two consistent but diverging models may be set up in the case of the electricity model. It is suggested to test forecasts about the development of the electricity demand on the basis of both assumptions (marginal technology with highest and lowest social costs, respectively).

**Joint Product Allocation in Small-scale Combined Heat and Power Plants**

The combined heat and power plant is compared with several single-function heat and power generating technologies on the basis of private, environmental external and social costs. The technology proves to be competitive compared to existing fossil and nuclear (low $CO_2$-damage costs scenario only) power plants combined with new heating systems. Thereby the competitiveness is improved by the inclusion of environmental aspects into the comparison (applying social instead of private costs). Gas-fired gas combined cycle (GCC) power plants combined with gas-fired boilers produce at about equal private *and* social costs. Therefore, small-scale combined heat and power plants are a valuable alternative for the displacement of old and expensive power plants or the installation of new electricity generating capacities.

Because joint product allocation does not depend on technical particularities of the corresponding process, the way how to allocate is not influenced by the time scope the decision-maker is confronted with. Be it a short-term, long-term or even a very long-term problem, the allocation *procedure* and the allocation *parameter* need not to change. The allocation *factors*, however, may of course vary from long-term to very long-term decisions due to changed boundary conditions such as new competing technologies expected in the far future.

[10] About 90% of the forecasted increase in electricity production within the European Union (including Norway and Switzerland) is due to an increase of the (direct and indirect) per capita consumption. Hence it is legitimate to apply the technology mix of the additional power generating capacity (the marginal technology mix).

[11] The UCPTE electricity mix used for this comparison considers the average electricity production during the years 1990-1994.

### 11.2.6 Summary

The main, generalizable conclusions may be summarised as follows:

The thesis shows that Hypothesis 1, namely to set up the LCI system model according to economic information, leads to a consistent and feasible methodology capable of representing changes within the economic system.

The methodology developed allows for a better representation of anticipated changes by considering marginal technologies (the technologies put in or out of operation next) compared to existing, merely descriptive approaches.

The disutility function introduced and applied for decisions and value choices in Inventory Analysis combines economic and environmental information. Tested on marginal power plants of a Long Run LCA, it proves to be accurate for the representation of default decisions (the choice of a technique required for all processes involved in a product system). However, refinements are needed in terms of quantifying environmental damages, in terms of its aggregation with private costs as well as in terms of including social aspects.

The context within which joint product allocation is performed (single or multiple decision-maker) proves to be a suitable discriminating criterion. It is able to consider conflicting value choices and we judge it to be superior to existing stepwise allocation procedures.

The thesis provides guidance for the choice of scope-dependent system models, and for the choice of context-specific joint product allocation procedures. Different generic LCI databases are required to represent the different scopes of an LCA relevant in decision-making. But in joint product allocation only one context exists for a particular multi-function process at a given point in time. Therefore, context-specific allocation leads to a single adequate set of allocation factors. According to the methodology presented in this thesis, the number of datasets required for decision-making is therefore limited to three, i.e., the Short, the Long and the Very Long Run system model.

## 11.3 Frequently Asked Questions

**What is the influence of the assumptions made on the outcome of this thesis?**

In Section 5.3.3 three assumptions have been introduced which are crucial for the set-up of the three system models used in decision-making with a short-, long-, and very long-term perspective, respectively. These assumptions help to structure the problems to cope with and to lay bare the main characteristics and consequences when trying to analyse changes. The outcome and conclusions drawn need to be interpreted in view of these assumptions. We do not claim that the results are a close picture of reality, but we hold that the system models developed in this thesis come closer to reality than existing models. However, there is no "moose test" available to prove the accuracy of the models developed in this thesis.

**Do firms decide as it is assumed in this thesis?**

In hypothesis 2 it is assumed that all firms involved in the production of a good decide based on economic *and* environmental information. Furthermore, the relative relevance of costs and environmental impacts is assumed to be the same for all processes within a certain political entity within a process network. Of course, the importance of decision criteria changes from one firm to the other because of their different social, economic, and legal environments. And other aspects such as support of jobs will be considered in real life decisions. However, the modelling of several hundred single decisions to be made in background processes about new investments or putting out of operation of old facilities requires a simplifying and mechanistic approach. A detailed representation of these decisions would be beyond the scope of any common LCA. The proposal made in this thesis shows how economic activities may develop (in terms of environmental impacts), if a (substantial) part of environmental externalities were included. On the other hand, environmental aspects prove to play a role in decision-making. The forecast report for the European electricity sector (UNIPEDE 1996), for instance, shows that environmental aspects influence the planning in the respective countries even without internalising environmental external costs. Hence, the simplifying disutility function used in this thesis is better justified compared to mere economic considerations[12].

**How realistic is the assumption that all firms decide with the same time horizon?**

In terms of calender time, the time horizon of short-, long- and very long-term decisions is highly variable from one industry to the other. In the production industry, for instance, the variability of technical possibilities is granted within a couple of years, whereas decades may be needed in the investment goods industries. The time horizon for a decision in the foreground system, e.g., a Long Run problem, may be either a Short Run or a Very Long Run problem for some of the firms involved in the process network. However, the main issues concern the inclusion or exclusion of the production of capital equipment as well as the definition of scenario for the technological development in the Very Long Run. Because new developments and its implementation of the most important infrastructures such as roads, railways and the energy generation take relatively long time, the question about corresponding very long-term scenario does not evolve with the comparative assertion of most consumer goods, a typical long-term LCA goal.

**Why introduce such complicated procedures for allocation when the economic parameters give accurate results?**

The proposal to use social costs instead of private costs to allocate environmental impacts to fully joint products is motivated by the assumption that the competitiveness of these goods is determined on the basis of social costs as well. Hence, competing products of joint product A may show a much better environmental performance than the joint product, whereas joint product B may be much worse compared to its competitors. Hence, the firm has to react on these circumstances by reducing the load allocated to product A and increasing the load allocated to product B. By that, the concept of the "ability to bear" is adapted to the firm's enlarged set of objectives. The game theory approach,

[12] The fact that the electricity sector is partly controlled by government may enhance the consideration of other than economic aspects.

which is a crude and limited model of human behaviour, is applied to allocation because (practically) no market yet exists for environmental externalities. Hence, the negotiations needed are modelled with such a makeshift solution. A similar procedure is applied for allocating joint private costs in selected situations such as the allocation of the costs for the erection of a dam to its several, mainly public functions (power generation, irrigation, drinking water supply, flood protection, and recreation).

**Do the marginal technologies determined with the procedure developed in this thesis match with "real" marginal technologies?**

In this thesis, marginal technologies are determined based on economic information. When one utility stops purchasing from one particular power plant to buy from another one, this will be represented in the LCI system model. However, it might be that no effect on the operation of the power plant left is observed in reality because another utility starts purchasing from the respective power plant. However, if the "real life" marginal technology would be considered irrespective of the actions taken by utilities, the incentives otherwise given by LCA would fall away.

**Is LCA the right instrument to reach a reduction in environmental impacts?**

From the answer given to the previous question it follows that LCA is a tool on a microeconomic level. Hence, environmental policy defines reduction targets for emissions, resource consumption or environmental impacts. LCA may then be used for the optimal allocation of such a new set of (environmental) resources while economics is used for the traditional ones, i.e., land, labour and capital. The main emphasis and pressure for an improvement of the state of the local, regional, and global environment should therefore be put on political negotiations about compulsory reduction targets.

**How many Life Cycle Inventory databases do we need when the approach developed in this thesis is followed?**

Theoretically, three main generic databases, i.e., the Short Run, the Long Run and the Very Long Run database, suffice. Because of national differences in environmental policies, the disutility functions used for modelling default choices of techniques need to be adjusted on a country-specific level. Therefore, several dozens of different disutility functions (i.e., environmental exchange rates) may be applied within each of the three databases. The allocation in joint production is made by the corresponding firm(s) in a particular context. Hence, only one accurate set of allocation factors for joint products exists per multi-function process. This results in one single LCI valid for a product traded within a certain market and a certain time period per generic database with a specific time scope (i.e., Short, Long and Very Long Run).

**Do the social costs developed in this thesis tell the whole truth?**

In this thesis, environmental external costs are determined on the basis of new knowledge about damages to human beings and nature as well as on information from the LCA weighting method Eco-indicator 95. This procedure entails the following deficiencies: First, different methodologies are mixed which may lead to inconsistent valuation of different environmental damages. Second, resource depletion aspects, i.e., mineral resource as well as non-renewable energy resource depletion, and immediate ecosystem degradation (land use aspects) are not considered. Third, "known" effects, effects for which environmental external effects have been determined (e.g., health effects due to particulates, or tropospheric ozone creation) are only one part of the variety of potential total effects. However, the effects of primary and secondary particulates show a large influence on the outcome. Forth, damages to nature and human beings caused by severe accidents as well as occupational effects are excluded. This list of deficiencies implies that environmental external costs shown in this thesis should be considered as indicative and as developed for illustrative purposes only.

**Are there important effects not considered in the case studies?**

In the case studies, various energy systems and their economic, technical and environmental performance are described. Several simplifying assumptions and omissions were necessary. The conventional thermal power plants (fossil and nuclear) are assumed to reach a capacity load factor of about 85%. Intermittent power generating technologies such as wind and photovoltaic power generation are considered disregarding any backup systems. The capacity of the small-scale wood chips boilers considered is five times higher compared to the one of gas-, and oil-fired boilers. Hence the difference in total private costs between the wood chips boiler and the oil and gas boiler tends to be higher than shown in this thesis when referred to a certain, equal amount of useful heat (e.g., the yearly heating energy requirements of a single-family dwelling).

The differences in economic power of the various technologies considered in the case studies in Part III leads to differences in economic competitiveness. Large and mature industries such as the oil and gas industry may spend more money in research and development compared to small and/or emerging industries such as the wood or the solar industry. Hence, the technological development is on a different level and technological progress comes at different speeds.

**Why is capital equipment, contrary to the theory developed, always included in the case studies?**

For the numerous industries involved in the process networks of energy systems, no investigations about the state of their market development (expansion, consolidation or degeneration) have been made for this thesis. Furthermore, the software used for the case studies is not (yet) prepared to partially exclude capital equipment. But as could be shown in Frischknecht et al. (1995b), the relevance of capital equipment is only of relevance for transport systems and for energy systems that harvest renewable energy (i.e., hydro, photovoltaic, wind power, *et cetera*). The latter, however, show a comparably good environmental performance which would even increase by excluding capital equipment. Hydropower might be called the only matured industry where the production of capital equipment is important. However, due to its good competitiveness, it will hardly disappear in the next century.

**Why are marginal power generating technologies defined as national averages?**

The marginal power generating technologies used in the case studies in Part III predominantly represent the national average performance of the technology using a particular energy carrier (i.e., Italy for heavy fuel oil, Germany for coal and lignite, The Netherlands for natural gas, France for nuclear, Switzerland for hydro). This is mainly due to problems of operability because only little and incomplete data about the environmental performance of individual power plants were available to us (except data for the Swiss nuclear power plants, and the comprehensive database on European coal and lignite power plants). The total costs per kWh for a large number of Swiss hydroelectric and nuclear power plants in operation are listed in Hess et al. (1997). However, information on total private costs about individual European power plants were not available to us.

The use of national averages means that for the most expensive power plant, social costs will tend to be even higher because some power plants show a worse environmental performance than the ones used in the case studies. For new technologies to be installed (the cheapest ones), however, some individual technologies such as gas combined cycle or pressurized fluidized bed combustion are considered.

**Is it possible to predict private costs in such a generic manner?**

Private costs of energy systems show large uncertainties due to variations in investment costs, the capacity load, the life time of the facility, and the development of the energy costs and of the interest rate. Some of these parameters, especially investment costs and the capacity load are very much case dependent and therefore need to be adjusted for any single investment decision to be made. Hence, private costs should be considered as indicative.

# 12. A Guide for LCI System Model Design

## 12.1 Choosing the Adequate System Model

LCA is used to provide information for various decision situations. The three system model designs developed in Part II help to choose the adequate model for a specific question. Fig. 12.1 provides guidance for LCA analysts, and shows the way to a particular system model depending on the problem at issue.

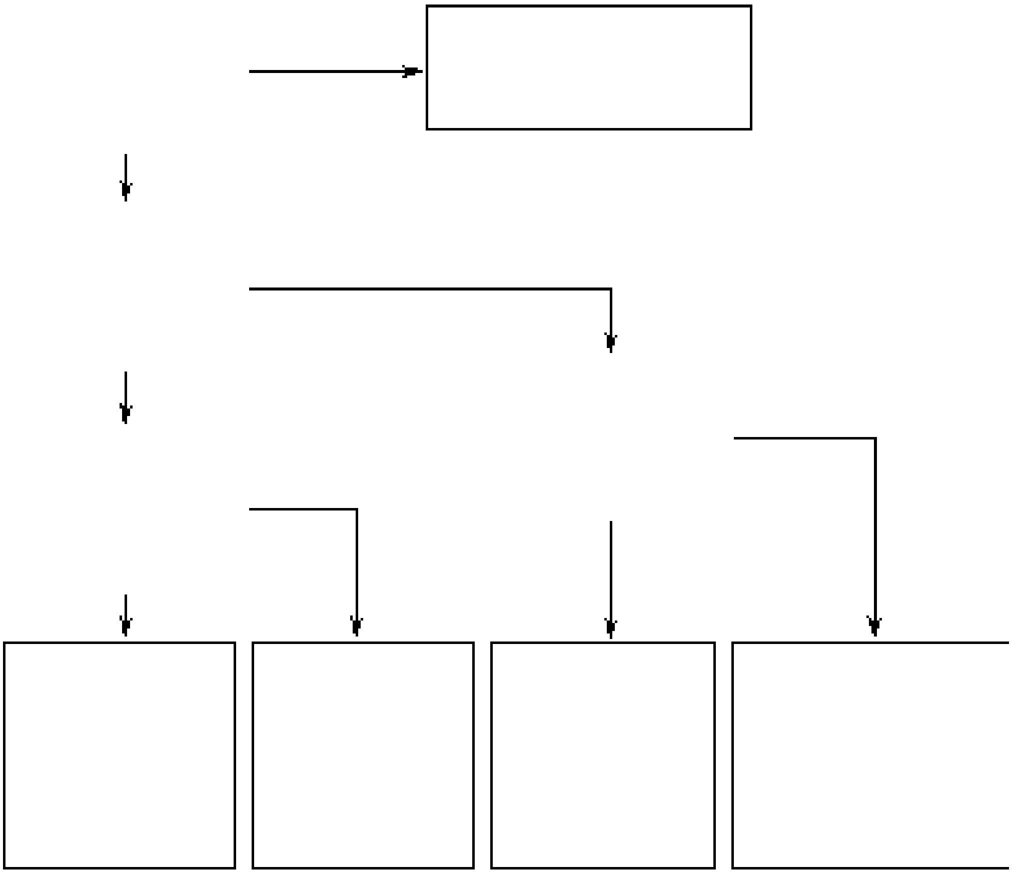

Fig. 12.1: Decision tree for the choice of an adequate LCI system model.
[1]): Linear programming has been applied in LCA by, e.g., Azapagic (1996);
[2]): Fixed and variable in relation to the environmental performance of known and new technologies.

First, the goal of the study needs to be defined in view of potential future actions. If an LCA is supposed to support decisions, system models suitable for planning should be chosen. If not, a *ceteris paribus* or Status Quo LCA system model is sufficient. Next, the temporal aspect of the functional unit at issue needs to be determined. The functional unit may either cover a "one time only"-demand or a forecasted trend of demand. In the case of a forecasted trend, the next question deals with the degree of freedom in respect to the technical possibilities. Either the production technologies used within the process network are known and show a given environmental performance (Long Run LCA system model), or new techniques or technological developments may emerge (Very Long Run LCA system model). The fact whether the technical possibilities are variable or not is mainly a matter of time horizon for which the functional unit is analysed. If the functional unit covers a "one time only"- (or stochastically varying) demand, the discriminating aspect is the number of intended outputs (single- or multi-function, i.e. combined process). In the former case, short-term negotiations with suppliers and changes in demand may be analysed using the Short Run LCA system model. In the latter situation, short-term optimisation of product portfolio in view of a firm's objective function may be performed using, e.g., linear programming. It may lead to allocation factors which follow physical causalities. These allocation factors may well be used in descriptive LCA because they mirror the course of production throughout a certain time period (e.g., a calendar year).

## 12.2 Choosing the Adequate Joint Allocation Approach

Joint allocation escapes a justification on an objective basis such as physical causality. That is why, the context within which allocation is performed is judged to be relevant. Fig. 12.2 provides guidance in choosing the adequate allocation method when confronted with joint production.

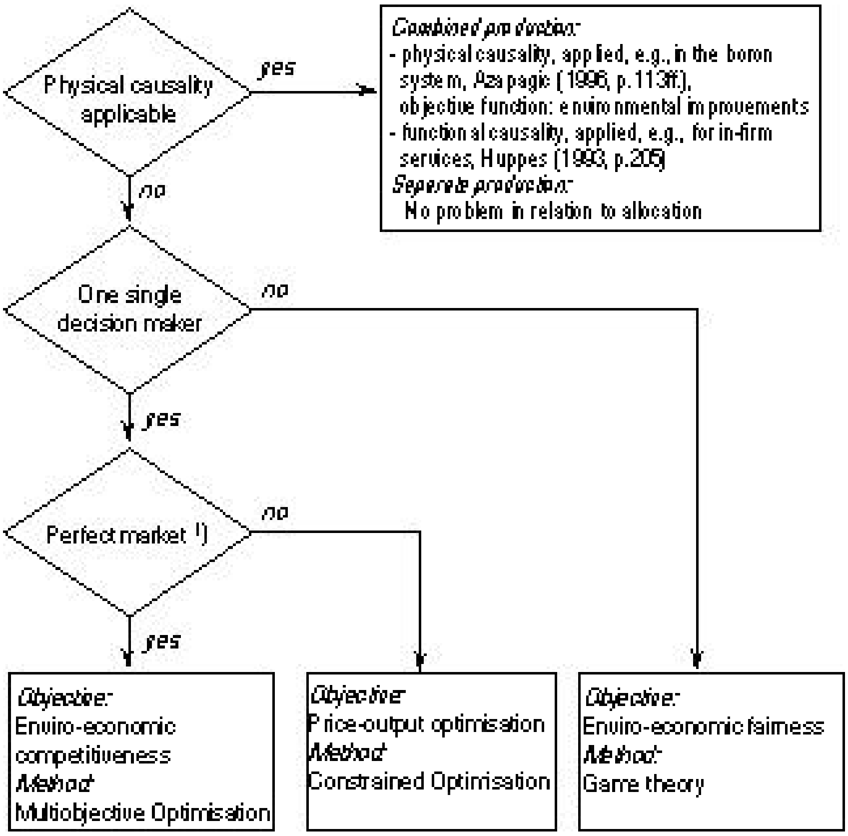


Fig. 12.2: Decision tree for the choice of an adequate allocation approach in joint product allocation.
[1]): Perfect in the sense that the firms are price-takers, but *not* in the sense that environmental external costs would already have been internalised.

First, one needs to check whether physical causality is applicable or not. If physical causalities may be established and make sense, other approaches such as linear programming may be applied. If not, the production process delivers really fully joint products or products whose identical physical units do not correspond to the real cause of the combined process (such as the weight of passengers and freight in the combined transportation in an airplane). One then moves to the second and major discriminative characteristic within joint production, namely, the number of decision-makers involved in the allocation process. Here, the two categories "single decision-maker", and "multiple decision-maker" are discerned. Third, the characteristics of the market for which products or services are produced are relevant for the single decision-maker situation. If several decision-makers are involved, a fair allocation key is required which results from a bargaining process. These approaches are independent of the allocation parameter applied (e.g., private costs, environmental impacts, social costs, *et cetera*).

# 13.Outlook

In this thesis, a new, economic information-based approach to set up the system model used in Life Cycle Inventory analysis has been developed. Furthermore, arguments have been given to apply decision relevant criteria on joint product allocation and on the default choice of a technique. The consequences of these proposals have been shown with generic data for the Swiss national electricity mix and the combined heat and power production. However, several aspects have not been treated which are or may prove to be relevant. In this final chapter, some trains of thought for future research are developed.

## 13.1The Disutility Function in LCI

The decision model applied for the aggregation of economic and environmental information is rather crude. Furthermore, this model is used to represent decisions made in the background systems, disregarding other aspects such as legal and social ones. For the future, decisions should be better modelled as far as they are needed in the LCI system model. On the one hand, the economic processes should be classified according to their social, legal and economic environment. The labour situation, the environmental policy, *et cetera*, of all nations within which processes take place that contribute to the production of a good (i.e., countries all over the world), should be known in order to accurately represent an "average", country-specific disutility function, which is applied in allocation and in the default choice of a technique in the background system. The disutility function would include environmental aspects to a variable extent, dependent on a country's environmental policy. We assume that the importance of environmental issues represented in the disutility function used in this thesis is overestimated. In several countries, decisions about investments are still made on mere economic information, whereas in other ones single environmental issues such as global warming entered decision-making (even without internalising the environmental external effects of climate change). In a second refinement step, the disutility functions of particular firms may be modelled if a high variability of the disutility function within economic areas has to be assumed.

Private and environmental external costs are assumed to show large ranges of uncertainty. In order to be able to quantify these uncertainties, and, maybe, to reduce them, attempts may be made to classify the uncertainties and to structure them in view of similarities, and of amplifying and compensating effects. Cultural theory has been applied successfully for the treatment of uncertainties with forecasts about the environmental damage of global warming (van Asselt et al. 1995), and is introduced in the Impact Assessment of LCA by Hofstetter (1996b). This may be a road to be followed in the context of Life Cycle Inventory Analysis too.

## 13.2Joint Product Allocation

In this thesis, we plead for an allocation procedure which strengthens the competitiveness of the actors involved. The decision on how to allocate is left to the responsible decision-maker (or problem-owner). This implies that per industrial process only one "true" or "adequate" allocation factor exists per joint production process. For generic databases such as the energy systems database, allocation factors should therefore be established in connection with the respective industries. Hence, the allocation of flows of commercial and ecological commodities among iron, blast furnace gas, *et cetera*, should be made by the iron and steel industry, the allocation between chlorine and caustic by its manufacturers, *et cetera*. This would guarantee that the allocation reflects the real situation in competitive markets and is therefore the best approximation for generic data. Of course, such allocations may change with time which makes it necessary to adjust the allocation factors just like the emission factors of a process for which the flue gas treatment is improved.

Some joint production processes deliver goods that are not traded on the market but are directly consumed. Decentralised, roof-integrated photovoltaic power plants, for instance, produce electricity and shelter from rain and wind, the latter being a service hardly quantifiable in economic terms. Here, the costs for other, alternative options which guarantee the same sheltering function may be used. In such cases, the environmental performance of photovoltaic electricity is depending on the environmental performance of tiles and such like and its social costs are depending on the social costs of roofing alternatives.

The game theoretic approach leads to rather simple results when applied in a two parties situation. But as soon as more parties are involved, negotiations get more complicated. In the energy sector, the cases with more than two parties or two types of parties are rare. Besides the classical example of the erection of a dam, the conversion of polymer waste to energy may be the most interesting and increasingly relevant case. The question about the environmental performance of different ways to produce cement, for instance, may be treated in this way. Three actors may be identified, namely, the management of polymer product manufacturing, of cement manufacturing, and of waste incineration. Cement may be produced with primary resources such as limestone and hard coal or (at least partly) with slags from waste incinerators and/or with used polymers , e.g., spent credit cards. In waste incineration, slags may be treated until they are inert and then sent to landfill and waste incinerators may also burn used polymers. The manufacturers of credit cards may use the used polymers as a secondary raw material or treat the used polymers in waste incinerators or in cement kilns. The grand coalition comprises cement production, waste treatment of slags and used polymers. Of course, the production of credit cards from virgin polymers must be added to the various coalitions with no material recovery.

## 13.3LCA and Financial Flows

In Chapter 3, the representation of unit processes is derived. Hereby, financial flows are used to set up the system model. Several activities that are induced by financial flows from a unit process (or a firm) have not been mentioned nor quantified in this thesis. The cumulative flows of ecological commodities of goods produced by firms which achieve profits of 20 to 30% of the total turnover may increase substantially when including activities caused by paid-out profits. However, this allegation still waits for verification.

In order to arrive at the satisfaction of the shareholder, the satisfaction of their clients is one important aim of the activities of a firm. For the banking sector, the question about environmentally favorable investments gains increasing importance for which LCA may be used. In such an analysis, the goods produced are not relevant and the functional unit is the profit rate achieved with a certain amount of money invested.

Insurances and their potential influence on the environmental performance of a certain good are not assessed in this thesis. Insurances distribute the financial risk of adverse, rarely occuring events. Such events may also show large environmental impacts such as the Tschernobyl-, or the Amoco Cadiz-accident. The interesting question is whether these environmental impacts should be distributed among the clients of the insurance company (and if yes then how?), or whether it should directly be allocated to the causing client. The former would imply that the clients of an insurancy get a mixture of environmental impacts of the various accidents happening within the firms insured. The latter case disregards the solidarity principle used on the level of financial risks. In any case however, the inclusion of environmental external costs into the consideration would influence the level of the premium. Activities with high potential environmental impacts would entail higher premiums compared to low environmental risk activities. Hence, the relation of premiums paid by the clients of an insurancy changes when including environmental information to determine the premiums.

## 13.4Database Development

A large part of the ETH database on energy systems has been developed based on average data. Most data rely on annual reports concerning the shares of technologies used and the flows of ecological commodities. That is why these data fit best with questions in relation to descriptive LCAs. One main improvement of existing descriptive databases for the future lies in an entire integration of the knowledge about contracts within the electricity sector in LCI system models. By that, the electricity trade and supply is modelled more accurately, and the electricity model would represent the "real" causalities within the electricity sector.

When an LCA shall deal with changes, either short-, long-, or very long-term changes, different datasets are needed. That is why at least three different datasets are required to represent changing economic systems, i.e., the Short, the Long, and the Very Long Run database. The following is needed to establish such a "marginal" Long Run database:

- First, the various economic sectors, or better, the numerous product markets need to be analysed in view of their stage of development. The inclusion or exclusion of the capital equipment is decided based on a discrimination between growing, maturing and declining markets. For the Short Run model, only variable flows of commercial and ecological commodities shall be comprised, whereas for the Long Run system model, flows caused by the capital equipment needed shall be included depending on the stage of development of the market.
- Second, information on the level of economic sectors, of markets or even of single firms are required about how decisions are made. Here, areas within which politics and legislation may be assumed to be "homogeneous" and within which firms are assumed to decide similarly shall be defined (e.g., economic areas such as North America or Europe, or nations). Within such areas, decision relevant information (e.g., private cost statements) is needed for each and every process. These data shall be used to determine marginal technologies. The data shall also be used to model allocation in background processes as long as their allocation has not yet been carried out by the decision-makers of the respective background processes.
- Third, the technologies put in or out of operation (marginal technologies) need to be established per background process. The choice of a technique in background processes can not directly be influenced by the one who decides about improvements in the foreground system. For instance, a banking institute can not directly influence the power generation technology put in or out of operation by planned changes in their electricity demand. The corresponding utility will take the decision on which power plant to shut down or to put in operation (depending, among other aspects, on the time horizon). Hence, either these marginal technologies or the disutility function

used by the firms acting in the background system must be known.

- Forth, information about the performance of these marginal technologies is required. For the refinery sector, for instance, this may comprise an analysis of a refinery where the share of light products (light fuel oil, gasoline) is further increased and/or where the sulphur content of light fuel oil is further diminished.

The set-up of generic LCA databases useful for the analysis of changes is a time- and labour-demanding task. However, in order to rationalise the compilation of LCA data for decision support in firms, such a work is indispensible. This is demonstrated by the demand for generic datasets such as the BUWAL packaging materials database or the ETH database on energy systems. However, the set-up of such databases should be performed in a decentralised way in order to charge the respective experts with it, and to avoid monopolistic situations. Furthermore, the independence of the LCA analysts involved should be guaranteed.

Any LCA should be the basis for actions to be taken in view of an optimal allocation of scarce environmental resources. Hence, an LCA should rely on a system model and on data which are capable of representing changes. The gain in efficiency, both in terms of money and time spent to carry out an LCA and in terms of a better allocation of scarce environmental resources through the increased effectivity and credibility of LCA, should be motivation enough to launch a project that deals with the complete restauration of existing, descriptive databases in the direction of new generic databases capable of predicting the consequences of a decision.

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# APPENDICES

# Appendix 1 Allocation Methods for Joint Production; A Synopsis

## A1.1Introduction

In this appendix, a survey is given of economic allocation methods used in joint production situations. The text relies mainly on the descriptions in Thomas (1977, p. 26ff.), Horngren et al. (1991, p. 530), Bierman et al. (1990), Hardy et al. (1981), Manes et al. (1988), and Young (1985a).

Some of the methods are also applied in energy analysis and LCA. Most of the allocation methods applied in joint costs situations are more sophisticated than reported here. However, the following description is restricted to the main principles and characteristics and to simple cases adequate to the intended purpose. In the next three Subchapters, five easy joint cost allocations using economic parameters, the marginal approach (in Subchapter A1.3), and the "democratic" approach (in Subchapter A1.4) are described.

It is emphasized that the production situation underlying the description of the methods is perfectly joint, i.e., the products are produced in fixed proportions. Fig. A1.1 illustrates the terms used in the following description of the allocation methods.

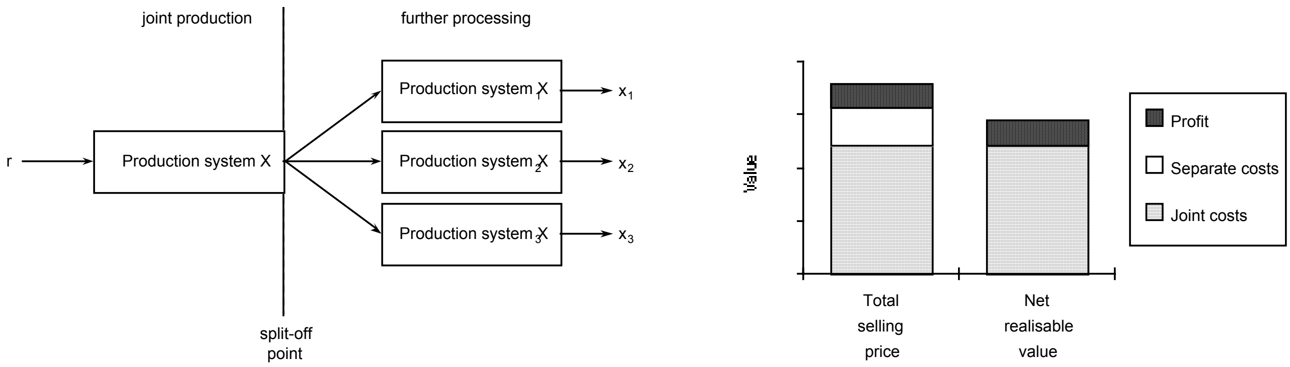


Fig. A1.1: Terms used in the description of allocation methods using economic information.

## A1.2Joint Cost Allocation Methods Using Economic Parameters

### A1.2.1The Sales Value Method

The sales value at split-off method, allocates joint costs on the basis of each products's relative sales value at the split-off point (cf., e.g., Horngren et al. (1991, p. 530), Bierman et al. (1990, p. 540)). This method shows two advantages. On the one hand it is simple because prices are systematically recorded in the accounting system. On the other, the allocation achieved reflects the revenue-generating power identifiable with the individual products. One has to pay attention not to confound this method with the constant gross margin percentage NRV method (net realisable value, see below), which is called "sales value method" by Thomas (1977, p. 29).

### A1.2.2The Estimated Net Realisable Value (NRV) Method

The estimated net realisable value method allocates joint costs on the basis of the relative estimated net realisable value. The separate costs are deducted from the final sales value to obtain the net realisable value. For that purpose the separate costs need to be known. Furthermore, changes in the further processing after the split-off point may lead to changes in separate costs and therefore in joint costs allocated to the individual products. This procedure recognises profit resulting from production and inventory increases rather than from sales and therefore is generally disapproved by accountants (Bierman et al. 1990, p. 541). However, if the book profits are low or zero, little or no profits not yet realised are set out. While this method focuses on estimated NRV, the next one focuses on a constant gross margin percentage.

### A1.2.3The Constant Gross Margin Percentage Net Realisable Value Method

Using the constant gross margin percentage method, the gross margin of each joint product should be the same percentage of its selling price as that of any other joint product. For that purpose, the profits (gross-margin) are allocated in proportion to selling prices. Then the profit is deducted from the final sales value to obtain the total costs that each joint product should bear. In a last step, the expected or known separate costs (further processing, finishing *et cetera*) are deducted from the total costs to obtain the allocated joint costs. However, a constant gross margin percentage is seldom observed in companies producing multiple products without any joint-cost situations (Horngren et al. 1991, p. 534). Hence, experience in companies do not provide any justification for this method.

### A1.2.4Moriarity's Approach

The methods presented so far, merely rely on the jointly producing firm's data about costs and sales values. Moriarity and Louderback developed allocation approaches for decisions about the purchase of joint products in view of their further joint processing in one firm[1]. Both methods rely on price information about externally available products.

Moriarity's central statement is that joint products may as well be produced separately, although at higher costs and that companies manufacture such products jointly in order to obtain cost savings over these alternatives. He then uses the costs of the least expensive way of acquiring joint products separately (internally or externally) and allocates according to the share of the costs saved compared to the costs of purchasing them jointly.

Louderback modified Moriarity's approach and compares costs of externally purchased products with the further processing costs of individual joint products (given that the costs of further processing are lower than the costs of the least expensive, externally acquired product). The allocation is based on the difference between the costs of the least expensive way to purchase a product externally and the separate costs (further processing costs) of the joint products produced internally.

Both approaches allocate costs according to a kind of the product's ability to bear them. The ability to bear is expressed in costs saved compared to competitive ways of producing these joint products.

[1] This text relies on a description given in Thomas (1977, p. 30).

### A1.2.5 Sales to Production Ratio Method

The sales to production ratio method allocates joint costs on the basis of the total *amounts* of products sold and produced respectively. It therefore differs from the methods described above which are based on the sales *value* or production costs of one single product unit. The method requires that the proportion of sales in units for each product line be computed in percentage terms. The sales percentage is then divided by the production percentage to get the sales to production ratio. This method, proposed by Hardy et al. (1981), is motivated by the ability to bear criterion. They redefine this criterion

> to mean that the products that sell the most should bear a greater proportion of the joint cost of current production than those products which are experiencing less demand.[2]

According to them, products that are moving slowlier (having a comparably lower sales to production ratio) bear less of the joint costs. This method has been criticized because situations may occur where the joint costs allocated to one joint product may be higher than its selling price. It is further argued that if one joint product is not selling at the current price in the desired quantities and accumulates as inventory, the firm anticipates either to sell that product in the next period at current price or to lower the price of that product. And for either of these cases,

> the cost allocation using the RSV [relative sales value] method represents a "fair" allocation with the higher cost allocation at higher expected sales price and lower cost with price reduction.[3]

This method helps firms in pricing products and by that shows us the way to the marginal approach, described in the next section.

## A1.3 The Marginal Approach

In the previous Subchapter, all methods except the sales to production ratio method, are based on sales values, production costs, profits, *et cetera*. In these models, costs of production and sales value are constant, i.e., prices reflect sufficiently working markets and firms are price-takers. If however a firm is producing for an imperfect market, the price may depend on the output of that firm. In such situations, the marginal approach is applied. The method is based on information about the demand curves of the joint products, and the costs of the joint process and eventually occurring individual finishing processes. The marginal approach, or supply-based allocation of joint costs may not be used for product pricing just because optimal prices are the basis for it. In fact, the marginal approach is not really an allocation procedure but a short-run price-output optimisation problem which is based on marginal revenues per joint product (Jensen 1974, p. 465). Manes et al. state in respect to the usefulness of the marginal approach:

> When optimal product decisions are made, a best cost allocation policy is generated simultanously from the model. Mathematical programming is used to generate optimal production plans and at the same time to indicate the shadow prices of the model constraints. These prices have economic meaning and provide a basis for cost allocations which are decision relevant. In addition (...) these prices will be shown to be useful in the valuation of joint product inventories and thus in the preparation of financial statements.[4]

To find the optimal allocation, constrained optimisation, Lagrange multipliers, and Kuhn-Tucker theory are used (cf., e.g., Pfouts (1961), Weil (1968, p.1343ff.), Jensen (1974, p. 468), Manes et al.

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[2] Hardy et al. (1981, p. 106)
[3] Bhada (1982, p. 58)
[4] Manes et al. (1988, p. 14)

(1988, p. 15ff.), Pavia (1995, p. 1063)). Most of the models rely on the following assumptions (Manes et al. (1988, p. 15):

- The demand functions are known with certainty and are independent.
- The amounts of inputs are not limited.
- Input costs per unit of the variable factors are constant, as is the marginal productivity of the variable factors.
- All joint costs are variable.
- Disposal of excess product inventories is costless.

Manes et al. (1988) also apply the marginal approach to situations where the firm is a price-taker (i.e., the price is independent from the amount sold, hence, the marginal revenue is constant). In these cases they alter the objective function and introduce demand conditions in the form of maximum estimated demands for each individual joint product. If no constraints were introduced, the marginal approach would result in the gross sales value method described above.

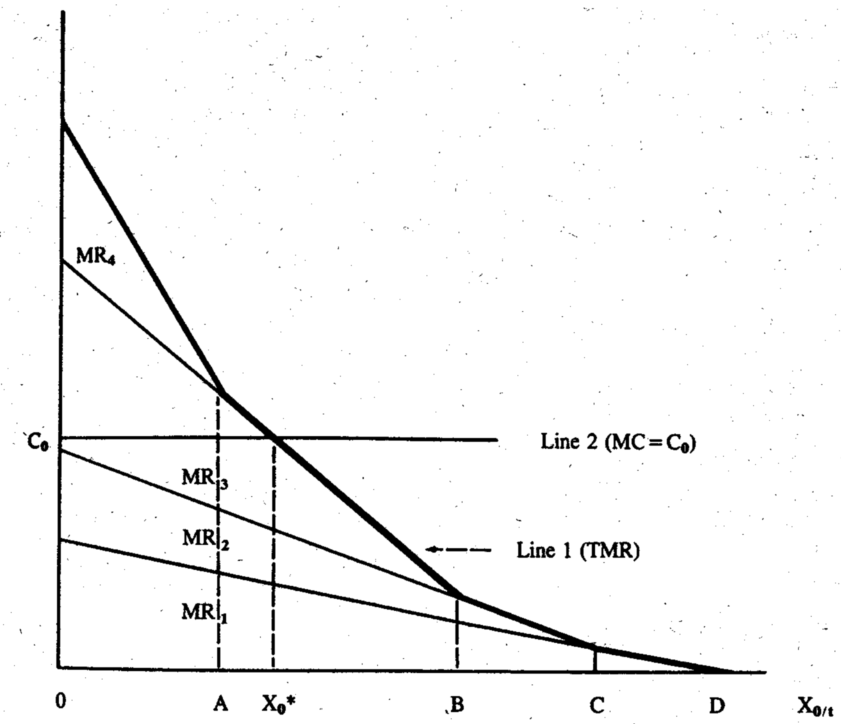


Fig. A1.2: Relationship between marginal revenues and marginal costs per unit joint product for a nonlinear model of joint production without further processing, depending on the amount of common raw material used, $X_{0/t}$, (Manes et al. 1988, p. 17)
TMR: total marginal revenue;
$MR_1$: marginal revenue of product 1;
$MR_2$: marginal revenue of product 2;
$MR_3$: marginal revenue of product 3;
$MR_4$: marginal revenue of product 4;
$MC=C_0$: marginal costs;
$X_0$*: optimal amount of raw material put into production;
A, B, C, D: maximum demand per joint product

Fig. A1.2 shows the situation of a four products joint production. At $X_0$*, the optimal amount of raw material is put into production to reach an equilibrium between the marginal revenue and the marginal costs. Line one shows the summation of individual marginal revenues. Line 2 indicates the constant marginal cost function. At $X_0$*, the marginal revenue of product 4 is zero and $C_0$ is composed of $MR_1$, $MR_2$, and $MR_3$. These marginal revenues may then be interpreted as inventory or opportunity costs (Weil 1968, p. 1342), and the gross sales value method is applied for allocation. The allocation is then straightforward. The share of the individual joint product *i* on total costs is its marginal revenue $MR_i$ at $X_0$* divided by the total marginal revenue TMR at $X_0$*.

However, one has to be aware of the fact that the allocation of joint costs emerges simultaneously with the optimal price-output strategy (Jensen 1974, p. 470). The allocated costs are not useful for pricing decisions because they rely on the very same prices. But the marginal approach helps a mono-(oligo-)polist to determine the prices of joint products in order to maximise profits. The marginal approach has its merits mainly when demand is not perfectly elastic (monopolistic situation), or when demand is restricted in perfectly competitive markets. As soon as the demand functions of the joint products are either constant (as is the case in reasonably working markets) or identical, the marginal approach will convert to the gross sales value method.

The demand curves of the individual joint products tell us something about their elasticity in demand[5]. The more inelastic the demand is (the steeper the demand curve), the more flexible a firm needs to be in pricing joint products which are produced in given quantities in order to influence the demand. On the other hand, as F.P. Ramsey points out in the context of taxation:

> If any one commodity is absolutely inelastic, either for supply or for demand, the whole of the revenue should be collected off it. This is independently obvious, for taxing such a commodity does not diminish utility at all.[6]

The more the supply of a joint product remains under its demand, and the more the demand is inelastic, the more a joint product may be charged with joint costs. On the other side, if joint products are produced in excess of their demand, its price needs to be lowered to avoid inventory accumulation (see also the "sales to production ratio" approach above). A lower price however, reduces the joint products' ability to bear joint costs. The marginal approach helps to improve the economic efficiency of the joint production process. Joint pricing helps to adjust the demand of the joint products in a way that maximum profit may be achieved.

## A1.4The Shapley ("Democratic") Approach

The Shapley approach allocates joint costs according to a set of axioms defined in the context of game theory. In cost accounting literature, it is said that Shubik (1962) has been the first who applied the game theory approach developed by Shapley (1953) to cost accounting (cf. Thomas 1977, Callen 1978, Verrecchia 1981, Biddle et al. 1984, Young 1985b, p. 8). It is applied in cases like multipurpose water reservoirs, municiple cost sharing (e.g., for water supply), airport landing fees, or travel expenses (e.g., for business tours, see Young (1985b, p. 4ff.) for further details). In LCA, a kind of game approach has been proposed by van Engelenburg et al. (1994), who state

> The allocation procedure has to be acceptable for all participants. So, justice has to be the major criterion for allocation procedures. In a gaming context (the allocation game) this criterion can be fulfilled.[7]

However, the paper does not adapt and apply the standard axioms of game theory. These, also called Shapley axioms, restated as "properties" by Shubik, may be summarised as follows[8]:

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[5] "*The (point) elasticity of a product may be defined as* $-\frac{dq}{dp} \times \frac{p}{q}$, *where* dq/dp *is the derivative of quantity with respect to price at a point on the demand curve and* p *and* q *are the price and quantity at that point.*" (Lipsey et al. 1972, p. 83).

[6] Ramsey (1927, p. 56ff.)

[7] van Engelenburg et al. (1994, p. 102)

[8] This text is mainly based on the description of the approach given in Biddle et al. (1984, p. 23ff.).

*Property 1:* The value allocated to one actor[9] depends only upon the various values which can be achieved by all possible combinations of one or more actor working together. Any actor is valued according to his incremental benefit he or she adds to the various coalitions.

*Property 2:* The value allocated to an actor depends symmetrically upon all actors involved. The incremental benefit is invariant to the order in which an actor is presumed to join the coalition. Because of that, each possible alternative is assumed to show the same probability and is weighted equally. Hence, the value allocated to any actor is independent on the sequence, actors enter a coalition.

*Property 3:* The procedure allocates all values of the actors involved in the grand coalition.

*Property 4:* An actor whose presence adds nothing to the value of any coalition should be allocated no value at all. This is called the "dummy" axiom.

*Property 5:* If two independent allocation problems are combined into one problem, then for each actor the value allocated under the combined allocation is the sum of the allocations under the two individual problems. It implies the additivity of allocation problems and is usually interpreted in such a way that various values can be disaggregated and then allocated separately.

The Shapley approach depends on several important underlying assumptions. On the one hand, actors involved in the negotiation procedure are supposed to be rational decision-makers. On the other, the characteristic function[10] includes all relevant information to a given evaluation or allocation. Any other information not represented in the characteristic function is excluded from the negotiation.

The characteristic function is assumed to be superadditive which means that the value of the players acting independently cannot be greater than their value in a coalition. A coalition is only a valuable option as long as there is a benefit for all actors involved compared to less comprehensive coalitions (coalitions with less actors)[11].

Let us look at a three actors (A, B, C) situation where the characteristic functions (values V) of all possible coalitions are (Callen 1978, p. 305):

V(A), V(B), V(C), V(A,B), V(A,C), V(B,C), V(A,B,C).

The absolute amounts in output each actor achieves with any of these coalitions remain constant.

If actor A enters the coalition first, his incremental value would be V(A), if he enters after actor B in a (A,B) coalition, it would be V(A,B)-V(B), *et cetera*.

The Shapley values allocated to the three actors would then be:

$$\begin{aligned} S_A &= 1/3V(A) + 1/6[V(A,B) - V(B)] + 1/6[V(A,C) - V(C)] + 1/3[V(A,B,C) - V(B,C)] \\ S_B &= 1/3V(B) + 1/6[V(A,B) - V(A)] + 1/6[V(B,C) - V(C)] + 1/3[V(A,B,C) - V(A,C)] \\ S_C &= 1/3V(C) + 1/6[V(A,C) - V(A)] + 1/6[V(B,C) - V(B)] + 1/3[V(A,B,C) - V(A,B)] \end{aligned} \tag{A1.1}$$

[9] In game theory, the actors are named "players", any coalition of actors is called "game".

[10] The characteristic function is the measure of interaction between actors in a joint venture in comparison to their effectiveness as individuals (Callen 1978, p. 305).

[11] This implies the non-negativity of coalition values (Thomas 1977, p. 50).

It may easily be verified that the total value allocated equals the value of the grand coalition (A,B,C):

$$S_A + S_B + S_C = V(A,B,C). \tag{A1.2}$$

Shapley values can be generalised to an n actor situation. The value of the *j*th actor in an *n* actor coalition is

$$S_j = \sum_{G \subset J} \frac{(n-g)! \cdot (g-1)!}{n!} \cdot \left[ V(G) - V(G - \{j\}) \right] \tag{A1.3}$$

where $J = \{j: j = 1, ..., n\}$ is the set of actors and G is any subset (coalition) of g actors. The incremental benefit attributed to the coalition by actor j when he or she is in the gth position is weighted by the first multiplicand in equation (A1.3), where $n!$ is the number of possible coalitions while $(g\text{-}1)!$ and $(n\text{-}g)!$ represent the number of ways of ordering the players in coalition $G$ and $J\text{-}G$, respectively.

The main purpose of this approach lies in structuring negotiations of possible coalition partners to start a joint venture. However, the Shapley approach does not help in cases where joint production is the only way delivering a certain product. In such cases no values of an actor proceeding individually are available. This is for instance the case in the oil industry (e.g., one cannot produce a litre of light fuel oil separately), in the meat industry, or in the chemical industry (e.g., chlor-alkali plants).

There is another important aspect which distinguishes situations where the Shapley approach is applied (e.g., for a common energy supply center in a multi-division company) from the ones of joint production of, e.g., chlorine and caustic soda. While in the former situations the committment to start a joint production is voluntary, and the discussion about allocation starts before the joint venture is initialised, the "coalition" is given before the problem about allocation is risen in the latter.

The arbitrariness of the Shapley values is discussed among cost accountants. According to Balachandran et al (1981), the Shapley approach

> does not solve the "arbitrary issue" in as much as the axioms themselves (like the ones by Shapley (1953)) are arbitrary. But they are found to be of great use in satisfying the behaviour of rational agents and hence they seem to be a possible solution to this dilemma.[12]

The Shapley approach does help in conflict situations where diverging interests of the partners are involved by equally considering the benefits contributed by the actors involved, and where reasonably working markets are lacking. That is why, Thomas (1977, p. 56) calles this approach "the *democratic* approach".

[12] Balachandran et al. (1981, p. 85)

# Appendix 2 Externality Studies and Eco-indicator 95^RF

## A2.1 External Costs Studies

Four recently published studies about environmental externalities (European Commission 1995a-f, Rowe et al. 1995a&b, Infras et al. 1996, IVM et al. 1997) are described in this appendix.

The environmental external costs presented in this appendix and used in the case studies in Part III, comprise the environmental damage caused in normal operation of the processes directly and indirectly involved in the production of a commercial commodity. They do not cover costs occuring related to occupational health or to severe accidents. Furthermore, they are limited to the economic losses related to the objects affected (i.e., fatalities and working days lost of human beings, reduced harvests in agriculture and forestry, *et cetera*). No intrinsic value in monetary terms is attributed to nature. The environmental damages of ionising radiation, is integrated over 100'000 years and determined based on a model world with a population of ten billion people living in today's environmental situation (i.e., with today's background levels). The corresponding environmental external costs used in this work are the ones based on a discount rate of 0%, although a social time preference rate of around 2 to 4% seems to be appropriate (European Commission 1995a, p. 450).

The description of the externalities-studies is limited to the aspects and peculiarities relevant for this work. For more details about the models and methodologies applied, the reader is referred to the original studies.

### A2.1.1 The ExternE Studies

In 1991, the European Commission launched an international research project about environmental external effects of electricity generation in collaboration with the US Department of Energy. The so-called ExternE project envisages four major stages:

- the development of a methodology for the evaluation of externalities associated with fuel cycles;
- the application of the methodology to a range of fuel cycles with the development of an accounting framework for each fuel cycle;
- the application of the accounting framework to different technologies and sites;
- the development of methods for the aggregation of the results such that they are of value to policy and decision-makers.[1]

Similar to the life cycle inventories for energy systems (Frischknecht et al. 1996a), a life cycle approach is chosen in the ExternE project. However, the methodology developed is based on single case studies for each of the stages in the life cycle of an energy carrier or energy system. In the case of the nuclear fuel cycle, for instance, the French production sites have been used to determine the emissions on the one hand and the effects on humans and the environment due to these emissions, on the other. The external costs per unit energy delivered are case specific and try to predict actual damages. In the strict sense, they are not compatible with generic LCA data. But the aim of this work is to use environmental external costs to illustrate the approaches developed and described in Part II.

The ExternE's frame work encompasses four stages, namely

[1] European Commission (1995a, p. 9)

Fuel cycle stage -> Activity
Activity -> Burden
Burden -> Impact
Impact -> Valuation[2].

The emissions (or source terms) of the relevant technologies and the environmental burdens they impose are characterised and used to calculate increased pollutants' concentrations in all affected regions. For that purpose, models of atmospheric dispersion and chemical reactions are used. Then, the population or receptor exposed to incremental pollution is characterised applying suitable exposure-response functions. In the last step, the impacts calculated will be economically valued. The methodology is also known under the name "damage function methodology" (European Commission 1995a, p.23).

Main differences to older studies (e.g., Hohmeyer (1989), Teufel et al. (1991)) in terms of ecology, health science and economy lie in

- the advanced knowledge due to new epidemiological studies on health effects caused by particulate matter and $SO_2$ (especially since about 1990) giving new insights concerning adverse health effects due to increments in air pollution (European Commission 1995b, p. 65).
- the inclusion of the health effects of secondary particles, formed by reactions involving gases emitted during power generation (i.e., sulfates emitted as $SO_2$, nitrates emitted as $NO_X$).
- the attempt to also include chronic effects.

| | Representative German site (Stuttgart) for a waste incineration plant, stack height 100m | Fossil fired power and cogeneration plants in Germany | Fossil fired power and cogeneration plants in UK | Coal fired power plant West Burton, UK | Coal fired power plant Lauffen, D |
|---|---|---|---|---|---|
| | ECU/t | ECU/t | ECU/t | ECU/t | ECU/t |
| Particulate matter, PM10 | 28'700 (144'000) [1]) | 18'655 | 16'934 | 18'730 | 23'857 |
| Sulphur oxides as $SO_2$ via $SO_4$ | 6'700 (34'000) [1]) | 9732 [2]) | 7'397 [2]) | 8'135 [2]) | 13'676 [2]) |
| Sulphur oxides as $SO_2$, materials | 609 | | | | |
| Nitrogen oxides, $NO_X$ via $NO_3$ | 15'500 (78'500) [1]) | 4214 [2]) | 2'332 [2]) | 5'413 [2]) | 15'684 [2]) |
| Nitrogen oxides, $NO_X$, materials | 311 | | | | |
| Nitrogen oxides, $NO_X$ via $O_3$ | 2'530 | | | | |
| Total organic carbon via $O_3$ | 2'530 | | | | |
| Arsenic, As, cancers [3]) | 999'000 | | | | |
| Cadmium, Cd, cancers [3]) | 81'400 | | | | |
| Chromium, Cr, cancers [3]) | 819'000 | | | | |
| Nickel, Ni, cancers [3]) | 16'800 | | | | |
| Dioxines, cancers [3]) [4]) | 2'000'000'000 | | | | |
| Value of human life [5]) | VSL | VLYL | VLYL | VLYL | VLYL |
| Reference | European Commission 1997 | Krewitt et al. 1997 | Krewitt et al. 1997 | Krewitt et al. 1997 | Krewitt et al. 1997 |

Tab. A2.1: Damage costs of some major air pollutants on hand of waste incinerators and fossil power plants in Germany and in the UK.
[1]): values in brackets: including chronic health[3]
[2]): Total damage costs (public health (mortality, morbidity), crops, and materials)
[3]): All cancers weighted with 3 million ECU per case, European Commission (1997, p. 7-5).
[4]): Total dose calculated by multiplying fifty times the inhalation dose, European Commission (1997, p. 7-5).

[2] *Op. Cit.* (p. 19)
[3] According to European Commission (1997, p. 5-9): *"chronic effects on mortality are the subject of considerable uncertainty."*

[5]): VSL: Value of statistical life; VLYL: Value of life year lost.

In a similar project, the cost effectiveness of abatement technologies for waste treatment plants has been investigated and reported in European Commission (1997). Finally, in Krewitt et al. (1997), external costs of electricity generation in Germany and the UK, based on the ExternE studies are summarised and published. Because no specific data on costs per pollutant is available in the ExternE reports, data from these later studies relying on the same methodology is used for a discussion in this work.

The pollutants' characteristics for fossil fuels and waste incineration for which damage costs have been determined are listed in Tab. A2.1. It becomes obvious that only a minor share of pollutants registered in Frischknecht et al. (1996a) are valuable on that basis. The cost figures for the incinerator represent external costs caused by an emittent in a relatively urbanized area (population of 600'000 citizens close to the incinerator) which explains the significant difference to the figures used for UK and German fossil power plants (European Commission 1997, p. 7-4).

Two different concepts to quantify the value of human life are used in ExternE studies. The concept of the "value of statistical life" (VSL) and of the "value of life years lost" (VLYL). According to the VSL concept, used in earlier ExternE studies, e.g. European Commission (1997), every excess death has the value of an average life, disregarding the remaining life time of the affected persons. The VLYL concept, used, e.g., in Krewitt et al. (1997) takes the remaining life time into account and considers only the value of these remaining years. This leads to substantially lower economic values per excess death. Chronic effects, disregarded in European Commission (1997) because of substantial uncertainties in their quantification, but included in Krewitt et al. (1997), seem to compensate for the lower value of life of the VLYL concept.

The model used in these studies determine the marginal or incremental effect of an increase in a pollutant's concentration (European Commission 1995b, p.13). In that sense, the model perfectly fits the methodology developed in Chapter 5 concerning an analysis of changes, at least for the Short and the Long Run (see Tab. 5.2 & 5.3).

### A2.1.2 The New York State (ESEERCO) Study

The main objective of the New York State study is the estimation of environmental externalities associated with new or relicensed electric resource options (power plants, energy saving measures) in New York. For that purpose a computer model ("EXMOD") has been developed which is based on damage function methods. The procedure is very much the same as the one used in the ExternE studies. However, the New York State study

a) gives less attention to technology characterisation than does the ExternE;
b) concentrates more exclusively on the electric power generation stage than the ExternE's full fuel cycle approach; and
c) unlike the ExternE study, assumes that externalities are zero for all renewable energy technologies.[4]

The computer model used in Rowe et al. (1995a&b) allows to quantify externalities of air- and waterborn pollutants (i.e., particulate matter, lead, mercury, $SO_2$, and air toxics emissions, surface water chemical and metals discharges, radioactive releases). These comprise human health effects (mortality, cancer risks, and morbidity), aquatic impacts, effects on fisheries, recreation, and

[4] European Commission (1995b, p. 429)

materials, as well as aesthetics, visibility effects, water consumption and the like. From the New York State study, data about the environmental externalities of airborn pollutants are individually available. External costs of water discharges and of land use are not applicable to LCA data due to their aggregated form of presentation. Tab. A2.2 shows the figures calculated with the EXMOD computer program for several case studies. The value of life for all ages is set to 3.3 million US-$ as the central estimate (50% probability), 1.7 million US-$ as the low estimate (33% probability) and 6.6 million US-$ as the high estimate (17% probability)[5]. Hence, the difference is about 5% to the external costs due to mortality used in the ExternE project (VSL-concept). Different sites (rural, suburban/urban, and urban[6]) and different power plant technologies are analysed. A comparison of different technologies at one site shows that the variation of technology is of minor importance in terms of environmental external costs per ton of pollutant (cf. Rowe et al. (1995b, p. 578)).

| | Natural gas combined cycle | | | Oil Distillate Combustion turbine | | |
|---|---|---|---|---|---|---|
| | rural | suburban/ urban | urban | rural | suburban/ urban | urban |
| | ECU/t | ECU/t | ECU/t | ECU/t | ECU/t | ECU/t |
| Particulates [1]) | 2'960 | 7'060 | 40'000 | 2'340 | 3'610 | 14'850 |
| Sulphur oxides as $SO_2$ | 36 (661) [2]) | 278 | 570 | 50 | 196 | 215 |
| Nitrogen oxides as $NO_2$ | 860 | 788 | -1'002 [3]) | 903 | 975 | 405 |
| Mercury, Hg | na | na | na | 634'000 | 949'000 | 3'881'000 |
| Lead, Pb | na | na | na | 137'000 | 137'000 | 137'000 |

Tab. A2.2: Damage costs in ECU per metric ton of selected air pollutants emitted by fossil power plants in New York State at three different sites (Sterling (rural), Capital District (suburban/ urban), and JFK Airport (urban)); Rowe et al. (1995b, p. 574);
1ECU = 1.21US-$.
[1]): including secondary sulfates, nitrates, and acid aerosols
[2]): values in brackets: excluding $SO_2$ trading[7]
[3]): Negative value due to local ozone reduction effects (Rowe et al. 1995b, p. 595).

Furthermore, the external costs for some additional air toxics have been determined for different technologies and for rural and urban/suburban situations. Tab. A2.3 shows the variation in costs per ton pollutant. The main difference between technologies is due to different stack heights which lead to different changes in ambient air concentrations.

It again shows the high relevance of particulates (primary and secondary). The values for $SO_X$, $NO_X$, and particulates calculated for the New York State sites are similar to the ones used in ExternE and related studies using a currency exchange rate of 1.21$/ECU (1990). The external costs due to cancer caused by heavy metals, dioxins, *et cetera*, differ substantially, with the New York State study showing much lower values than the "incineration directive" study (European Commission 1997) even if the difference in economic value per cancer is taken into account (factor 2).

[5] Rowe et al. (1995a, p. 493)

[6] Population within 30km: rural 90'000, suburban/ urban 640'000, urban 7'720'000; between 30 and 80 km: rural 1'000'000, suburban/ urban 500'000, urban 3'140'000.

[7] The $SO_2$ emissions and subsequent damages occuring at the site under analysis are offset by an equal amount at a reference trade facility due to the $SO_2$ emissions cap for the United States (Rowe et al. 1995a, p. lviii).

| | Rural central case estimate, within 50km, 305'000 people affected | | | Urban/ suburban central case estimate, within 50km, 3'660'000 people affected | | |
|---|---|---|---|---|---|---|
| | Coal/Oil, 46m stack | MSW [1]), 30m stack | Wood, 15m stack | Coal/ Oil, 46m stack | MSW [1]), 30m stack | Wood, 15m stack |
| | ECU/t | ECU/t | ECU/t | ECU/t | ECU/t | ECU/t |
| Arsenic | 434 | 1007 | 2013 | 5266 | 12080 | 17036 |
| Beryllium | 248 | 558 | 0 | 2943 | 6659 | 9757 |
| Cadmium | 186 | 418 | 805 | 2168 | 5111 | 7279 |
| Chromium | 1208 | 2788 | 5420 | 14558 | 34071 | 48010 |
| Nickel | 25 | 56 | 108 | 294 | 666 | 960 |
| Dioxin [2]) | 0 | $3.60 \cdot 10^9$ | $1.22 \cdot 10^{10}$ | 0 | $7.59 \cdot 10^{10}$ | 0 (?) |
| Formaldehyde | 2 | 17 | 0 | 24 | 201 | 155 |
| Furans [3]) | 0 | $9.01 \cdot 10^8$ | 0 | 0 | $1.08 \cdot 10^{10}$ | 0 |
| PCBs [4]) | 0 | $2.08 \cdot 10^8$ | $4.09 \cdot 10^8$ | 0 | $2.48 \cdot 10^9$ | $4.75 \cdot 10^9$ |
| POMs [5]) | 3252 | 11615 | 0 | 38718 | 139383 | 0 |

Tab. A2.3: Damage costs in ECU per metric ton of pollutant emitted for different power generating technologies in rural and urban/ suburban environment in the New York State; Rowe et al. (1995a, p. 363); Values are based on cancer costs of 3.4 million US-$ with 50% probability (hence, 1.7 million US-$ per cancer).
1ECU = 1.21US-$.
[1]): MSW: Municipal Solid Waste
[2]): Dioxins, inhalation risk factor based on TCDD, (Rowe et al. 1995a, p. 356)
[3]): based on 0.1 times the inhalation risk factor of dioxins, (Rowe et al. 1995a, p. 356)
[4]): PCBs: Polychlorinated biphenyls
[5]): POMs: Polycyclic organic matter, inhalation risk factor based on Benzo(a)Pyrene, (Rowe et al. 1995a, p. 356)

### A2.1.3 The City Air Quality Study

In 1997, the costs and the benefits of reductions in $SO_2$, $NO_2$, $PM_{10}$, and Pb emission in European cities have been estimated (IVM et al. 1997). Suitable data about air quality for about 150 and 36 cities ($SO_2$, $NO_2$, and $PM_{10}$, respectively) covering about 75 and 27 million, respectively, inhabitants were used. Besides the emissions from industry, transport emissions are also included. In the city-air-quality model, the relative influence of emissions from industry is roughly estimated to be a fifth of the ground level transport sources (IVM et al. 1997, p. iv). The quantification of benefits due to emission reductions are restricted to human health and materials, thus neglecting effects on crops, ecosystems, *et cetera*. In line with European Commission (1995b), the value of life is assumed to be 2.6 million ECU.

The benefits estimated for emission reductions of 50, 70, and 15kt for $SO_2$, $NO_2$, and $PM_{10}$, respectively, are dominated by reduced mortality from long-term exposure for particulate matter and nitrous oxides whereas the benefits achievable by a reduction in sulphur dioxide emissions are mainly due to reduced short term exposure. The corresponding figures are shown in Tab. A2.4. The emission reductions for lead are not quantified and therefore lead is left out.

| | Emission reduction | short-term exposure | long-term exposure | materials | Total benefit | total benefit per unit emission | benefit per unit emission, only short term effects and materials |
|---|---|---|---|---|---|---|---|
| Unit | t | mio. ECU | mio. ECU | mio. ECU | mio. ECU | ECU/t | ECU/t |
| Sulphur oxides as $SO_2$ | 50'000 | 1-3'470 | 26-255 | - | 85-3'783 | 1'700-76'000 | 20-69'000 |
| Nitrogen oxides as $NO_2$ | 70'000 | 0-1'955 [1]) | 408-3'945 | 58 | 408-5'900 | 5'800-84'000 | 830-29'000 |
| Particulates | 15'000 | 1-2'734 | 5'006-48'512 | n.q. | 5'007-51'246 | 330'000-3'400'000 | 67-180'000 |

Tab. A2.4: Emission reductions and benefits from reduced short- and long-term exposure as well as reduced materials damage in European cities (IVM et al. 1997, p. x).

[1]): Sum of benefits related to $NO_2$ and secondary $PM_{10}$ (nitrates).

Based on a simple city-air-quality model, the results show much higher damage costs (or benefits) related to an increase (or decrease) in emissions of $SO_2$, $NO_2$, and $PM_{10}$, compared to the ExternE and the ESEERCO studies. This is mainly due to the fact that ground transport air emissions cause higher immission concentrations resulting in higher effect scores. The lower values for $NO_2$ compared to $SO_2$ may be reasoned by not considering effects related to crop damages, effects outside of the cities (which are included in the ExternE studies), and by different human health exposure-response functions (cf. IVM et al. 1997, p. 56ff.). The industrial emissions are assumed to have lower effects (one fifth compared to transport emissions). If this is considered in the figures shown in Tab. A2.4, the maximum damage costs for acute effects per pollutant become comparable to the ones published in the ExternE and ESEERCO studies.

### A2.1.4 The Infras/Econcept/Prognos Study

While the ExternE and the New York State study are based on a detailed bottom-up approach, Infras et al. (1996) apply a top-down approach for the allocation of damage costs to single pollutants. For the determination of energy related external costs, they consider health effects, damages in agriculture, on forests, and on buildings. The damage costs (between 1.8 and 4.3 billion Swiss francs, 1993) are allocated to the emission flows that exceed the national emission targets[8] set by the Swiss federal clean air concept. In Tab. A2.5, the environmental external costs are listed.

Considering that a substantial part of the health effects caused by sulphur and nitrous oxides stems from secondary particulates, the figures for $NO_X$ and $SO_2$ are rather accurate and show a reasonable range. The hydrocarbons, on the contrary, seem to be overestimated by a factor of about ten.

| | SFr./t (1993) |
|---|---|
| Particulates | 11'000-25'000 |
| Sulphur oxides as $SO_2$ | 15'000-34'000 |
| Nitrogen oxides as $NO_2$ in winter time | 15'000-34'000 |
| Nitrogen oxides as $NO_2$ in summer time | 16'000-36'000 |
| NMVOC in summer time | 16'000-36'000 |

Tab. A2.5: Extra charges for pollutants to cover environmental external costs according to Infras et al. (1996, p. 94); 1SFr. = 0.595ECU (1990)

[8] Except for particulates, for which the total amount of current emissions is used.

## A2.2 Eco-indicator 95$^{RF}$

### A2.2.1 Ionising Radiation

The emission factors, and the physical impact factors for radionuclides are based on information given in European Commission (1995e).

| Emissions | Mining/ Milling | Conversion Malvesi | Conversion Pierrelatte | Enrichment | Fuel fabrication | Electricity Generation | Reprocessing |
|---|---|---|---|---|---|---|---|
| Unit | MBq/y | MBq/y | MBq/y | MBq/y | MBq/y | MBq/y | MBq/y |
| *emitted to air* | | | | | | | |
| Radio. C14 p [1]) | | | | | | 3.00E+05 | 5.80E+06 |
| Radio. Co58 p | | | | | | 1.13E+01 | |
| Radio. Co60 p | | | | | | 1.13E+01 | |
| Radio. Cs134 p | | | | | | 1.13E+01 | |
| Radio. Cs137 p | | | | | | 1.31E+01 | |
| Radio. H3 p | | | | | | 3.50E+06 | 3.73E+06 |
| Radio. I129 p | | | | | | | 4.16E+03 |
| Radio. I131 p | | | | | | 6.71E+01 | 5.76E+01 |
| Radio. I133 p | | | | | | 1.35E+02 | 2.55E+01 |
| Radio. Kr85 p | | | | | | 1.75E+06 | 5.80E+10 |
| Radio. Pu alpha p | | | | | | | 1.90E-03 |
| Radio. Pu238 p | | | | | | | 8.28E-04 |
| Radio. Rn222 p | 5.10E+08 | | | | | | |
| Radio. U234 p | 2.10E+03 | 1.28E+02 | 45.6 | 114.5 | 0.42 | | |
| Radio. U235 p | 8.90E+01 | 5.50E+00 | 2.00E+00 | 5.83 | 0.03 | | |
| Radio. U238 p | 2.10E+03 | 1.21E+02 | 43.1 | 60.17 | 0.1 | | |
| Radio. Xe133 p | | | | | | 2.45E+07 | |
| *emitted to water* | | | | | | | |
| Rad. Ag110m f | | | | | | 1.10E+04 | |
| Rad. Am241 s | | | | | | | 7.50E+03 |
| Rad. C14 s | | | | | | | 3.70E+06 |
| Rad. Cm alpha s | | | | | | | 3.60E+03 |
| Rad. Co58 f | | | | | | 1.60E+04 | |
| Rad. Co60 f | | | | | | 5.80E+03 | |
| Rad. Co60 s | | | | | | | 7.40E+05 |
| Rad. Cs134 f | | | | | | 7.00E+02 | |
| Rad. Cs134 s | | | | | | | 1.20E+05 |
| Rad. Cs137 f | | | | | | 1.20E+03 | |
| Rad. Cs137 s | | | | | | | 1.12E+06 |
| Rad. H3 f | | | | | | 3.30E+07 | |
| Rad. H3 s | | | | | | | 2.35E+09 |
| Rad. I129 s | | | | | | | 5.57E+04 |
| Rad. I131 f | | | | | | 3.00E+02 | |
| Rad. Mn54 f | | | | | | 6.00E+02 | |
| Rad. Pu alpha s | | | | | | | 12020 |
| Rad. Ru106 s | | | | | | | 7.14E+06 |
| Rad. Sb124 f | | | | | | 2.60E+03 | |
| Rad. Sb125 s | | | | | | | 5.02E+06 |
| Rad. Sr90 s | | | | | | | 1.19E+07 |
| Rad. U 238 f | | 6.03E+03 | 6.67 | 12 | 148.57 | | |
| Rad. U 238 s | | | | | | | 1.20E+03 |
| Rad. U234 f | | 6.37E+03 | 7.05 | 22.9 | 605.71 | | |
| Rad. U235 f | | 2.74E+02 | 3.03E-01 | 1.2 | 40 | | |

Tab. A2.6: Yearly releases of radionuclides by French nuclear facilities, European Commission (1995e).
[1]): to air: p: process specifc emission; to water: f: to fresh water; s: to sea water.

| Physical impacts | Mining/ Milling | Conversion Malvesi | Conversion Pierrelatte | Enrichment | Fuel fabrication | Electricity Generation | Reprocessing |
|---|---|---|---|---|---|---|---|
| Unit | man.Sv/y | man.Sv/y | man.Sv/y | man.Sv/y | man.Sv/y | man.Sv/y | man.Sv/y |
| *emitted to air* | | | | | | | |
| Radio. C14 p [1]) | | | | | | 4.24E+01 | 8.22E+02 |
| Radio. Co58 p | | | | | | 3.22E-06 | |
| Radio. Co60 p | | | | | | 1.23E-04 | |
| Radio. Cs134 p | | | | | | 8.89E-05 | |
| Radio. Cs137 p | | | | | | 1.17E-04 | |
| Radio. H3 p | | | | | | 3.81E-02 | 1.40E-01 |
| Radio. I129 p | | | | | | | 6.26E+00 |
| Radio. I131 p | | | | | | 6.95E-06 | 5.62E-06 |
| Radio. I133 p | | | | | | 8.65E-07 | 5.31E-08 |
| Radio. Kr85 p | | | | | | 1.67E-04 | 5.41E+00 |
| Radio. Pu alpha p | | | | | | | 1.04E-07 |
| Radio. Pu238 p | | | | | | | 3.68E-08 |
| Radio. Rn222 p | 8.00E+00 | | | | | | |
| Radio. U234 p | 1.33E-01 | 6.13E-03 | 6.23E-03 | 1.55E-02 | 5.68E-05 | | |
| Radio. U235 p | 1.20E-03 | 5.15E-05 | 5.10E-05 | 1.42E-04 | 6.48E-07 | | |
| Radio. U238 p | 1.13E-02 | 4.20E-04 | 3.48E-04 | 4.34E-04 | 6.28E-07 | | |
| Radio. Xe133 p | | | | | | 2.30E-03 | |
| *emitted to water* | | | | | | | |
| Rad. Ag110m f | | | | | | 3.67E-03 | |
| Rad. Am241 s | | | | | | | 1.54E-01 |
| Rad. C14 s | | | | | | | 2.89E+00 |
| Rad. Cm alpha s | | | | | | | 1.36E-01 |
| Rad. Co58 f | | | | | | 4.33E-04 | |
| Rad. Co60 f | | | | | | 1.70E-01 | |
| Rad. Co60 s | | | | | | | 1.93E-01 |
| Rad. Cs134 f | | | | | | 6.67E-02 | |
| Rad. Cs134 s | | | | | | | 6.23E-03 |
| Rad. Cs137 f | | | | | | 1.33E-01 | |
| Rad. Cs137 s | | | | | | | 5.87E-02 |
| Rad. H3 f | | | | | | 8.37E-03 | |
| Rad. H3 s | | | | | | | 1.94E-03 |
| Rad. I129 s | | | | | | | 1.16E-02 |
| Rad. I131 f | | | | | | 1.00E-04 | |
| Rad. Mn54 f | | | | | | 1.23E-04 | |
| Rad. Pu alpha s | | | | | | | 5.89E-02 |
| Rad. Ru106 s | | | | | | | 6.80E-01 |
| Rad. Sb124 f | | | | | | 1.40E-03 | |
| Rad. Sb125 s | | | | | | | 4.90E-02 |
| Rad. Sr90 s | | | | | | | 3.17E-02 |
| Rad. U 238 f | | 9.33E-05 | 9.97E-06 | 1.80E-05 | 2.22E-04 | | |
| Rad. U 238 s | | | | | | | 1.33E-05 |
| Rad. U234 f | | 9.50E-05 | 1.11E-05 | 3.60E-05 | 9.52E-04 | | |
| Rad. U235 f | | 4.47E-06 | 4.66E-07 | 1.80E-06 | 6.15E-05 | | |

Tab. A2.7: Yearly physical impacts of the emissions from nuclear facilities, European Commission (1995e).
[1]): to air: p: process specifc emission; to water: f: to fresh water; s: to sea water.

| Specific dose in man.Sv/kBq | Mining/ Milling | Conversion Malvesi | Conversion Pierrelatte | Enrichment | Fuel fabrication | Electricity Generation | Reproces-sing | Average dose 3) |
|---|---|---|---|---|---|---|---|---|
| *emitted to air* | | | | | | | | |
| Radio. C14 p 1) | | | | | | 1.41E-07 | 1.42E-07 | **1.42E-07** |
| Radio. Co58 p | | | | | | 2.85E-10 | | **2.85E-10** |
| Radio. Co60 p | | | | | | 1.09E-08 | | **1.09E-08** |
| Radio. Cs134 p | | | | | | 7.87E-09 | | **7.87E-09** |
| Radio. Cs137 p | | | | | | 8.92E-09 | | **8.92E-09** |
| Radio. H3 p | | | | | | 1.09E-11 | 3.75E-11 | **1.71E-11** |
| Radio. I129 p | | | | | | | 1.51E-06 | **1.51E-06** |
| Radio. I131 p | | | | | | 1.04E-10 | 9.76E-11 | **1.02E-10** |
| Radio. I133 p | | | | | | 6.41E-12 | 2.08E-12 | **6.19E-12** |
| Radio. Kr85 p | | | | | | 9.54E-14 | 9.32E-14 | **9.32E-14** |
| Radio. Pb210 p 2) | | | | | | | | **1.00E-09** |
| Radio. Po210 p 2) | | | | | | | | **1.00E-09** |
| Radio. Pu alpha p | | | | | | | 5.46E-08 | **5.46E-08** |
| Radio. Pu238 p | | | | | | | 4.45E-08 | **4.45E-08** |
| Radio. Rn222 p | 1.57E-11 | | | | | | | **1.57E-11** |
| LT Radio. Rn222 p 1) | 1.57E-11 | | | | | | | **1.57E-11** |
| Radio. Th230 p 2) | | | | | | | | **3.00E-08** |
| Radio. U234 p | 6.36E-08 | 4.79E-08 | 1.37E-07 | 1.35E-07 | 1.35E-07 | | | **6.40E-08** |
| Radio. U235 p | 1.35E-08 | 9.36E-09 | 2.55E-08 | 2.44E-08 | 2.16E-08 | | | **1.36E-08** |
| Radio. U238 p | 5.38E-09 | 3.47E-09 | 8.08E-09 | 7.22E-09 | 6.28E-09 | | | **5.38E-09** |
| Radio. Xe133 p | | | | | | 9.39E-14 | | **9.39E-14** |
| *emitted to water* | | | | | | | | |
| Rad. Ag110m f | | | | | | 3.34E-10 | | **3.34E-10** |
| Rad. Am241 s | | | | | | | 2.05E-08 | **2.05E-08** |
| Rad. C14 s | | | | | | | 7.81E-10 | **7.81E-10** |
| Rad. Cm alpha s | | | | | | | 3.78E-08 | **3.78E-08** |
| Rad. Co58 f | | | | | | 2.71E-11 | | **2.71E-11** |
| Rad. Co60 f | | | | | | 2.93E-08 | | **2.93E-08** |
| Rad. Co60 s | | | | | | | 2.61E-10 | **2.61E-10** |
| Rad. Cs134 f | | | | | | 9.53E-08 | | **9.53E-08** |
| Rad. Cs134 s | | | | | | | 5.19E-11 | **5.19E-11** |
| Rad. Cs137 f | | | | | | 1.11E-07 | | **1.11E-07** |
| Rad. Cs137 s | | | | | | | 5.24E-11 | **5.24E-11** |
| Rad. H3 f | | | | | | 2.54E-13 | | **2.54E-13** |
| Rad. H3 s | | | | | | | 8.26E-16 | **8.26E-16** |
| Rad. I129 s | | | | | | | 2.08E-10 | **2.08E-10** |
| Rad. I131 f | | | | | | 3.33E-10 | | **3.33E-10** |
| Rad. Mn54 f | | | | | | 2.05E-10 | | **2.05E-10** |
| Rad. Pu alpha s | | | | | | | 4.90E-09 | **4.90E-09** |
| Rad. Ra 226 f 4) | | | | | | | | **8.45E-11** |
| Rad. Ru106 s | | | | | | | 9.52E-11 | **9.52E-11** |
| Rad. Sb124 f | | | | | | 5.38E-10 | | **5.38E-10** |
| Rad. Sb125 s | | | | | | | 9.76E-12 | **9.76E-12** |
| Rad. Sr90 s | | | | | | | 2.66E-12 | **2.66E-12** |
| Rad. U 238 f | | 1.55E-11 | 1.49E-09 | 1.50E-09 | 1.49E-09 | | | **1.74E-11** |
| Rad. U 238 s | | | | | | | 1.11E-11 | **1.11E-11** |
| Rad. U234 f | | 1.49E-11 | 1.57E-09 | 1.57E-09 | 1.57E-09 | | | **1.77E-11** |
| Rad. U235 f | | 1.63E-11 | 1.54E-09 | 1.50E-09 | 1.54E-09 | | | **1.96E-11** |

Tab. A2.8: Specific doses, calculated on the basis of the emissions (Tab. A2.6) and the corresponding physical impacts (Tab. A2.7) of the French nuclear fuel cycle, according to European Commission (1995e).

1): to air: p: process specifc emission; to water: f: to fresh water; s: to sea water; LT: long term; (Radon emissions occuring during 80'000 years (Frischknecht et al. 1996a, Part VII Kernenergie, p. 48)

2): specific doses given in UNSCEAR (1993, p. 137)

3): The average dose is determined based on the specific doses per step in the fuel cycle weighted with the respective emissions (see Tab. A2.6).

4): based on the assumption that the $^{226}$Ra-emission of 2kBq/kg natural uranium released during mining and milling (Frischknecht et al. 1996, Part VII Kernenergie, p. 56) leads to the $^{226}$Ra concentration in rivers of 40Bq/m$^3$ reported in European Commission (1995e, p. 109).

### A2.2.2 Reduction Factors and European Yearly Impact Scores

| | Unit | European Score | Reduction factor | Reference [1]) |
|---|---|---|---|---|
| Greenhouse effect 100a 1995 | kg $CO_2$-equiv. | $6.65 \cdot 10^{12}$ | 5 | Müller-Wenk et al. 1996 |
| Ozone layer depletion | kg R11-equiv. | $4.67 \cdot 10^{8}$ | 10 | Müller-Wenk et al. 1996 |
| Acidification | kg $SO_X$-equiv. | $4.98 \cdot 10^{10}$ | 10 | Goedkoop 1995 |
| Eutrophication | kg $PO_4$-equiv. | $1.94 \cdot 10^{10}$ | 5 | Goedkoop 1995 |
| Heavy metals | kg Pb-equiv. | $3.47 \cdot 10^{7}$ | 5 | Goedkoop 1995 |
| Carcinogenic substances | kg PAH-equiv. | $1.38 \cdot 10^{7}$ | 10 | Goedkoop 1995 |
| Winter smog | kg $SO_2$-equiv. | $3.77 \cdot 10^{10}$ | 100 | This thesis |
| Summer smog | kg $C_2H_4$-equiv. | $1.94 \cdot 10^{10}$ | 25 | This thesis |
| Ionising Radiation | kBq $^{129}I$-equiv. | $1.46 \cdot 10^{10}$ | 2.2 | This thesis |
| Pesticides | active ingr. kg | $4.8 \cdot 10^{8}$ | 10 | Müller-Wenk et al. 1996 |

Tab. A2.9: Reduction factors and impact scores in the Eco-indicator $95^{RF}$. For the reasoning about changes of reduction factors and impact scores, see Chapter 8. The European flows of ecological commodities are shown in Tab. A2.10, the characterisation factors to calculate the European scores in Tab. A2.12. The Eco-indicator $95^{RF}$ of Europes yearly emissions amounts to 182.2 points.
[1]): Reference in relation to the reduction factors.

### A2.2.3 European Yearly Emissions

| European emissions 1990 | kg | Reference | European emissions 1990 | kg | Reference |
|---|---|---|---|---|---|
| *Emissions to air:* | | | R113 FCKW p | 3.47E+07 | Goedkoop (1995) |
| 1,1,1-Trichlorethan p | 2.30E+08 | Berdowski (1997) | R114 FCKW p | 2.87E+06 | Goedkoop (1995) |
| As Arsen p | 9.04E+05 | Berdowski (1997) | R115 FCKW p | 3.04E+06 | Goedkoop (1995) |
| BaP Benzo(a)pyren p | 143000 | Schmucki (1996) | R12 FCKW p | 1.32E+08 | Goedkoop (1995) |
| Benzol p | 1.80E+08 | Schmucki (1996) | R13 FCKW p | 8.70E+04 | Goedkoop (1995) |
| Cd Cadmium p | 3.80E+05 | Berdowski (1997) | R141b H-FKW p | 7.25E+05 | Goedkoop (1995) |
| CH3Br p | 2.58E+06 | Goedkoop (1995) | R142b H-FKW p | 2.97E+07 | Goedkoop (1995) |
| CH4 Methan p | 3.47E+10 | Eurostat (1995) | R22 FCKW p | 6.15E+07 | Goedkoop (1995) |
| CO Kohlenmonoxid p | 6.76E+10 | Eurostat (1995) | SOx als SO2 p | 2.73E+10 | Eurostat (1995) |
| CO2 Kohlendioxid p | 4.42E+12 | Eurostat (1995) | TCDD-Aequivalente [1]) | 8.83E+12 | Berdowski (1997) |
| Cr Chrom p | 1560000 | Berdowski (1997) | Tetrachlormethan p | 2.25E+07 | Goedkoop (1995) |
| H 1211 Halon p | 6.15E+06 | Goedkoop (1995) | Xylole p | 9.63E+08 | Berdowski (1997) |
| H 1301 Halon p | 4.93E+06 | Goedkoop (1995) | Zn Zink p | 1.73E+07 | Berdowski (1997) |
| Hexachlorbenzol HCB s | 8.04E+03 | Berdowski (1997) | *Emissions to water:* | | |
| Hg Quecksilber p | 3.36E+05 | Berdowski (1997) | Ion Antimon Sb f | 5.58E+05 | Schmucki (1996) |
| Mn Mangan p | 6.49E+05 | Goedkoop (1995) | Ion Arsen f | 1.63E+06 | Goedkoop (1995) |
| N2O Lachgas p | 1.32E+09 | Eurostat (1995) | Ion Barium f | 2.99E+04 | Goedkoop (1995) |
| NH3 Ammoniak p | 5.52E+09 | Eurostat (1995) | Ion Blei f | 5.00E+05 | Goedkoop (1995) |
| Ni Nickel p | 5.97E+06 | Berdowski (1997) | Ion Bor f | 9.11E+05 | Goedkoop (1995) |
| Nitrate p | 1.78E+10 | Goedkoop (1995) | Ion Cadmium f | 4.70E+05 | Schmucki (1996) |
| NMVOC p | 1.71E+10 | Eurostat (1995) | Ion Chrom-III f | 4.66E+05 | Goedkoop (1995) |
| NOx Stickoxide als NO2 p | 1.73E+10 | Eurostat (1995) | Ion Kupfer f | 5.40E+06 | Schmucki (1996) |
| PAH Polyzyklische aromatische HC p | 1.10E+07 | Berdowski (1997) | Ion Mangan f | 1.45E+07 | Goedkoop (1995) |
| Partikel p | 1.13E+10 | Goedkoop (1995) | Ion Molybdaen f | 6.21E+04 | Goedkoop (1995) |
| Pb Blei p | 2.48E+07 | Berdowski (1997) | Ion Nickel f | 5.20E+06 | Schmucki (1996) |
| Pentachlorphenol PCP s | 1.45E+06 | Berdowski (1997) | Ion Quecksilber f | 1.13E+04 | Goedkoop (1995) |
| R11 FCKW p | 1.32E+08 | Goedkoop (1995) | Phosphate f | 7.70E+09 | Goedkoop (1995) |

Tab. A2.10: Yearly Emissions in 23 European countries (used as normalisation values in Eco-indicator $95^{RF}$).
[1]): in ng

### A2.2.4 European Gross Domestic Product

| Country | Gross domestic product 1990 | Country | Gross domestic product 1990 |
|---|---|---|---|
| | $10^9$ US-$ | | $10^9$ US-$ |
| Austria | 159.5 | Norway | 115.5 |
| Belgium | 193.8 | Portugal | 67.5 |
| Denmark | 129.1 | Spain | 491.9 |
| Finland | 134.8 | Sweden | 229.8 |
| France | 1195.4 | Switzerland | 228.4 |
| Germany | 1640.1 | United Kingdom | 975.5 |
| Greece | 82.9 | CSSR | 45.2 |
| Iceland | 6.2 | Hungary | 35.9 |
| Ireland | 45.6 | Romania | 38.2 |
| Italy | 1093.9 | Bulgaria | 20.7 |
| Luxembourg | 10.3 | Ex-Yugoslavia | 31.9 |
| Netherlands | 283.7 | Total Western Europe | 7083.9 |
| | | Total Europe | 7255.8 |

Tab. A2.11: Gross Domestic Product 1990 of European countries considered in Eco-indicator $95^{RF}$, in US-$; OECD (1997), UN (1996).

### A2.2.5 Characterisation Factors and Eco-indicator $95^{RF}$ Points

Substances not included in this list are not weighted due to lack of data or relevance. Land use and resource (incl. energy) consumption, in particular, are not included due to missing adequate methodological knowledge and missing data for the processes within the product systems analysed in this work.

| | Unit | Green-house effect 1995 [1]) | Ozone layer depletion | Acidifi-cation | Eutrophi-cation | Heavy metals | Carcino-genic sub-stances | Winter smog | Summer smog | Ionising radiation | Eco-indicator $95^{RF}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | kg $CO_2$-equiv. | kg R11-equiv. | kg $SO_X$-equiv. | kg $PO_4$-equiv. | kg Pb-equiv. | kg PAH-equiv. | kg $SO_2$-equiv. | kg $C_2H_4$-equiv. | kBq $^{129}$I-equiv. | $1\cdot10^{-9}$ points |
| *Emissions to air:* | | | | | | | | | | | |
| 1,1,1-Trichlorethan p | kg | -225 | 0.12 | 0 | 0 | 0 | 0 | 0 | 0.021 | 0 | 2.43E+00 |
| Acetaldehyd s | kg | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.527 | 0 | 6.80E-01 |
| Aceton s | kg | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.178 | 0 | 2.30E-01 |
| Aldehyde p | kg | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.443 | 0 | 5.72E-01 |
| Alkane p | kg | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.398 | 0 | 5.14E-01 |
| Alkane s | kg | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.398 | 0 | 5.14E-01 |
| Alkene p | kg | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.906 | 0 | 1.17E+00 |
| Alkene s | kg | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.906 | 0 | 1.17E+00 |
| Aromaten p | kg | 0 | 0 | 0 | 0 | 0 | 0.000044 | 0 | 0.761 | 0 | 9.90E-01 |
| Aromaten s | kg | 0 | 0 | 0 | 0 | 0 | 0.000044 | 0 | 0.761 | 0 | 9.90E-01 |
| As Arsen m | kg | 0 | 0 | 0 | 0 | 0 | 0.044 | 0 | 0 | 0 | 3.18E+01 |
| As Arsen p | kg | 0 | 0 | 0 | 0 | 0 | 0.044 | 0 | 0 | 0 | 3.18E+01 |
| As Arsen s | kg | 0 | 0 | 0 | 0 | 0 | 0.044 | 0 | 0 | 0 | 3.18E+01 |
| BaP Benzo(a)pyren m | kg | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 7.24E+02 |
| BaP Benzo(a)pyren p | kg | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 7.24E+02 |
| BaP Benzo(a)pyren s | kg | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 7.24E+02 |
| Benzaldehyd s | kg | 0 | 0 | 0 | 0 | 0 | 0 | 0 | -0.334 | 0 | -4.31E-01 |
| Benzol m | kg | 0 | 0 | 0 | 0 | 0 | 0.000044 | 0 | 0.189 | 0 | 2.52E-01 |
| Benzol p | kg | 0 | 0 | 0 | 0 | 0 | 0.000044 | 0 | 0.189 | 0 | 2.52E-01 |
| Benzol s | kg | 0 | 0 | 0 | 0 | 0 | 0.000044 | 0 | 0.189 | 0 | 2.52E-01 |
| Butan p | kg | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.36 | 0 | 4.65E-01 |
| Butan s | kg | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.36 | 0 | 4.65E-01 |
| Buten p | kg | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.976 | 0 | 1.26E+00 |
| C2F6 p | kg | 9200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 6.91E+00 |
| Cd Cadmium m | kg | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1.44E+02 |
| Cd Cadmium p | kg | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1.44E+02 |
| Cd Cadmium s | kg | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1.44E+02 |
| CF4 p | kg | 6500 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4.88E+00 |
| CH3Br p | kg | 0 | 0.6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.28E+01 |
| CH4 Methan m | kg | 21 | 0 | 0 | 0 | 0 | 0 | 0 | 0.007 | 0 | 2.48E-02 |
| CH4 Methan p | kg | 21 | 0 | 0 | 0 | 0 | 0 | 0 | 0.007 | 0 | 2.48E-02 |
| CH4 Methan s | kg | 21 | 0 | 0 | 0 | 0 | 0 | 0 | 0.007 | 0 | 2.48E-02 |
| CO2 Kohlendioxid m | kg | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 7.52E-04 |
| CO2 Kohlendioxid p | kg | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 7.52E-04 |
| CO2 Kohlendioxid s | kg | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 7.52E-04 |
| Cr Chrom m | kg | 0 | 0 | 0 | 0 | 0.44 | 0 | 0 | 0 | 0 | 6.35E+01 |
| Cr Chrom p | kg | 0 | 0 | 0 | 0 | 0.44 | 0 | 0 | 0 | 0 | 6.35E+01 |
| Cr Chrom s | kg | 0 | 0 | 0 | 0 | 0.44 | 0 | 0 | 0 | 0 | 6.35E+01 |
| Dichlormethan p | kg | 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0.01 | 0 | 1.97E-02 |
| Ethan p | kg | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.082 | 0 | 1.06E-01 |
| Ethan s | kg | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.082 | 0 | 1.06E-01 |
| Ethanol p | kg | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.268 | 0 | 3.46E-01 |
| Ethanol s | kg | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.268 | 0 | 3.46E-01 |
| Ethen p | kg | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1.29E+00 |
| Ethen s | kg | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1.29E+00 |
| Ethylbenzol p | kg | 0 | 0 | 0 | 0 | 0 | 0.000044 | 0 | 0.593 | 0 | 7.73E-01 |
| Ethylbenzol s | kg | 0 | 0 | 0 | 0 | 0 | 0.000044 | 0 | 0.593 | 0 | 7.73E-01 |
| Ethylenoxid p | kg | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.377 | 0 | 4.87E-01 |
| Formaldehyd p | kg | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.421 | 0 | 5.43E-01 |
| Formaldehyd s | kg | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.421 | 0 | 5.43E-01 |
| H 1211 Halon p | kg | 0 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 8.56E+01 |
| H 1301 Halon p | kg | -22400 | 16 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3.26E+02 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| HCl Salzsaeure p | kg | 0 | 0 | 0.88 | 0 | 0 | 0 | 0 | 0 | 0 | 1.77E-01 |
| HCl Salzsaeure s | kg | 0 | 0 | 0.88 | 0 | 0 | 0 | 0 | 0 | 0 | 1.77E-01 |
| Heptan p | kg | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.529 | 0 | 6.83E-01 |
| Hexan p | kg | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.421 | 0 | 5.43E-01 |
| HF Fluorwasserstoff p | kg | 0 | 0 | 1.6 | 0 | 0 | 0 | 0 | 0 | 0 | 3.21E-01 |
| HF Fluorwasserstoff s | kg | 0 | 0 | 1.6 | 0 | 0 | 0 | 0 | 0 | 0 | 3.21E-01 |
| Hg Quecksilber m | kg | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1.44E+02 |
| Hg Quecksilber p | kg | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1.44E+02 |
| Hg Quecksilber s | kg | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1.44E+02 |
| LT Radio. Rn222 | kBq | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.04E-05 | 1.57E-06 |
| Methanol s | kg | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.123 | 0 | 1.59E-01 |
| Mn Mangan p | kg | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1.44E+02 |
| Mn Mangan s | kg | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1.44E+02 |
| N2O Lachgas m | kg | 310 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2.33E-01 |
| N2O Lachgas p | kg | 310 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2.33E-01 |
| N2O Lachgas s | kg | 310 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2.33E-01 |
| NH3 Ammoniak p | kg | 0 | 0 | 1.88 | 0.3494 | 0 | 0 | 0 | 0 | 0 | 4.68E-01 |
| NH3 Ammoniak s | kg | 0 | 0 | 1.88 | 0.3494 | 0 | 0 | 0 | 0 | 0 | 4.68E-01 |
| Ni Nickel m | kg | 0 | 0 | 0 | 0 | 0 | 0.0044 | 0 | 0 | 0 | 3.18E+02 |
| Ni Nickel p | kg | 0 | 0 | 0 | 0 | 0 | 0.44 | 0 | 0 | 0 | 3.18E+02 |
| Ni Nickel s | kg | 0 | 0 | 0 | 0 | 0 | 0.44 | 0 | 0 | 0 | 3.18E+02 |
| Nitrate p | kg | 0 | 0 | 0 | 0.42 | 0 | 0 | 0 | 0 | 0 | 1.09E-01 |
| NMVOC m | kg | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.416 | 0 | 5.37E-01 |
| NMVOC p | kg | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.416 | 0 | 5.37E-01 |
| NMVOC s | kg | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.416 | 0 | 5.37E-01 |
| NOx Stickoxide als NO2 m | kg | 0 | 0 | 0.7 | 0.13 | 0 | 0 | 0.6 | 0.645 | 0 | 2.60E+00 |
| NOx Stickoxide als NO2 p | kg | 0 | 0 | 0.7 | 0.13 | 0 | 0 | 0.6 | 0.645 | 0 | 2.60E+00 |
| NOx Stickoxide als NO2 s | kg | 0 | 0 | 0.7 | 0.13 | 0 | 0 | 0.6 | 0.645 | 0 | 2.60E+00 |
| PAH Polyzykl. aromatische HC p | kg | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 7.24E+02 |
| PAH Polyzykl. aromatische HC s | kg | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 7.24E+02 |
| Partikel m | kg | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 5.31E+00 |
| Partikel p | kg | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00E+00 |
| Partikel s | kg | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 5.31E+00 |
| Pb Blei m | kg | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1.44E+02 |
| Pb Blei p | kg | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1.44E+02 |
| Pb Blei s | kg | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1.44E+02 |
| Pentan p | kg | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.408 | 0 | 5.27E-01 |
| Pentane s | kg | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.408 | 0 | 5.27E-01 |
| Propan p | kg | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.42 | 0 | 5.42E-01 |
| Propan s | kg | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.42 | 0 | 5.42E-01 |
| Propen p | kg | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.03 | 0 | 1.33E+00 |
| Propen s | kg | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.03 | 0 | 1.33E+00 |
| Propionaldehyd s | kg | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.603 | 0 | 7.78E-01 |
| Radio. C14 p | kBq | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 9.41E-02 | 1.42E-02 |
| Radio. Co58 p | kBq | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.89E-04 | 2.85E-05 |
| Radio. Co60 p | kBq | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 7.24E-03 | 1.09E-03 |
| Radio. Cs134 p | kBq | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 5.23E-03 | 7.88E-04 |
| Radio. Cs137 p | kBq | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 5.92E-03 | 8.93E-04 |
| Radio. H3 p | kBq | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.14E-05 | 1.71E-06 |
| Radio. I129 p | kBq | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1.51E-01 |
| Radio. I131 p | kBq | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 6.80E-05 | 1.03E-05 |
| Radio. I133 p | kBq | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4.11E-06 | 6.20E-07 |
| Radio. Kr85 p | kBq | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 6.20E-08 | 9.34E-09 |
| Radio. Kr85m p | kBq | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 6.20E-08 | 9.34E-09 |
| Radio. Pu alpha p | kBq | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3.63E-02 | 5.47E-03 |
| Radio. Pu238 p | kBq | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2.96E-02 | 4.45E-03 |
| Radio. Rn222 p | kBq | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.04E-05 | 1.57E-06 |
| Radio. Rn222 s | kBq | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.04E-05 | 1.57E-06 |
| Radio. U234 p | kBq | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4.25E-02 | 6.41E-03 |
| Radio. U235 p | kBq | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 9.01E-03 | 1.36E-03 |
| Radio. U238 p | kBq | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3.58E-03 | 5.39E-04 |
| Radio. U238 s | kBq | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3.58E-03 | 5.39E-04 |
| Radio. Xe133 p | kBq | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 6.24E-08 | 9.40E-09 |
| Radio. Xe133m p | kBq | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 6.24E-08 | 9.40E-09 |
| R11 FCKW p | kg | 1320 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2.24E+01 |
| R113 FCKW p | kg | 3100 | 1.07 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2.52E+01 |
| R114 FCKW p | kg | 0 | 0.8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.71E+01 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| R115 FCKW p | kg | 0 | 0.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.07E+01 |
| R12 FCKW p | kg | 6650 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2.64E+01 |
| R13 FCKW p | kg | 0 | 1.07 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2.29E+01 |
| R134a FKW p | kg | 1300 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 9.77E-01 |
| R141b H-FKW p | kg | 270 | 0.11 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2.56E+00 |
| R142b H-FKW p | kg | 1650 | 0.065 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2.63E+00 |
| R22 FCKW p | kg | 1350 | 0.055 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2.19E+00 |
| SF6 p | kg | 23900 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.80E+01 |
| SOx als SO2 m | kg | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 2.85E+00 |
| SOx als SO2 p | kg | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 2.85E+00 |
| SOx als SO2 s | kg | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 2.85E+00 |
| Styrol p | kg | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.761 | 0 | 9.82E-01 |
| TCDD-Aequivalente | ng | 0 | 0 | 0 | 0 | 0 | 5E-10 | 0 | 0 | 0 | 3.62E-07 |
| Tetrachlormethan p | kg | -1530 | 1.08 | 0 | 0 | 0 | 0 | 0 | 0.021 | 0 | 2.20E+01 |
| Toluol p | kg | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.563 | 0 | 7.27E-01 |
| Toluol s | kg | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.563 | 0 | 7.27E-01 |
| Trichlormethan (Chloroform) p | kg | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3.01E-03 |
| Vinyl Chlorid p | kg | 0 | 0 | 0 | 0 | 0 | 0.000011 | 0 | 1.2 | 0 | 2.71E-02 |
| Xylole p | kg | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.849 | 0 | 1.10E+00 |
| Xylole s | kg | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.849 | 0 | 1.10E+00 |
| ***Emissions to water:*** | | | | | | | | | | | |
| Ammoniak als N f | kg | 0 | 0 | 0 | 0.4243 | 0 | 0 | 0 | 0 | 0 | 1.10E-01 |
| Ammoniak als N s | kg | 0 | 0 | 0 | 0.4243 | 0 | 0 | 0 | 0 | 0 | 1.10E-01 |
| COD f | kg | 0 | 0 | 0 | 0.022 | 0 | 0 | 0 | 0 | 0 | 5.68E-03 |
| COD s | kg | 0 | 0 | 0 | 0.022 | 0 | 0 | 0 | 0 | 0 | 5.68E-03 |
| Ion Antimon Sb f | kg | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 2.88E+02 |
| Ion Arsen f | kg | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1.44E+02 |
| Ion Arsen s | kg | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1.44E+02 |
| Ion Barium f | kg | 0 | 0 | 0 | 0 | 0.014 | 0 | 0 | 0 | 0 | 2.02E+01 |
| Ion Barium s | kg | 0 | 0 | 0 | 0 | 0.014 | 0 | 0 | 0 | 0 | 2.02E+01 |
| Ion Blei f | kg | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1.44E+02 |
| Ion Blei s | kg | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1.44E+02 |
| Ion Bor f | kg | 0 | 0 | 0 | 0 | 0.03 | 0 | 0 | 0 | 0 | 4.33E+00 |
| Ion Bor s | kg | 0 | 0 | 0 | 0 | 0.03 | 0 | 0 | 0 | 0 | 4.33E+00 |
| Ion Cadmium f | kg | 0 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 4.33E+02 |
| Ion Cadmium s | kg | 0 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 4.33E+02 |
| Ion Chrom-III f | kg | 0 | 0 | 0 | 0 | 0.2 | 0 | 0 | 0 | 0 | 2.88E+01 |
| Ion Chrom-III s | kg | 0 | 0 | 0 | 0 | 0.2 | 0 | 0 | 0 | 0 | 2.88E+01 |
| Ion Chrom-VI f | kg | 0 | 0 | 0 | 0 | 0.2 | 0 | 0 | 0 | 0 | 2.88E+01 |
| Ion Chrom-VI s | kg | 0 | 0 | 0 | 0 | 0.2 | 0 | 0 | 0 | 0 | 2.88E+01 |
| Ion Kupfer f | kg | 0 | 0 | 0 | 0 | 0.005 | 0 | 0 | 0 | 0 | 7.21E-01 |
| Ion Kupfer s | kg | 0 | 0 | 0 | 0 | 0.005 | 0 | 0 | 0 | 0 | 7.21E-01 |
| Ion Mangan f | kg | 0 | 0 | 0 | 0 | 0.02 | 0 | 0 | 0 | 0 | 2.88E+00 |
| Ion Mangan s | kg | 0 | 0 | 0 | 0 | 0.02 | 0 | 0 | 0 | 0 | 2.88E+00 |
| Ion Molybdaen f | kg | 0 | 0 | 0 | 0 | 0.14 | 0 | 0 | 0 | 0 | 2.02E+01 |
| Ion Molybdaen s | kg | 0 | 0 | 0 | 0 | 0.14 | 0 | 0 | 0 | 0 | 2.02E+01 |
| Ion Nickel f | kg | 0 | 0 | 0 | 0 | 0.5 | 0 | 0 | 0 | 0 | 7.21E+01 |
| Ion Nickel s | kg | 0 | 0 | 0 | 0 | 0.5 | 0 | 0 | 0 | 0 | 7.21E+01 |
| Ion Quecksilber f | kg | 0 | 0 | 0 | 0 | 10 | 0 | 0 | 0 | 0 | 1.44E+03 |
| Ion Quecksilber s | kg | 0 | 0 | 0 | 0 | 10 | 0 | 0 | 0 | 0 | 1.44E+03 |
| Phosphate f | kg | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 2.58E-01 |
| Phosphate s | kg | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 2.58E-01 |
| Rad. Ag110m f | kBq | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2.22E-04 | 3.34E-05 |
| Rad. Am241 s | kBq | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.36E-02 | 2.06E-03 |
| Rad. C14 s | kBq | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 5.19E-04 | 7.82E-05 |
| Rad. Cm alpha s | kBq | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2.51E-02 | 3.78E-03 |
| Rad. Co58 f | kBq | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.80E-05 | 2.71E-06 |
| Rad. Co60 f | kBq | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.95E-02 | 2.93E-03 |
| Rad. Co60 s | kBq | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.73E-04 | 2.61E-05 |
| Rad. Cs134 f | kBq | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 6.33E-02 | 9.54E-03 |
| Rad. Cs134 s | kBq | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3.45E-05 | 5.20E-06 |
| Rad. Cs137 f | kBq | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 7.36E-02 | 1.11E-02 |
| Rad. Cs137 s | kBq | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3.48E-05 | 5.25E-06 |
| Rad. H3 f | kBq | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.69E-07 | 2.54E-08 |
| Rad. H3 s | kBq | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 5.48E-10 | 8.26E-11 |
| Rad. I129 s | kBq | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.38E-04 | 2.08E-05 |
| Rad. I131 f | kBq | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2.21E-04 | 3.34E-05 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Rad. Mn54 f | kBq | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.36E-04 | 2.05E-05 |
| Rad. Pu alpha s | kBq | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3.26E-03 | 4.91E-04 |
| Rad. Ra 226 f | kBq | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 5.61E-05 | 8.46E-06 |
| Rad. Ru106 s | kBq | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 6.33E-05 | 9.53E-06 |
| Rad. Sb124 f | kBq | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3.58E-04 | 5.39E-05 |
| Rad. Sb125 s | kBq | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 6.49E-06 | 9.77E-07 |
| Rad. Sr90 s | kBq | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.77E-06 | 2.67E-07 |
| Rad. U 238 f | kBq | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.16E-05 | 1.74E-06 |
| Rad. U 238 s | kBq | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 7.36E-06 | 1.11E-06 |
| Rad. U234 f | kBq | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.18E-05 | 1.78E-06 |
| Rad. U235 f | kBq | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.30E-05 | 1.96E-06 |
| Stickstoff Gesamt f | kg | 0 | 0 | 0 | 0.42 | 0 | 0 | 0 | 0 | 0 | 1.09E-01 |
| Stickstoff Gesamt s | kg | 0 | 0 | 0 | 0.42 | 0 | 0 | 0 | 0 | 0 | 1.09E-01 |
| Vinyl Chlorid in Wasser f | kg | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.021 | 0 | 2.71E-02 |

Tab. A2.12: Characterisation factors and Eco-indicator 95RF points. The values are based on Goedkoop (1995), and Tab. A2.9-A2.11. For explanations related to changes of characterisation factors in the categories "greenhouse effect", "winter smog", "summer smog", "ionising radiation", "heavy metals" and "carcinogenic substances" see Chapter 8.

[1]): The global warming potentials for a time horizon of 2090 (i.e., after 100 years) are applied including the indirect cooling effects of ozone depleting substances.

# Appendix 3 Private Costs of Energy Systems

## A3.1Introduction

The determination of "average" internal or private costs of heat and eletricity generated is not straightforward. Several parameters have an important influence on the costs. First, the interest rate applied may alter the competitiveness of the different technologies. In some cases the investments are decisive for the costs of energy delivered (i.e., nuclear power, photovoltaics, hydroelectric power plants, wind power, *et cetera*) whereas for other systems the price for the energy carrier contributes most to the costs. Second, the costs for the energy carriers (i.e., lignite, hard coal, heavy fuel oil, uranium, wood chips, light fuel oil, natural gas, and electricity) vary not only within time but, especially for natural gas and electricity, also from one country to another one and even within different regions of one country. Third, the load factor of the systems plays an important role. Whether a hard coal power plant is running during 6'000h per year or only during 2'000h influences the writing-off of the plant. Forth, the investment costs per kW is dependent on the surrounding conditions within which the technology is supposed to be installed. Taking these aspects into account, it gets obvious that the figures developed here and used in the case studies in Chapters 9 and 10 are for illustrative purposes only. They shall not be generalised and not be used to generally rank energy systems in terms of private costs. In this appendix, the calculation of private costs for a set of power plants and heating systems is described and reasoned. All cost calculations are performed using two different interest rates (2% as it is applied in Prognos (1996a&b) and 5%).

### A3.2Power Plants

In general, electricity for which the costs are determined in this appendix is base load electricity from fuel oil, lignite, hard coal, natural gas, nuclear, and run of river power plants. In addition, the specific costs for intermittent power generation systems, i.e., wind power, and two different photovoltaic power plants are computed without considering back-up systems. The costs for an energy saving measure completes the list of alternative systems. The CHP plant is described together with the heating systems in the next subchapter. The thermal power plants (fossil and nuclear) are assumed to run for 30 years (gas-fired power plant: 25 years) during 7'500h per year which is equivalent to a load factor of 85%. The hydroelectric run of river power plant is assumed to work at full load during 80 years and 4'570h per year (load factor of 52%, Frischknecht et al. (1996a, Part VIII Wasserkraft, p. 3)). For photovolatic systems, the Swiss average load factor of about 860h and a life time of 30 years is chosen for roof integrated systems (Frischknecht et al. 1996a, Part XII Photovoltaik, p. 90), whereas for the wind power plant the load factor is assumed to be 9% or 800h per year with a life time of 20 years. According to Buser et al. (1996), modern wind power plants recently installed on the Mont Crosin in Switzerland are expected to reach 1'000h. The efficiencies represent the average country specific situation of the technologies considered as summarised in Frischknecht et al. (1996a). They are only important for thermal power plants (fossil and nuclear).

The investment costs per kW vary between 155SFr. (energy saving bulb replacing an incandescent bulb) and 14'500SFr. (photovoltaic power plants, SOFAS (1997, p. 5)). According to Mutzner (1997, p. 57) the private investment costs for coal power plants vary between 2'700 and 3'600 SFr. per $kW_e$. Friedrich (1997) for hard coal and Hlubek et al. (1997) for a new lignite power plant indicate a value of about 2'300SFr. per $kW_e$. This value is used for both hard coal and lignite power plants. Dupuis et al. (1997) report generation costs in European countries based on a survey carried out by UNIPEDE. Based on fuel price scenario for coal and gas (see Tab. A3.1), interest rates of 5 and 10% respectively, nuclear fuel costs of 0.77 cECU (5%) and 0.84cECU (10%), base load facilities with a load factor of 85%, and a life time of 30 years for coal and nuclear and 25 years for gas combined cycle, the generation costs of electricity varies between 3 and 4.5 cECU for nuclear, 3.1 and 4.4 cECU for coal, and 3.0 and 4.5 cECU for gas.

| Per 1 TJ electricity | Unit [1]) | Nuclear | Coal | Natural Gas |
|---|---|---|---|---|
| *Fuel costs* | | | | |
| high | cECU/kWh | - | 1.12 | 2.2 |
| medium | cECU/kWh | 0.77/ 0.84 [2]) | 0.97 | 1.9 |
| low | cECU/kWh | - | 0.72 | 1.2 |
| *Electricity costs:* | | | | |
| high | cECU/kWh$_e$ | | 3.50/4.39 | 4.14/4.50 |
| medium | cECU/kWh$_e$ | 3.06/4.49 | 3.29/4.18 | 3.57/3.96 |
| low | cECU/kWh$_e$ | | 3.10/3.99 | 2.97/3.30 |

Tab. A3.1: Fuel and electricity costs of power plants to be commissioned in 2005 according to a European survey in 1996 carried out by UNIPEDE. Data about nuclear facilities was provided by France and Spain only; (Dupuis et al. 1997).
[1]): 1cECU= 0.01ECU, 1ECU _ 1.7SFr.
[2]): 5%/10% interest rate.

The variable and fixed operation costs are based on information given in Prognos (1996b, p. 64), Mutzner (1997, p. 57), Buser et al. (1996, p.50), and Friedrich (1997). In the case of nuclear energy, the costs for reprocessing, final disposal and the dismantling of the power plant are listed as variable operational costs which amount to 0.0075SFr. per kWh$_e$ according to Rogenmoser et al. (1995, p. 23).

| | Capacity | Efficiency | Operating hours | Energy demand/ production | Life time | Invest-ment costs | Fixed operation costs | Variable operation costs | Energy costs | Transmis-sion and distribu-tion costs |
|---|---|---|---|---|---|---|---|---|---|---|
| unit | kW | - | h | kWh | a | SFr./kW$_e$ | SFr./kWh$_e$ | SFr./kWh$_e$ | SFr./kWh$_e$ | SFr./kWh$_e$ |
| Heavy fuel oil power plant in Italy | 1'000'000 | 0.382 | 7500 | 7.5E+09 | 30 | 1500 | 0.009 | 0.003 | 0.052 | 0.104 |
| Natural gas power plant in NL | 256'000 | 0.39 | 7500 | 1.92E+09 | 25 | 1400 | 0.008 | 0.003 | 0.064 | 0.104 |
| Lignite power plant in Germany | 1'230'000 | 0.309 | 7500 | 9.23E+09 | 30 | 2300 | 0.021 | 0.003 | 0.016 | 0.104 |
| Hard coal power plant in Germany | 1'326'000 | 0.347 | 7500 | 9.95E+09 | 30 | 2300 | 0.011 | 0.003 | 0.029 | 0.104 |
| Nuclear power plant in France | 3'000'000 | 0.33 | 7500 | 2.25E+10 | 30 | 6000 | 0.022 | 0.008 | 0.015 | 0.104 |
| Hydro run of river power | 100'000 | 1 | 4570 | 4.57E+08 | 80 | 1500 | 0.016 | 0.009 | 0.000 | 0.104 |
| Gas combined cycle | 300'000 | 0.57 | 7500 | 2.25E+09 | 25 | 1400 | 0.008 | 0.003 | 0.044 | 0.104 |
| Pressurized Fluidized bed combustion | 500'000 | 0.47 | 7500 | 3.75E+09 | 30 | 2300 | 0.011 | 0.003 | 0.021 | 0.104 |
| Photovoltaics, roof integrated | 3 | 1 | 860 | 2580 | 25 | 14500 | 0.169 | 0.01 | 0.000 | 0.000 |
| Photovoltaics, wall integrated | 3 | 1 | 610 | 1830 | 25 | 14500 | 0.238 | 0.01 | 0.000 | 0.000 |
| Wind power | 150 | 1 | 800 | 120000 | 20 | 2000 | 0.125 | 0.00 | 0.000 | 0.082 |
| Energy saving measure | 0.049 | 1 | 2640 | 98 | 4 | 155 | 0.000 | 0.00 | 0.000 | 0.000 |
| References | a | a | b,a,c,i | | b,a | d,e,f,g | g,i | g,h | d,b | e |

Tab. A3.2: Economic parameters for the profitability calculations for different electricity generating technologies. References: a: Frischknecht et al. (1996a); b: Dupuis et al. (1997); c: Horbaty (1997); d: Friedrich (1997); e: Mutzner (1997); f: SOFAS (1997); g: Prognos (1996b); h: Rogenmoser et al. (1995); i: Buser et al. (1996)

The data for the energy costs are based on information given in Friedrich (1997) for fossil power plants, and in Dupuis et al. (1997) for nuclear power plants. The costs vary between 0.005SFr. per kWh$_{th}$ for uranium and lignite to 0.025SFr. per kWh$_{th}$ for natural gas.

Finally, average costs for transmission, and distribution to the clients (0.104SFr. per kWh$_e$, Mutzner (1997, p. 64)) is added to the large, centralised technologies (i.e., fossil and nuclear power plants and hydroelectric power plants). For wind power, only the distribution and clients costs are considered (0.087SFr. per $kWh_e$). Photovoltaic power plants, CHP plants and the energy saving measure are assumed to cause no additional costs. As already mentioned, no back-up systems are considered for power plants with intermittent electricity generation (i.e., photovoltaic and wind power plants). The data used for the profitability calculations are summarised in Tab. A3.2.

Based on these parameters, the total private costs per $kWh_e$ may be computed. The cost data for coal power plants coincide fairly well with the ones shown in the UNIPEDE survey (Dupuis et al. 1997), which was made in view of a power plant commissioning in 2005. The capital costs for fossil-fueled power plants are low compared to nuclear and wind power plants. Total costs, however, are rather close together with nuclear electricity being the most expensive and hydro electricity being the least expensive of today's most important electricity generating technologies[1]. The costs for wind power amount to between 0.41SFr. and 0.47SFr. per $kWh_e$ whereas photovoltaic electricity shows private costs between 1.05 and 1.93SFr. per $kWh_e$, dependent on the orientation of the panels (roof or wall integrated). In addition to these cost figures, the price paid for electricity delivered to the grid by decentralised CHP plants is shown (redelivery tariff). It is lower by about 35% compared to the average costs of electricity for private clients (0.187SFr. per $kWh_e$).

| in SFr./$kWh_e$ | Capital costs | | Total costs | |
|---|---|---|---|---|
| | 2% [1]) | 5% [1]) | 2% [1]) | 5% [1]) |
| Heavy fuel oil power plant in Italy | 0.009 | 0.013 | 0.177 | 0.181 |
| Natural gas power plant in NL | 0.010 | 0.013 | 0.189 | 0.193 |
| Lignite power plant in Germany | 0.014 | 0.020 | 0.158 | 0.165 |
| Hard coal power plant in Germany | 0.014 | 0.020 | 0.160 | 0.167 |
| Nuclear power plant in France | 0.036 | 0.052 | 0.185 | 0.201 |
| Hydro run of river power | 0.008 | 0.017 | 0.137 | 0.146 |
| Gas combined cycle | 0.010 | 0.013 | 0.169 | 0.172 |
| Pressurized Fluidized bed combustion | 0.014 | 0.020 | 0.153 | 0.159 |
| Photovoltaics, roof integrated | 0.864 | 1.196 | 1.042 | 1.375 |
| Photovoltaics, wall integrated | 1.218 | 1.687 | 1.465 | 1.934 |
| Wind power | 0.202 | 0.265 | 0.409 | 0.471 |
| Energy saving measure | 0.020 | 0.022 | 0.020 | 0.022 |
| Average redelivery tariff [2]) | | | 0.12 | 0.12 |

Tab. A3.3: Capital and total private costs for the generation of electricity with different technologies. The costs are calculated on the basis of the parameters given in Tab. A3.2.
[1]): Interest rate.
[2]): Average redelivery tariff based on information provided by 9 Swiss utilities (incl., e.g., ATEL, BKW, CKW, EKZ, EWZ), listed in Ruch et al. (1997, p. 61).

## A3.3Heating Systems

The systems considered in the profitability calculations and in the allocation comparison are condensing light fuel oil, and natural gas boiler with a capacity of about 100kW, a 300kW wood chips boiler, and a gas-fueled spark ignition engine combined heat and power plant with a thermal capacity of $543kW_{In}$. In Chapter 8, a comparison of an earth coupled electric heat pump ($10kW_{th}$) with other small-scale heating systems, i.e., condensing light fuel oil and natural gas boilers (10kW), and a 50kW wood chips boiler, is performed. The investment costs are divided in costs to be written-off within 15 and within 30 years, respectively.

[1] Important in terms of actual production shares.

The systems are assumed to have a load factor of about 24%, except the CHP plant which is operating during about 4'700 hours per year (load factor 54%). To be able to reach such a high load factor, a rather large peak load boiler is needed. In our case, two peak load boiler are installed, one of 600 and one of '1200kW capacity. The latter is mainly used for revision and heavy winter periods. The energy efficiency as well as the environmental performance of the systems corresponds to the ones described in Frischknecht et al. (1996a). For the CHP plant, costs are on the one hand referred to the total amount of energy delivered (electricity to the grid and heat to the district heating network), and, on the other hand, to electricity and heat, respectively, applying different allocation parameters.

The investment costs comprise the costs for the boiler, the stack, the tank or silo (for oil and wood, respectively), additional equipment like the hot water storage tank, the connection to the gas distribution grid, installation costs, *et cetera*.

| | Capacity | Efficiency | Operating hours | Useful/final energy demand | Life time | Investment costs | Fixed operation costs | Variable operation costs | Energy costs |
|---|---|---|---|---|---|---|---|---|---|
| unit | kW | - | h | kWh | a | SFr./$kW_{th}$ | SFr./$kWh_{th}$ | SFr./$kWh_{th}$ | SFr./$kWh_{th}$ |
| CHP plant [1]) | 543 | 0.87 | 4'700 | 2'220'000 | 15 | 1'000 | 0.003 | 0.022 | 0.040 |
| | | | | | 30 | 200 | | | |
| Light fuel oil boiler [2]) | 1'200 | 0.87 | 533 | 556'000 | 15 | 150 | | | 0.034 |
| Light fuel oil boiler [2]) | 600 | 0.87 | 1'418 | 740'000 | 15 | 150 | | | 0.034 |
| Light fuel oil boiler, condensing | 10 | 0.94 | 2'167 | 20'370 | 15 | 1'200 | 0.047 | | 0.032 |
| | | | | | 30 | 1'400 | | | |
| Light fuel oil boiler, condensing | 100 | 0.94 | 2'167 | 203'700 | 15 | 350 | 0.005 | | 0.032 |
| | | | | | 30 | 100 | | | |
| Natural gas boiler, condensing | 10 | 0.97 | 2'100 | 20'370 | 15 | 1'200 | 0.045 | | 0.036 |
| | | | | | 30 | 1'400 | | | |
| Natural gas boiler, condensing | 100 | 0.97 | 2'100 | 203'700 | 15 | 350 | 0.004 | | 0.036 |
| | | | | | 30 | 100 | | | |
| Wood chips boiler | 50 | 0.65 | 2'100 | 68'250 | 15 | 1'200 | 0.047 | | 0.031 |
| | | | | | 30 | 500 | | | |
| Wood chips boiler | 300 | 0.75 | 2'100 | 472'500 | 15 | 700 | 0.021 | | 0.027 |
| | | | | | 30 | 900 | | | |
| Heat pump, earth coupled | 10 | 1 (3.39) | 2'037 | 20'370 | 15 | 1'300 | 0.007 | | 0.044 |
| | | | | | 30 | 1'800 | | | |
| References | a | a | | | | b | a,c,d,e | g | d,e,f |

Tab. A3.4: Economic parameters for the profitability calculations of different heating systems and a CHP plant.
[1]): Technical data from the "Jakobsberg" CHP plant (Rapp 1996). The costs are allocated to the whole energy output of the CHP plant.
[2]): Used as peak load boilers together with the CHP plant.
References: a: Frischknecht et al. (1996a); b: own estimations based on Afiej (1997), EKZ (o.J.), EV (o.J.), Graf (1996), Graf (1997), Kaufmann (1997), Keel (1997), PACER (1995), WKK (1996); c: EV (o.J.); d: Keel (1997); e: Afiej et al. (1996); f: own estimations based on Afiej (1997), EKZ (o.J.), EV (o.J.), Kaufmann (1997); g: Kaufmann (1997)

The investment costs per kW are rough estimates based on information from several offers, and on knowledge of associations. Attention is given to the relative differences of different technological options for one particular project. Because a new connection to the gas distribution grid is not always needed for gas boilers as well as an oil boiler does not always need a new room for the oil tanks, the investment costs for light fuel oil and natural gas boilers are assumed to be equal (including both a new connection and a new room for oil tanks). Furthermore the amount of useful energy delivered is assumed to be equal for systems with the same capacity (oil, gas and heat pump). That is why the operation time for the various systems varies between 2'040h, and 2'170h. The investment costs for the heat pump is derived from information given in EKZ (o.J.), Infel (1997, p. 13), Afiej et al. (1996, p. 112ff.) and several prospectus of utilities. Finally, the investment costs for wood chips boilers are based on an extensive survey of Swiss projects made by Keel (1997). New heating systems of less than 200kW (with an average capacity of 146kW), and new heating systems between 200 and 450kW (average: 314kW) are considered to determine the average investment costs of the boilers used in the case studies.

For light fuel oil, and natural gas, the energy costs are based on experiences of consultancies. For electricity used in heat pumps, information from utilities (special tariff for heat pumps provided by, e.g., EKZ, and BKW) is used[2] and for wood chips the average, suggested Swiss value for wood chips from saw mills given in PACER (1995) is applied. Fixed and variable operating costs are based on experience of consultancies and associations.

The total private costs for small units (about $10kW_{th}$) are higher by a factor of three compared with larger units using the same energy carrier. Within about the same range of capacity, the differences between the technologies is relatively minor. The costs per kWh useful energy varies between 0.14 and 0.19SFr. for small units, and between 0.05 and 0.13 for larger units. The total costs for energy produced in a CHP plant amounts to about 0.09SFr. per kWh electricity and heat delivered.

| | Life time | Capital costs, 2% | Capital costs, 5% | Total costs, 2% | Total costs, 5% |
|---|---|---|---|---|---|
| unit | a | SFr./kWh | SFr./kWh | SFr./kWh | SFr./kWh |
| CHP plant [1]) | 15 | 0.019 | 0.024 | 0.087 | 0.093 |
| | 30 | 0.002 | 0.003 | | |
| Light fuel oil boiler [2]) | 15 | 0.025 | 0.031 | 0.051 | 0.055 |
| Light fuel oil boiler [2]) | 15 | 0.009 | 0.012 | | |
| Light fuel oil boiler, condensing, 10kW | 15 | 0.046 | 0.057 | 0.155 | 0.180 |
| | 30 | 0.031 | 0.045 | | |
| Light fuel oil boiler, condensing, 100kW | 15 | 0.013 | 0.017 | 0.052 | 0.056 |
| | 30 | 0.002 | 0.003 | | |
| Natural gas boiler, condensing, 10kW | 15 | 0.046 | 0.057 | 0.157 | 0.182 |
| | 30 | 0.031 | 0.045 | | |
| Natural gas boiler, condensing, 100kW | 15 | 0.013 | 0.017 | 0.056 | 0.060 |
| | 30 | 0.002 | 0.003 | | |
| Wood chips boiler, 50kW | 15 | 0.068 | 0.085 | 0.163 | 0.187 |
| | 30 | 0.016 | 0.024 | | |
| Wood chips boiler, 300kW | 15 | 0.035 | 0.043 | 0.108 | 0.127 |
| | 30 | 0.026 | 0.037 | | |
| Heat pump, earth coupled, $10kW_{th}$ | 15 | 0.050 | 0.061 | 0.141 | 0.171 |
| | 30 | 0.039 | 0.057 | | |

Tab. A3.5: Capital and total private costs for the generation of heat with different technologies. The costs are calculated on the basis of the parameters given in A3.4.
[1]): The costs are allocated to the whole energy output of the CHP plant.
[2]): Used as peak load boilers together with the CHP plant.

The allocation factors used for the CHP plant are based on energy, exergy, and economic parameters. Furthermore, the allocation factors are set equal to zero and one, respectively. With these values the extreme positions are covered where all costs are allocated to the heat or to the electricity produced with the spark ignition engine of the CHP system (see Tab. A3.6). Due to the fact that a share of the electricity produced is used by a heat pump feeding the district heating network, the costs per kWh heat does not equal to zero even when no costs are directly allocated to the heat from the CHP plant.

[2] The electricity costs in winter time of nine utilities listed in Ruch et al. (1996, p. 61), vary between 0.192 and 0.292 with an average of 0.254 SFr./kWh for high tariff periods and between 0.05 and 0.235SFr./kWh with an average of 0.12SFr./kWh for low tariff periods. Assuming equal shares of high and low tariff periods, the average electricity costs amount to 0.187SFr./kWh which is 25% higher than tariffs for interruptable electricity offered to clients operating heat pumps by some utilities in Switzerland.

The total costs for heat delivered to the district heating network vary between 0.03SFr. and 0.09SFr. per $kWh_{th}$ (at an interest rate of 5%). The corresponding total costs for electricity delivered to the grid amounts to between 0.26 and 0 SFr. per $kWh_e$. The modest variation and the relatively low level of the costs for heat are a consequence of the "energy mix" delivered to the district heating grid, namely, heat from the electric heat pump (13%), from the peak load oil boilers (40%) and from the CHP plant (47%).

| | Allocation factor | Total costs, 2% | Total costs, 5% |
|---|---|---|---|
| unit | - | $SFr./kW_{th}$ | $SFr./kW_{th}$ |
| *Heat:* | | | |
| CHP plant, alt. 1, energy | 0.643 | 0.064 | 0.068 |
| CHP plant, alt. 2, exergy | 0.247 | 0.041 | 0.044 |
| CHP plant, alt. 3, relative sales value | 0.742 | 0.049 | 0.053 |
| CHP plant, alt. 4, motivation electricity | 0 | 0.028 | 0.030 |
| CHP plant, alt. 5, motivation heat | 1 | 0.084 | 0.089 |
| *Electricity:* | | | |
| CHP plant, alt. 1, energy | 0.357 | 0.087 | 0.093 |
| CHP plant, alt. 2, exergy | 0.753 | 0.184 | 0.196 |
| CHP plant, alt. 3, relative sales value | 0.258 | 0.150 | 0.160 |
| CHP plant, alt. 4, motivation electricity | 1 | 0.244 | 0.260 |
| CHP plant, alt. 5, motivation heat | 0 | 0.000 | 0.000 |
| *Technical performance:* | | *unit* | |
| Share of heat from oil peak load boilers | 0.405 | - | |
| Share of heat from CHP plant | 0.465 | - | |
| Share of heat from heat pump [1]) | 0.130 | - | |
| Electricity produced | 667 | MWh | |
| Heat produced by the CHP plant | 1'373 | MWh | |
| Heat produced by the heat pump | 382 | MWh | |

Tab. A3.6: Capital and total private costs for the generation of heat and electricity with a CHP plant applying different allocation factors. The costs are calculated on the basis of the parameters given in A3.4.
[1]): average coefficient of performance: 4.5.

In allocation alternatives 1 and 5, the costs for the heat delivered are higher than the costs of its competitive technologies. However, in these cases the costs for electricity are substantially lower than the costs of electricity from thermal power plants or power plants converting solar or wind energy. On the other hand, when the costs for heat are low (alternatives 2, 3 and 4), the costs for electricity are comparable to the costs of electricity from convential thermal power plants.

In the following figure, the relation between costs for heat and electricity produced by the CHP system is shown. The points of intersection that are on the left and below the CHP plant line (in heavy type) are combinations with lower costs than the CHP plant. With the actual average redelivery tariff, natural gas and light fuel oil boilers can produce at slightly lower costs compared to the CHP system. If however, we compare the CHP system with marginal electricity generating technologies, they become competitive compared to the natural gas and the light fuel oil boiler option. Furthermore, any combination of electricity and heat generating systems that uses wood for heat production is more expensive than the CHP system.

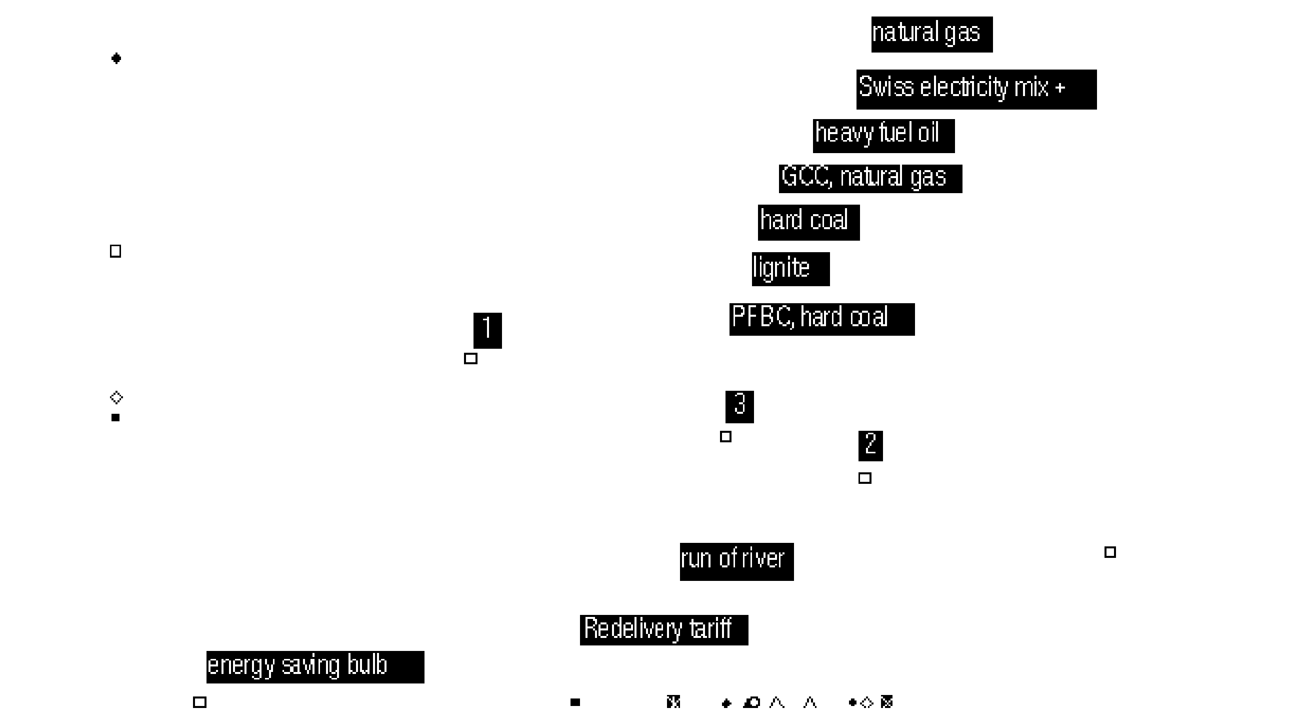


Fig. A3.1: Total private costs for the generation of heat and electricity with different single function technologies, and with a CHP plant where different allocation factors are applied. The numbers close to the CHP curve correspond to the five allocation parameters introduced in Tab. 10.12
Swiss electricity mix +: Electricity mix including trade, see Subchapter 9.2 for more details.

If, for instance, we limit the possible alternatives to a combination of nuclear power plant and a gas-fired condensing boiler, the allocation factor for heat from the CHP plant may be varied between 0.52 and 0.77[3]. Within this range, the costs for CHP electricity are lower than the costs for electricity produced in a nuclear power plant and the costs for CHP heat are lower than the costs for the heat produced with a gas-fired condensing boiler.

3 $\frac{1-0}{0.089-0.030}\cdot(0.060-0.030)=0.516$; $\frac{1-0}{0.260-0.000}\cdot(0.201-0.000)=0.774$, see Section 7.5.1 for its mathematical derivation.

# Curriculum Vitae

| | |
|---|---|
| Name | Rolf Frischknecht |
| Born | 17. August 1962 |
| Citizen of | Basel-Stadt and Schwellbrunn (Appenzell Ausserrhoden) |
| Parents | Dora and Jakob Frischknecht-Zimmerli |
| | |
| 1969-1973 | Primary school Basel-Stadt. |
| 1973-1981 | Secondary school, mathematics and natural sciences, Basel-Stadt. |
| 1981-1986 | Studies at ETH Zürich, civil engineering department, with emphasis on structrural and hydraulic engineering. |
| 1986 | Diploma in civil engineering ETH Zürich, diploma thesis on wood construction, PD Dr. E. Gehri. |
| | |
| 1986-1988 | Project leader at the structural engineering office H. Schaub, Basel-Stadt. |
| | Statics, opinions on physical problems of buildings. |
| 1988-1989 | Post-graduate studies on energy, Ingenieurschule beider Basel, Muttenz. |
| 1989 | Diploma in energy engineering, diploma thesis on energy planning in communities. |
| 1989-1990 | Consultancies in energy management of buildings. |
| | |
| 1990-1998 | Research assistant at the Energy Systems Laboratory, ETH Zürich, Prof. Dr. P. Suter, Mechanical Engineering Faculty. |
| 1990-1994 | Project "Ökoinventare für Energiesysteme" – "Life Cycle Inventories for Energy Systems". Set-up of the energy systems' database ECOINVENT. |
| 1994 | ABB-award "energy technology" for the final report "Ökoinventare für Energiesysteme" together with P. Hofstetter (ETHZ), I. Knoepfel (ETHZ), and R. Dones (PSI). |
| 1995-1998 | Research on Life Cycle Inventory Analysis, with focus on system modelling and allocation. |
| | Extension of the existing energy systems' database ECOINVENT. |
| 1996-1997 | Leader of the Energy-Materials-Environment group (ESU), Energy Technology Department. |
| 1998 | Foundation of ESU-services, an office for consultancy services and research in the field of Life Cycle Assessment. |