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Project GaBE:
Comprehensive Assessment of Energy Systems

Environmental Inventories for Future Electricity Supply Systems for Switzerland

Dones R., Gantner U. and Hirschberg S.
Paul Scherrer Institute

Doka G. and Knoepfel I.
Swiss Federal Institute of Technology Zurich

Paul Scherrer Institut
CH - 5232 Villigen PSI
Telefon 056 310 21 11
Telefax 056 310 21 99

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Dones R., Gantner U. and Hirschberg S.
Paul Scherrer Institute

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Swiss Federal Institute of Technology Zurich

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Abstract

This report provides the analysis of environmental inventories for selected electricity supply systems considered as possible options to meet the expected electricity demand in Switzerland in year 2030. The work was carried out by the Paul Scherrer Institute (PSI) and the Swiss Federal Institute of Technology Zurich (ETHZ), and was supported by the Swiss Association of Producers and Distributors of Electricity (VSE).

Two possible electricity demand level cases were postulated by VSE, both under the basic assumption of economic growth: a high-growth demand case corresponding to a yearly increase of 2% from year 1995 to year 2010 and 1% from year 2010 to year 2030, and a low-growth demand case corresponding to a yearly increase of 1% from year 1995 to year 2010 and 0.5% from year 2010 to year 2030.

The base (i.e. secured) supply in year 2030 will be, according to VSE, totally dominated by hydro with rather minor contributions from combined heat-and-power plants, small gas turbines, incinerators and solar photovoltaic plants. Due to decommissioning of the currently operating nuclear power plants and expiration of long-term electricity import contracts there will eventually occur a gap between the postulated electricity demand and the base supply. VSE provided seven options to cover this gap, defined in terms of mixes with different contributions from gas, coal, nuclear and solar chains; in this context a distinction is also made with respect to shares of domestic and imported electricity. The systems considered represent advanced technologies, regarded as either typical or most suitable for the Swiss conditions. System-specific input to the present analysis has been partially generated based on direct contacts with the industry.

Life Cycle Analysis (LCA) was used to establish environmental inventories for the systems analysed. This means that complete fuel cycles are covered and all systems are described on a "cradle to grave" basis, using consistent set of boundaries as well as a standardised set of modules to represent material production, transportation, construction and disposal services.

The analysis has been performed on three levels: (1) individually for each system considered; (2) comparison of systems; (3) comparison of supply options. Results are also provided for these three levels.

The feasibility of applying the LCA approach to the analysis of electricity supply options for the future has been demonstrated. The use of a process-oriented approach allows to focus the work on these parts of fuel cycles which are the most significant contributors to emissions and/or are being subject to major changes. Due to the significant advancements in power plant technologies the relative importance of the other steps in fossil and nuclear fuel cycles, and of the contributions from transportation and material production, significantly increases in the case of future systems. In the absolute sense the emissions of the major pollutants considered in this work are reduced in comparison with the currently operating systems, in most cases very significantly. As expected, fossil-based systems exhibit the highest emissions of combustion products; hydro has the lowest emissions of these pollutants, followed by nuclear and solar. The expected improvements in the solar cell manufacturing processes result in a very considerable reduction of "grey" emissions.

The radioactive emissions are obviously highest for the nuclear fuel cycle; the relative contribution of the nuclear power plant is in this context very small.

The results from systems analyses are reflected in the results obtained for the supply options, which are either primarily fossil- or nuclear-based, or represent mixtures of these with some contribution from photovoltaic. In order to provide some perspective on the results comparisons with the current emission levels in Switzerland are provided for some pollutants. Limitations of the current analysis, including a certain conservative bias are addressed, and suggestions are given with respect to possible improvements.

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1. Background

The Swiss Federal Institute of Technology Zurich (ETHZ) and Paul Scherrer Institute (PSI) are since 1991 engaged in a co-operation concerning the establishment of environmental inventories for the different fuel cycles represented in the **current** Swiss and UCPTE[1] electricity supply system and in heating systems. Further work in this area, pursued within the project "Comprehensive Assessment of Energy Systems" — Project GaBE "Ganzheitliche Betrachtung von Energiesystemen" (Hirschberg et al., 1993) — addresses among other topics environmental inventories associated with the **future** alternative configurations of the Swiss electricity supply. This work has been supported by the Swiss Association of Producers and Distributors of Electricity (VSE) and is covered in the present report.

The starting point for the work performed within the present project was constituted by the comprehensive analyses of environmental inventories reported in the recently published ETHZ/PSI report (Frischknecht et al., 1994). These results were based on the Life Cycle Analysis (LCA) approach, applied to the **currently operating** energy systems in Switzerland and in Europe. Table 1.I shows the systems included in this analysis.

Energy and material balances for the systems shown in Table 1.I were established by linking about 500 process modules. A typical bottom-up process chain methodology was used. The interactions between the different systems, of relevance for the balances, were fully considered. For example, mining and refining of coal also has an input of the applicable electricity mix which in turn may have a coal component.

A very broad spectrum (more than 200) of resources and air and water pollutants was covered. This also includes non-energetic resources, land depreciation and waste heat. Organic compounds, trace elements and radioactive isotope emissions were treated with a high degree of detail.

Using the generated data as the basis, comparisons of electricity generating systems were carried out (Hirschberg et al., 1994). This work includes analyses of e.g. greenhouse gases, SO_x, NO_x, and NMVOC emissions, land use, radiation and wastes; the importance of considering full energy chains has been highlighted. Later, a detailed comparison of greenhouse gas inventories was carried out using the same database (Dones et al., 1994).

The results obtained for the current energy systems have only limited relevance as the input for decisions concerning preferred future configurations. Naturally, they can serve as a reference in the context of comparison. The present report addresses environmental inventories for a number of advanced electricity supply systems that might be the candidates for the supply mix for year 2030. This means that the existing data and methodological base needed to be extended to reflect technological advancements and new options, as well as structural changes. These extensions are reflected in the present report.

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[1] Union pour la coordination de la production et du transport de l'électricité.

Table 1.I

Energy systems and relevant products covered in (Frischknecht et al., 1994).

Systems	Products
Coal	**Electricity** from power plants; natural and synthetic coal; hard coal and lignite; heat from residential and industrial boilers.
Oil	**Electricity** from power plants; fuel oil; leaded and unleaded gasoline; diesel oil; kerosene; naphtha; bitumen; refinery gas; heat from residential and industrial boilers.
Natural Gas	**Electricity** from power plants; natural gas for residential and industrial use; heat from residential and industrial boilers.
Nuclear	**Electricity** from boiling water reactors and pressurised water reactors
Hydro	**Electricity** from reservoir, flow-through and pumped storage hydropower plants typical of the alpine region.
Electricity mix	**Electricity generation mix** in Switzerland and in UCPTE countries for high, medium and low voltage applications. It includes the above listed systems.
Photovoltaic[a]	**Electricity** from building-integrated 3 kW units, and from 100 kW and 500 kW power plants.
Solar thermal	Warm water from solar collectors and hybrid systems for residential use.
Energy from wood	Heat from boilers using different types of wood and wood waste typical for the Swiss situation.
Geothermal	Heat from small (shallow) residential heat pump units.

[a] Photovoltaic systems have been treated separately from other electricity generating systems since they contribute very little to the present electricity mixes.

The current domestic Swiss electricity supply is primarily based on hydro power (approximately 61%) and nuclear power (about 37%). The contribution of fossil systems is, consequently, minimal (the remaining 2%). In addition, long-term (but limited in time) contracts exist, with regard to imports of (nuclear) electricity from France. Gradual decommissioning of the current Swiss nuclear plants (40 years life-time has been assumed) and expiration of the import contracts will inevitably lead to a gap between the demand on the one hand and the supply capacity on the other. VSE defined seven supply mix options that could cover the gap, thus meeting the expected demand in year 2030. The supply mix options were defined in terms of shares of the different systems (fossil, nuclear and renewable), and in terms of the shares of domestic and imported electricity. The definition of the options is given in Sections 6.1 and 6.2. The estimated environmental inventories, associated with these options, are provided in this report.

2. Project Objectives and Scope

2.1 Objectives

The project objectives were as follows:

- To develop Life Cycle Analysis (LCA)-based material (i.e. requirements and emissions) and energy balances for electricity supply systems considered (by VSE) as relevant alternatives for the electricity supply in Switzerland in year 2020/2030;
- To quantify the emissions of major pollutants and estimate magnitudes of some other residuals associated with selected supply options.

2.2 Scope

After discussions with VSE the following systems were chosen for the overall analysis:

- Hydro
- Nuclear
- Hard coal
- Gas, combined cycle (with the option of using oil as the alternative fuel)
- Gas turbines
- Combined Heat and Power Plants (CHPP)
- Photovoltaic

Hydro, gas turbines, CHPPs and some nuclear (remaining capacity prior to decommissioning and imported according to existing contracts), constitute together the base supply. The supply to be provided by these systems is considered by VSE as secured for year 2020/2030. Hereby the contribution of gas turbines (assuming 30 MW per unit) is of the order of 1.5% and of CHPPs about 2-3% of the total demand in year 2030. The specific power plant technologies chosen for the analysis were limited to rather few (e. g. two advanced nuclear designs and two advanced coal designs), considered either as typical (nuclear) or most suitable for the Swiss conditions (coal). Cogeneration was included by means of small gas turbines and CHPPs but not for the gas combined cycle power plants. For photovoltaic only roof panels were considered, being the most attractive option for the Swiss conditions. The choices made are explained and supported in Chapter 4 which contains systems analyses and their results.

The advanced technologies considered are in some cases expected to be commercially available in the not very distant future, while in other cases they represent the best performance available already today. Thus, no revolutionary technologies have been covered. Basically, the performance parameters chosen should in most cases be

representative for technologies that could be implemented on a large scale between 2010 and 2020.

Evaluations of the seven options, corresponding to different mixes of the systems above, have been carried out for year 2030. In this context, two possible electricity demand level cases were postulated by VSE, both under the basic assumption of economic growth: a high-growth demand case corresponding to a yearly increase of 2% from year 1995 to year 2010 and 1% from year 2010 to year 2030, and a low-growth demand case corresponding to a yearly increase of 1% from year 1995 to year 2010 and 0.5% from year 2010 to year 2030.

The main difference between VSE supply options for years 2020 and 2030, respectively, is that in 2020 the nuclear power plant Leibstadt is still expected to be in operation. From the point of view of the performance of technologies as analysed in this report, there is no distinction between years 2020 and 2030; the resolution of the bottom-up (process analysis) approach used does not support such a differentiation.

The work performed addresses the two basic steps of the Life Cycle Analysis (LCA), i.e. goal definition and inventorisation. The classification and valuation of the environmental impacts — see (Heijungs et al., 1992) — has not been carried out. The only remarkable exception has been the calculation of total greenhouse gases using IPCC's recommended warming potentials (see Sections 5.2 and 6.3.1).

The analysis has been performed on three levels. Chapter 4 provides the core of the work, i.e. summaries of the analyses of the different systems. For each system more extensive documentation has been generated in form of system notes. These are not included in the present report but can be made available on request. Chapter 5 includes comparisons of the different systems. Finally, the supply options are outlined and compared in Chapter 6.

3. Analysis Approach and Limitations

3.1 Basic Methodology

Detailed descriptions of the basic LCA methodology used can be found in (Frischknecht et al., 1994). Some basic features are:

- Complete fuel cycles (fuel extraction and conversion, energy production, waste management) are covered.
- All systems are described on a "cradle to grave" basis, with each step in the cycle being decomposed into construction, operation and dismantling phases.
- Not only direct (concentrated) emissions from the plants are covered but also indirect (grey or diffuse), in order to provide an as complete as possible representation of the total environmental fluxes.
- A set of rules was established for the definition of systems boundaries to achieve a high level of consistency and detail for all energy systems.
- Material inputs and transportation needs are considered in connection with all steps of a fuel cycle; also construction efforts and materials for road and rail infrastructure are included in the analysis.
- A consistent set of data for material production, transportation, construction and disposal services was developed to be used by all energy systems. Particular attention was given to materials used in large quantities in energy systems (concrete, steel, aluminium) as well as to materials used in small quantities but having associated potentially highly-toxic emissions during production, operation or disposal. Standard modules for transportation include road (trucks of different sizes, cars), rail, river (barges) and sea (ships and tankers). Standard disposal systems were defined, covering landfills, contained repositories, industrial and communal incinerators.
- For electricity inputs results from the average UCPTE generation were used throughout all analyses of the currently operating systems. Services and materials that have been accounted for represent the European situation.
- Allocation criteria were developed for multi-output processes.

For data input, filing and handling purposes a relational database program called ECOINVENT is used. The different parts of each energy system are linked together to constitute the process chain of the analysed system. Direct fluxes within each part are then established. The linking of each part with the preceding ("upstream") parts in the relational database allows to calculate the cumulated fluxes. Mathematically, cumulated emissions and resources depletion are calculated by the inversion of the process unit input matrix followed by the multiplication with the emission matrix.

Temporal boundaries are defined by the general inclusive approach ("cradle to grave" analysis). With respect to **spatial boundaries** all energy and material fluxes are accounted for, regardless of geographic or political boundaries; this stems from the LCA methodology which, when consequently applied, covers the whole chain from the stage of exploiting the resources from the environment down to the end point of emissions to the environment.

3.2 Specific Features of the Approach Used

The LCA methodology has been developed and primarily applied for operating systems. Consequently, the input is normally based on the actual experience. Furthermore, the standard approach is static and its applications to future systems require extensions, extrapolations and a number of additional assumptions.

The extension of the existing material to include and characterise new technologies was based on literature, direct information from the industry and consultants, and on expert judgement. Of particular importance was the input received from ABB on coal and gas plants, from BNFL and Cogema on some steps in the nuclear chain, and from Alfa Real on photovoltaic. These and other valuable contributions are gratefully acknowledged. Availability of essential, LCA-specific process information and knowledge about the relative importance of the various sources of emissions made it possible to focus the analysis and economise the use of resources. In view of the objectives of the project the parameters of primary interest are: emissions, efficiencies, material intensities (for construction and operation), and transportation requirements.

When selecting performance parameters, and having ranges of values as the starting point, the best values were normally chosen as the most representative for the time horizon under consideration in this work. When in doubt conservative rather than speculative values were applied. It is inevitable in this type of analysis that a mixture of data must be used, although the effort was made to be as consistent as practically possible under the constraints of this project.

For electricity inputs needed for the modules external to Switzerland an European mix for year 2010 was used, based on the extrapolation of a forecast by the International Energy Agency for year 2005 (IEA, 1994a). As compared to the current situation the mix reflects the expansion of gas, reduction of oil shares and a relatively small but significantly increased contribution of photovoltaic. Coal, hydro and nuclear remain on about the same level. Also for Switzerland a mix for 2010 was used as an input; this mix was provided by VSE and includes a large share of imported electricity. Table 3.2.I shows the Swiss and UCPTE electricity mixes assumed for year 2010. A table specifying the shares of energy systems in year 1990 used in (Frischknecht et al., 1994) is provided in Appendix A. Detailed flow charts illustrating the structure used in ECOINVENT to describe the two assumed electricity mixes for year 2010 are given in Appendix B.

The "new" systems generally show better performance and lower emissions than the "old" ones. For this reason within the mixes assumptions needed to be made with respect to the market penetration of the "new" systems in order to establish the relative shares of "old"

and "new" systems; this was done individually for each energy source taking into account their specificity and the expected developments reflected by the assumed overall contribution of each source to the mix.

Table 3.I

Swiss and UCPTE electricity mixes assumed for year 2010.

Electricity Mix	Electricity Supply System	Share %
CH mix 2010	Hydro (2010)	48.2
	Nuclear (domestic)[a]	28.4
	Nuclear (imported from UCPTE 2010[b])	20.0
	CHPP 160 kW_e (1995)	2.1
	Gas turbine 30 MW (2010)	1.3
UCPTE mix 2010	Nuclear (UCPTE 2010)[b]	32.0
	Hard coal (UCPTE 2010)[c]	19.2
	Lignite (today's UCPTE best technology)	10.8
	Gas (UCPTE 2010)[d]	18.0
	Hydro (2010)	12.0
	Oil (today's UCPTE best technology)	6.5
	Photovoltaic 3kW roof panels m-Si (1995)	1.5

a Currently operating modern nuclear power plants.
b Assumed types of nuclear power plants: 90% currently operating modern PWRs and 10% currently operating modern BWRs.
c Assumed types of hard coal power plants: 60% currently operating PC; 22.5% PFBC; and, 18.5% next generation PC (for the two last mentioned power plant types, performance expected in year 2010).
d Assumed 20% Combined Cycle power plants fuelled with natural gas only; the rest — currently operating modern gas plants.

3.3 Limitations and Basic Assumptions

The most important limitations and assumptions of the present work are listed below. System-specific constraints are accounted for in the systems analysis sections. Some of the limitations and assumptions, particularly these related to the scope and the overall methodology have already been mentioned in the preceding sections.

- The focus of this work has been on selected emissions to air (CO_2, CH_4, SO_x, NO_x, NMVOC, particles and radioactivity), and on materials/energy requirements. Emissions

to water, land use and wastes have not been treated in detail for all future systems (detailed results exist for currently operating systems). For some systems where the analysis is sufficiently well developed such emissions and residuals are provided. To avoid inconsistencies they are not included in systems and supply options comparisons.

- The impacts of specific emissions are beyond the scope of this work. Therefore, the data presented here give no direct information about the environmental damage that may result from the emissions. Extensions of the analysis to cover the impacts are possible.

- The analysis addresses the emissions associated with the normal operation of the systems analysed. This includes also expected releases in connection with incidents but excludes large releases that could result from rare severe accidents.

- The analysis does not cover the economic aspects of the systems considered although in some cases the economy was taken into account when selecting the systems of primary interest for Switzerland. For example, given the assumed specific coal quality, emissions and investment costs of the various options, it was not considered to be of interest to include some advanced but very costly coal technologies (such as coal gasification).

- The demand-side management is implicitly reflected in the demand levels provided by VSE as an input to this work. Here, only the production of energy carriers and their use in energy systems is covered. If the assessment of energy services as such (useful heat, useful electrical or mechanical power) is of interest, measures on the demand side would have to be added.

- Cogeneration has been included to a relatively small extent, in connection with small gas turbines and CHPPs. According to VSE, this assumption is supported by the low economic potential of cogeneration.

- No revolutionary technologies have been included. This reduces the speculative element in the analysis and makes it more conservative, defensible and possibly realistic. By necessity, in the case of the very young solar technology the assumptions about the future advancements in the commercial environment are more speculative and highly dependent on the market development.

- No new processes for material production (except for the solar cell manufacturing) and no new means of transportation have been considered. This introduces a definite conservative bias, although for the basic materials the efficiency of the current processes is considered to be high. On the other hand, the possibility that extraction of resources might become more difficult due to reduced availability of easily accessible resources (and lead to more extensive environmental interventions), has not been taken into account.

- Systems that constitute the options for filling the gap between the expected demand and assured supply, i.e. gas, coal, nuclear, photovoltaic, are treated in a more detailed way than "base" systems (hydro and CHPP). For CHPP no extrapolation was made from the

current to the future performance; furthermore, only a gas-based CHPP system has been analysed.

- Oil chain (which is not a part of any of the VSE supply options, except that oil is used as an alternative fuel within the gas combined cycle), has not been changed. However, a larger share of "extra light" oil has been assumed for the products from refining.

- The reported results contain the cumulated environmental interventions without geographical restrictions and are based on the assumed conditions specifically for the Swiss electricity supply. This applies to the fuel origin and quality, materials production, electricity mixes, infrastructure, transportation, etc. Direct use of the results for applications to other conditions is not recommended, although given appropriate adjustments the existing material could be made useful for such purposes.

- Electricity distribution lines were not included in systems comparisons, i.e. the environmental inventories are normalised by the electricity at power plant busbar. This is justified by the fact that the contributions from transmission lines would not significantly differ for the systems used for the defined supply options[1]. However, differences may be expected when comparing systems generating electricity at different voltage levels with the end use as a boundary. To take this into account would require an analysis of expected losses in future networks, which is beyond the scope of the study.

- All material production is assumed to utilise the projected UCPTE electricity mix for year 2010. With respect to the Swiss mix (relevant for example for the electricity supply to the railway transportation taking place within Switzerland) also the mix for year 2010 is assumed as the reference. The impact of the latter simplification (compared to using the actual mix in 2030 as reflected in the options), is of secondary importance. For the advanced systems specific shares within the UCPTE mix have been assumed.

- Emissions associated with imported electricity (as defined in the different supply options) are fully accounted for.

- The present analysis is subject to general limitations with respect to the information sources. First, the availability of such information is restricted and to some extent limited by commercial considerations. Second, the amount and quality of the information depends on the time available for collecting it. Third, the improvements of the performance of the technical systems and the structural changes are occurring more or less continuously. For these reasons the results provided in this report should be revised, updated and supplemented in a not too distant future.

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[1] It is assumed that the losses in the high voltage lines for the transportation of imported electricity are small.

4. Systems Analyses

This chapter provides the summaries of the analyses carried out for the systems considered to be of primary interest in view of the objectives of this work. Gas-based systems, i.e. Combined Cycle (CC), small gas turbines and CHPP are covered in one of the sections. Each one of the other systems has its own section. All sections have the same structure:

- Overview
- Structure of the energy chain
- Specific prioritisations and assumptions
- Technologies
- Results

More detailed notes/reports exist for the some of the considered systems (Dones, 1995), (Gantner, 1995); summaries provided here contain the essence considered necessary for the understanding and uses of the present work.

4.1 Advanced Hard Coal Systems

4.1.1 Overview

4.1.1.1 Role of hard coal

Hard coal systems are one of the most significant contributors to the UCPTE mix, approximately 18% in year 1990. For the future, coal technology will most probably maintain its role or even expand world-wide due to the large and assured coal reserves and the competitive prices (IEA, 1994a), (IEA, 1989). Furthermore, many potential suppliers are available on the market and coal can easily be stored (huge volume of stocks is needed), which makes it an attractive option with regard to the security of supply. Advanced hard coal plants are considered in this study for covering part of the future electricity deficit for Switzerland; coal is represented scenarios 1 and 6 as part of domestic generation capacity, and in scenarios 4 and 5 as a contributor to imported electricity (see Chapter 6).

4.1.1.2 General assumptions

A wide spectrum of advanced clean coal technologies is currently under development (see for example (Booras et al., 1991)). Revolutionary technologies are not described here, in agreement with the general scope limitation of this study. Coal technology types among the various advanced coal power plants considered as the most likely for implementation in Switzerland are the Pulverized Fuel Combustion (PC) plant and the Pressurized Fluidized Bed Combustion (PFBC) plant. The Fully Integrated Coal Gasification Combined Cycles plant (IGCC) is not a primary candidate for Switzerland because of the

dimensions and complexity of the facility, the significantly higher cost per unit of installed power and the appropriateness of the relevant process for high-sulphur coal; Switzerland is expected to import high quality coal in case that coal systems would be implemented. The same two types of advanced coal technologies have been assumed for the other UCPTE countries to build the relevant coal mixes together with the currently operating plants, whereas the IGCC, which might be a candidate for specific situations, has not been described for simplicity of analysis.

For the development of the installed capacity of hard coal power plants in UCPTE, it has been assumed that in year 2010 half of the additional plants will be either advanced PC or PFBC (with performance characteristics expected in year 2010); after year 2010 only clean coal technology will be installed. In the following sections, only results obtained for year 2030 are discussed.

For the upstream steps, only the parameters which had been identified as the most important were reconsidered for the study of future systems. It is predicted that for the next 20 years there will be a growing demand for oversea coal (Coal Info 1993). As a consequence, transportation will become an increasingly important contributor to the total emissions associated with the coal full energy chain. Due to the shift in the origin of coal, the shares of underground and surface mining will also change. It is assumed that mining technologies will not be dramatically modified. However, methane emissions from underground mining are expected to decrease in the ten largest coal producing countries because of improvements in the recovery techniques (OECD/IEA, 1994).

Lignite, which has substantially lower heating value than hard coal, is burned in power plants in the vicinity of mining areas to minimise transport requirements. Therefore, lignite can not be considered a viable option for Switzerland. No increase in the total installed power of lignite plants has been assumed for UCPTE for the next 30 years. All operating plants are assumed to be retrofitted with the same abatement technologies that are presently already applied in West Germany.

4.1.2 Structure of the energy chain

In the earlier LCA study (Frischknecht et al., 1994) the UCPTE countries having operating coal power plants were considered one by one to reflect the different circumstances. In the present study, it is assumed that the selected types of coal power plants are implemented in all UCPTE countries with the same standards for the considered time horizon. The coal energy chains for Switzerland and UCPTE have been treated separately to reflect the specific conditions.

Figure 4.1.1 shows the hard coal chain assumed for Switzerland. Upstream steps include prospecting (not shown because of minor importance), mining, storage and transportation of coal. Each type of power plant is assumed to contribute 50 % to the total electricity generated by hard coal systems for the proposed scenarios. PC plants are supplemented with abatement technologies which are shown separately in the picture. Hard coal is assumed to be supplied to the Swiss plants by European and oversea mines: Polish underground mines are considered to be the only European suppliers; South Africa and USA are assumed to be the overseas suppliers, with a share of 46 % open pit and 54 % underground mining.

Figure 4.1.2 shows the hard coal chain assumed for UCPTE. According to (IEA, 1994a) an additional capacity of 9.4 GW coal-based electric power is being installed in UCPTE countries between 1992 and 2000; here it is assumed that half are conventional plants, half advanced. From year 2000 to year 2010, the coal capacity is expected to continue to grow at the same yearly rate of 1% (Torrens, 1991); likely no further conventional power plant will be built, while some among the previously installed ones will be retrofitted. After year 2010 it is assumed that the old conventional plants will be progressively substituted at the end of their operational lifetime with PC or PFBC. Therefore, the share of the currently operating PC power plants changes from 60% assumed for year 2010 to about 20% for year 2030. Advanced PC and PFBC plants are assumed to contribute about 20% each in year 2010, and about 40% each by year 2030. Hard coal is assumed to be supplied to UCPTE plants from domestic and foreign sources.

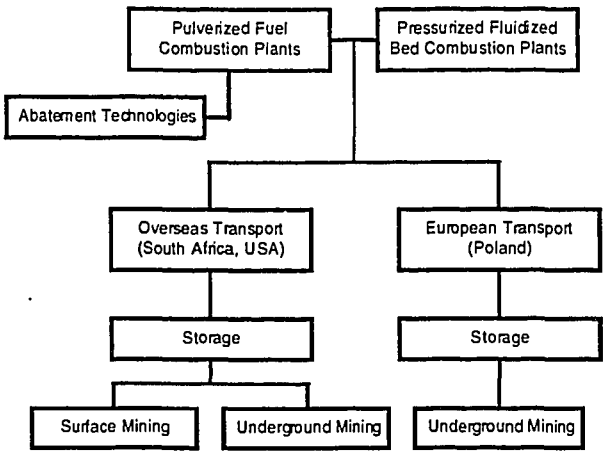

Figure 4.1.1 Hard coal energy chain for Switzerland in year 2030

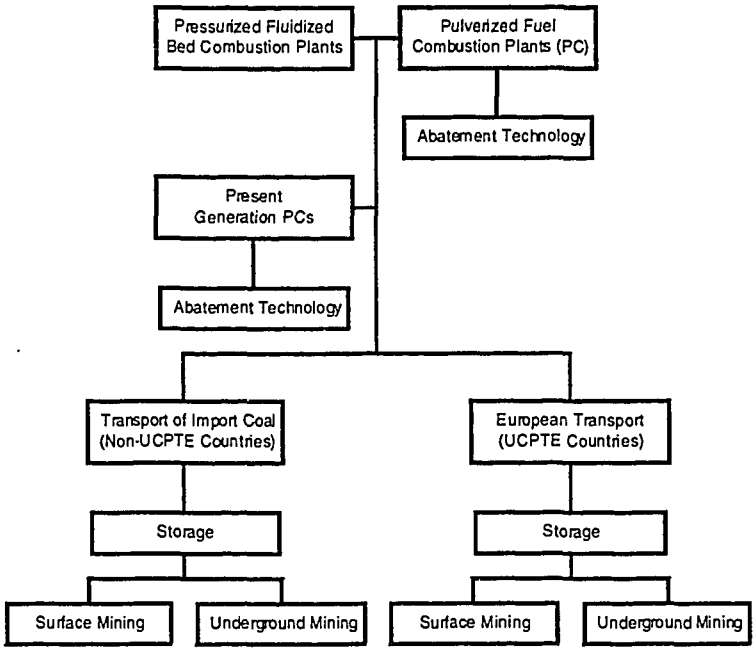

Figure 4.1.2 Hard coal energy chain for UCPTE in year 2030

4.1.3 Specific prioritizations and assumptions

If implemented, electricity production by hard coal power plants would be a novelty for Switzerland. Therefore, the conditions specific for this country have been carefully considered. Key assumptions on the fuel quality, the origin of coal, the type of mining, the methane releases from mining as well as the transport means and distances, are discussed in this section.

The quality of fuel is one of the main parameters for the analysis of coal systems. It is assumed (Source: VSE) that only coal of a very good quality will be imported in Switzerland. In this study, hard coal with heating value of 28 MJ/kg, low-sulphur content of 0.5 % and ash content of about 10 % is taken into consideration for the Swiss scenarios (EPRI, 1993).

The average sulphur content of the coal burned in UCPTE power plants is expected to be at least twice as high as the amount in the coal assumed for Switzerland. This assumption reflects the present situation in the European countries with the best (from the environmental point of view) implemented coal power plant technology (Austria and West Germany). Higher values are also expected for the ash content, between 12 % and 15 %.

The shares of surface and underground mining may change according to the origin of coal. Tables 4.1.I and 4.1.II show the current state and prospective development of hard coal trade for UCPTE countries and the effect on the ratio between surface and underground mining. The value for Switzerland in year 2020, shown in the table, does not include any coal for power plants.

Surface mining of coal for UCPTE countries appears to increase from approximately 28 % in year 1993 to about 42 % in year 2020. Only 6 % of the total coal produced in UCPTE countries in year 2020 is expected to originate from surface mining. For the Swiss case, Polish coal is exclusively mined underground, while 46 % of the coal imported from South Africa and the USA will originate from open-pits. The share of domestic coal in UCPTE will dramatically decrease from 47 % in year 1993 to 18 % in year 2020.

No major changes are expected for the upstream steps with respect to the present practice. The only exception is the release of methane to the environment from underground mining, which is predicted to be reduced due to developments in recovery technologies. It has been estimated (OECD/IEA, 1994) that the total emission of methane from the coal industry world-wide is today about 25 million tonnes per year, thereof only 7 % is recovered. Under ideal conditions, 60 to 70 % of the coal-bed methane emissions can be recovered at a specific underground mine.

Shallow underground mines and surface mines seem to offer little potential for commercially viable projects for recovery of methane. Therefore, data for surface mining are the same used in the earlier LCA study. Methane releases to air from coal mines, expected in year 2020 in the ten largest producing countries (90 % of today's world-wide coal production), are shown in Table 4.1.III.

Table 4.1.I

Share of surface mining of hard coal for the suppliers to UCPTE countries in year 1993, after (Coal Info, 1993).

Country	Hard coal consumption	Domestic production		Share of total used in UCPTE	Share open pit
	Mt	Mt	Domestic share of total %	%	%
Austria	3.04	0	0	0	0
Belgium	11.80	0.71	0.90	0.43	0
Germany	72.80	59.43	75.55	36.17	0
France	20.30	8.30	10.55	5.05	15
Greece	1.26	0	0	0	0
Italy	14.72	0.01	0.01	0.01	0
the Netherlands	13.26	0	0	0	0
Portugal	4.44	0.11	0.14	0.07	0
Spain	22.06	10.10	12.84	6.15	15
Switzerland	0.11	0	0	0	0
Domestic production		**78.66**	100	47.87	**3.51**
Supplier		Imported by UCPTE			
		Mt	Imported share of total %		
Australia	-	14.20	16.57	8.64	71
Canada	-	1.22	1.43	0.74	100
China	-	1.05	1.22	0.64	10
South America	-	7.86	9.17	4.78	100
Poland	-	10.30	12.02	6.27	0
South Africa	-	21.76	25.40	13.24	40
former USSR	-	3.39	3.95	2.06	40
UK	-	0.30	0.35	0.19	15
USA	-	25.59	29.88	15.58	52
Total import UCPTE	-	85.66	100	52.13	**49.82**
Total UCPTE	**163.79**	**164.32**	-	100	**27.65**

Table 4.1.II

Share of surface mining of hard coal for the suppliers to UCPTE countries in year 2020, after (Coal Info, 1993).

Country	Hard coal consumption	Domestic production		Share of total used in UCPTE	Share open pit
	Mt	Mt	Domestic share of total %	%	%
Austria	5.5	0	0	0	0
Belgium	12	0.7	1.64	0.30	0
Germany	95	25	58.55	10.60	0
France	32	5	11.71	2.12	15
Greece	10	0	0	0	0
Italy	25	0	0	0	0
the Netherlands	13	0	0	0	0
Portugal	9	0	0	0	0
Spain	32	12	28.10	5.09	15
Switzerland	2	0	0	0	0
Domestic production		**42.7**	100	18.10	**5.97**
Supplier		Imported in UCPTE			
		Mt	Imported share of total %		
Australia	-	32.01	16.57	13.57	71
Canada	-	2.75	1.42	1.17	100
China	-	2.36	1.22	1.00	10
South America	-	17.72	9.17	7.51	100
Poland	-	23.22	12.02	9.84	0
South Africa	-	49.07	25.40	20.80	40
former USSR	-	7.64	3.95	3.24	40
UK	-	0.69	0.36	0.29	15
USA	-	57.72	29.88	24.47	52
Total import	-	193.18	100	81.90	**49.82**
Total UCPTE	**235.50**	**235.88**	-	100	**41.88**

The methane emissions per unit of dug coal have been estimated using the shares of the suppliers: for underground coal, it decreases from 15.9 m^3/t in year 1990 (Frischknecht et al., 1994) to 9.7 m^3/t in year 2020 for UCPTE, while 7.8 m^3/t are calculated for the Swiss case in year 2020.

After mining coal is first stored in stocks, before it is transported to the users. Data for storage are directly taken from the earlier LCA study. Technological advancements in transportation have not been credited for future systems. Due to the shifting of the assumed origin of coal, the share of different transport systems changes for UCPTE with respect to the current situation.

Table 4.1.III

Methane releases to air from hard coal mining for supply to UCPTE countries in year 2020, after (OECD/IEA, 1994).

Country	Production surface mining %	Methane emissions surface mining m^3/t	Production underground %	Methane emissions underground m^3/t
Belgium	0	0	0.5	20.0
Germany	0	0	18.2	13.6
France	0.8	2.0	3.1	20.0
Spain	1.8	2.0	7.4	10.0
Australia	23.0	2.0	6.8	9.3
Canada	2.8	1.7	0	0
China	0.2	2.0	1.6	7.0
Columbia	17.9	3.0	0	0
Poland	0	0	17.0	7.4
South Africa	19.9	2.0	21.5	7.5
former USSR	3.1	1.7	3.3	12.2
UK	0.1	0.5	0.4	7.7
USA	30.4	1.5	20.2	8.5
Total	**100.0**		**100.0**	
Average UCPTE		**2.01**		**9.71**
Average CH		**2.01**		**7.80**

Figure 4.1.1 shows the two different routes that have been assumed for Switzerland to separately evaluate the transport requirements for European and oversea coal. European coal from Poland will be imported by rail. Oversea coal is assumed to be transported by railway from mine to the harbour (distance of approximately 700 km), shipped to Northern Europe by freighters (about 10000 km), then transported by inland navigation to Switzerland (approximately 700 km), and finally by rail to the power plants (nearly 100 km). Therefore, at least three intermediate ports are necessary. The distances up to the

delivery to Europe are averages for South Africa and the USA (Frischknecht et al., 1994), (Gantner, 1995). Losses of coal (2 ‰) and emissions of particles (2 kg/t) associated with oversea transport for the supply to the Swiss power plants are assumed to be twice as high as for the European coal.

Following the same approach as used in the earlier LCA study, the coal burned in UCPTE plants is split into domestic coal (including trading among UCPTE countries) and coal imported from non-UCPTE countries. The present study uses the weighted distances of the different transport systems (rail, freighters for oversea transport and barges for inland waterway transport), as calculated in (Gantner, 1995).

4.1.4 Technologies

In the following sections the types of coal power plants considered for Switzerland and for the rest of UCPTE in year 2030 are described and the expected emissions to air as well as the material and energy requirements discussed. The expected performance of PC and PFBC systems operating in UCPTE in year 2010 is moderately lower (Gantner, 1995). These performance characteristics are not shown here since minor differences in relation to technologies of year 2030 have practically no influence on the calculations carried out for the supply mix options.

The load factor assumed by VSE for all coal power plants in Switzerland is 80%; the assumed lifetime is 30 years. Only river cooling has been considered for Swiss coal plants, while cooling towers are today in operation in most of the plants in other UCPTE countries. However, this assumption has very limited influence on the inventories.

Table 4.1.IV

Emission limits and emission factors of hard coal power plants.

	Efficiency %	SO_x kg/GWh$_{th}$	NO_x kg/GWh$_{th}$	N_2O kg/GWh$_{th}$
Limits CH 1990	-	504	252	-
Limits Austria 1990	-	525	252	-
UCPTE 1990	36.5	up to 3060	up to 1584	1.8
Austria 1990	36.5	216	252	1.8
PC 2010	46	216	216	1.8
PFBC 2010	47	72	144	198
PC 2030	50	108	180	1.8
PFBC 2030	53	18	36	90

Table 4.1.V shows an overview of selected material requirements and emissions to air for the coal power plants which are considered to be the most important for the calculation regarding for year 2030, namely PC 2030, PFBC 2030 and Present generation PC. These data have been used in the current analysis. Table 4.1.IV shows separately plant efficiencies, present and future emission factors for main air pollutants, as well as today's emission limits.

Table 4.1.V

Selected material requirements and emissions for present and future hard coal power plants.

Hard coal power plants		Present [a] generation PC	PC in CH (year 2030)	PFBC in CH (year 2030)	PC in UCPTE (year 2030)	PFBC in UCPTE (year 2030)
Direct requirements						
Aluminium	kg/GWh$_{th}$	2.26	2.26	2.88	2.26	2.88
Concrete		671	576	576	720	864
Copper		4.32	4.32	5.76	4.32	5.76
Steel high alloyed		2.6	2.88	2.88	2.88	2.88
Steel low alloyed		23.5	25.2	25.2	25.2	25.2
Steel unalloyed		129.6	129.6	169.2	129.6	169.2
Water for cooling towers		5.4E5	0	0	5.4E5	5.4E5
Total water		1.26E7	5.04E7	5.04E7	1.26E7	1.26E7
Rail transport	t·km/GWh$_{th}$	1512	720	720	1512	1512
Limestone $CaCO_3$	kg/GWh$_{th}$	0	0	6480	0	6480
NO_x retained in SCR		1080	1224	0	1224	0
SO_x retained in Wet Scrubbing (WS)		1944	1116	0	2052	0
Direct emissions						
Waste heat to air [b]	GWh/GWh$_{th}$	0.55	0.145	0.145	0.46	0.46
Waste heat to water [b]		0.13	0.39	0.39	0.1	0.1
CO_2	kg/GWh$_{th}$	331200	331200	331200	331200	331200
CH_4		3.6	3.6	3.6	3.6	3.6
N_2O		1.8	1.8	90	1.8	90
SO_x as SO_2		216	108	18	108	36
NO_x as NO_2		252	180	36	180	36
Particles		32.4	18	18	18	18
Total ash produced		16200 [c]	10800	10800	16200 [c]	16200 [c]

[a] Values for Austrian power plants (representative for the environmentally best performing plants in UCPTE)

[b] The total waste heat is calculated using the high heating value, about 5% higher than the low value.

[c] In West Germany and other UCPTE-countries up to 90 % of the ash is recycled

The emission limits for released pollutants are regulated by law. In this study it is assumed that the limits of pollutants to air are adjusted in all UCPTE countries in accordance with the improvements of clean coal technologies. Moreover, two sets of values have been used to distinguish the emission limits for pollutants for Swiss plants from the limits in the other UCPTE countries. CO_2 emissions depend upon the coal quality and the efficiency of the power plant. For coal with a low heating value of 28 MJ/kg and a carbon content of about 70 %, approximately 331200 kgCO_2/GWh$_{th}$ are produced.

No new data for emissions to water from the coal power plants were available for future systems. Therefore, the corresponding input used in the earlier LCA study on present electricity systems remained unchanged. The normalised emissions were, however, reduced as the result of the overall efficiency improvements. Radioactive emissions to air

are based on the previous study, where it was assumed that actinides and aerosols released are proportional to the amount of flue ash[1]. Due to the improvements in the ash removal systems and efficiency increase of future power plants these emissions are expected to decrease. The radon emissions which are proportional to the plant efficiency, will also decrease. In terms of weight, solid wastes from mining are one order of magnitude higher than the produced amount of ashes from the operation of power plants. The amount of gypsum produced by desulphurisation process is comparable with the weight of ash.

4.1.4.1 Present Pulverized Fuel Combustion Plants

This type of power plant is well known and in operation in different countries. It can be expected that it will still be dominant in UCPTE by year 2010, while by year 2030 there will be just few of them still in operation. For the future, it has been assumed that all plants of the present generation remaining in operation will be retrofitted to the state-of-art of existing plants in Austria, which have the most strict emission standards (Frischknecht et al., 1994). This means in particular that all plants will be equipped with abatement technologies such as limestone wet scrubbing (WS), selective catalytic reduction (SCR) and dust removal systems. All data for abatement technologies are the same as assumed in the earlier LCA study with the exception of the amount of limestone that it is necessary to obtain higher removal efficiencies in the desulphurisation process. The requirements on different materials have been changed with respect to the earlier LCA study, to be consistent with the main source of the data for advanced technologies used here (ABB, 1995). Present pulverized fuel combustion plants are not relevant for Switzerland.

4.1.4.2 Advanced Pulverized Fuel Combustion Plants

The development of materials resistant to high heat and pressure allows steam conditions higher than in old plants (up to 300 bar and 600 °C) to drive the turbines. The efficiency increases up to 50 % because of the better thermodynamic conditions (ABB, 1995), (Booras et al., 1991). The technology of auxiliary systems is not expected to change substantially. Thicker tubes and vessels, made of improved steel quality are needed because of the higher thermal stresses. The requirements of concrete are lower for the Swiss plants compared to UCPTE plants because of the lack of cooling towers.

The efficiency of SCR will reach nearly 90 % (OECD, 1993). The most strict NO_x limits are today in Sweden (145 mg/Nm^3, 500 kg/GWh). In Austria and the Netherlands the limit is 200 mg/Nm^3 (680 kg/GWh) for present best technology (Coal Info, 1993). With the assumed improvement of SCR and power plant efficiencies, it may be expected that the NO_x emission limit for Swiss PCs will be set of about 360 kg/GWh.

The SO_x emission limit for Switzerland has been set up by considering the feasibility of the new abatement technologies in connection with the use of low sulphur coal. Desulphurisation technologies are able already today to retain more than 95 % of SO_x. Because of the assumptions on coal quality, an efficiency of 92 % has been conservatively used to comply with the SO_x emission limit.

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[1] The origin of coal was not considered in (Frischknecht et al., 1994), but typical data from (UNSCEAR, 1988) were used for UCPTE.

4.1.4.3 Pressurized Fluidized Bed Combustion Plants

The main reason for developing PFBC plants is the advantage of using coal in combined cycles, i.e. lower investment costs and reduction of main pollutants such as SO_x and NO_x integrated within the combustion process (Maude, 1993). Moreover, they have a high efficiency, that should reach 53 % (ABB, 1995).

In PFBC plants pulverized coal is burned under pressure (10-16 bar) and at relatively low temperature (approximately 800 °C). Limestone is added into the combustion chamber (approximately 6500 kg/GWh_{th} (PFBC, 1991)), reacting with sulphur to yield calcium sulphate (gypsum). The efficiency of this process depends on the Ca/S ratio and can reach 97 % (PFBC, 1991). For the Swiss PFBC plants, SO_x production may go down to about 18 kg/GWh_{th} for the excellent coal quality chosen, whereas for the rest of UCPTE, about 36 kg/GWh_{th} can be estimated on the basis of the lower fuel quality. Conditioned by the low combustion temperature, only very low NO_x are formed, 36 kg/GWh_{th}, but N_2O emissions increase to 72-216 kg/GWh_{th} compared to 1.8 kg/GWh_{th} generated in PCs (ABB, 1995), (Frischknecht et al., 1994), (Gulyurtlu, 1992), (Indo, 1992), (Eyre, 1991). N_2O is a gas with a relatively high global warming potential.

From the combustion chamber the flue gas is routed to cyclones and other dust removal systems. The cleaned flue gas drives gas turbines that contribute 25-30 % to the total electricity generated by the plant. Moreover, the turbine drives an air compressor to keep the combustion chamber under pressure (DE, 1991). Before reaching the stack, the flue gas is further used to preheat the feedwater for the steam cycle.

Data on material requirements have been taken from the Swedish pilot plant Värtan (ABB, 1995). In particular, a higher amount of high quality steel is required in comparison to PC systems because of the higher pressures.

4.1.5 Results

The discussion of results is divided to three parts. In the first part comparative results for the upstream steps are described. In the second part the requirements and emissions associated with the power plants are compared to the total obtained for the entire energy chain. The third part considers the lumped results obtained for the chains of the Swiss (year 2030) and UCPTE (years 1990, 2010, and 2030) coal mixes, along with the Austrian plants (1990). The results are normalised by the unit of electricity.

4.1.5.1 Upstream steps

One of the conclusions of the earlier LCA study on current electricity systems was that transportation and mining contribute significantly to many emissions calculated for the coal chain. Some important material requirements (concrete and steel), the electricity requirements and selected pollutants to air (CO_2, CH_4, NMVOC, SO_x and NO_x) are compared in Figures 4.1.3 through 4.1.9 for the upstream part of the coal chain; as may be seen, some different routes for the transportation of the fuel were assumed in this study. Thus, coal is assumed to be delivered to Switzerland either overseas or from Poland ("Overseas to CH" and "Europe to CH", respectively, as shown in the charts). Coal used in other UCPTE countries is divided into domestic coal and coal imported to UCPTE (in the

picture: "Domestic UCPTE" and "Import to UCPTE", respectively). For some selected parameters, the calculated total (direct and indirect) contributions from transportation are explicitly shown.

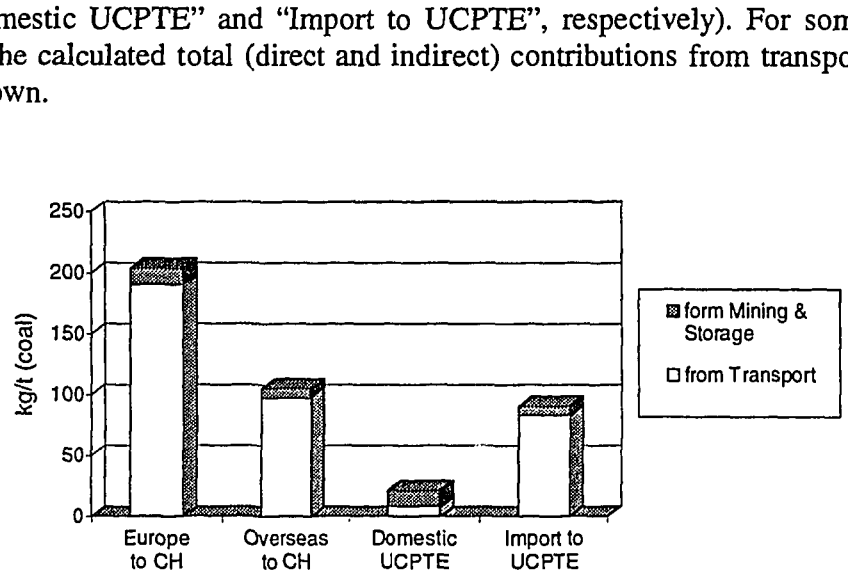

Figure 4.1.3 Concrete requirements for the upstream steps of the hard coal chain.

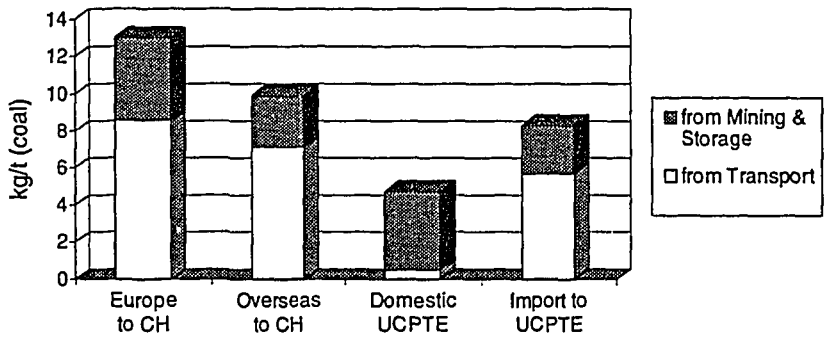

Figure 4.1.4 Requirement of steel for the upstream steps of the hard coal chain.

For the upstream steps, long distance transportation dominates the requirements for concrete and steel (Figures 4.1.3 and 4.1.4); the former are mainly due to the infrastructure of the rail transportation systems in Europe and abroad.

For the upstream steps, the electricity requirements are mainly function of the rail transport distances (Figure 4.1.5). In fact, among transportation systems, the railway is the only one using significant amounts of electricity during operation. Therefore, the transportation of Polish coal to Switzerland ("Europe to CH" in Figure 4.1.5) requires the highest amount of electricity per unit of weight of transported coal.

The emissions of CO_2, SO_x, NO_x and NMVOC clearly show that transport distances have the dominant influence on the upstream steps. Emissions associated with oversea coal are twice to ten times higher than for coal mined in Europe (Figure 4.1.7). Methane emissions mostly originate from underground mining. Therefore, coal mined in Poland and UCPTE

countries (mostly underground) have associated higher CH_4 emissions than oversea coal, whose share of open-pit mining is much higher than in Europe (see Table 4.1.I). It can be concluded that with the exception of methane, the emissions associated with transportation prevail in the upstream steps.

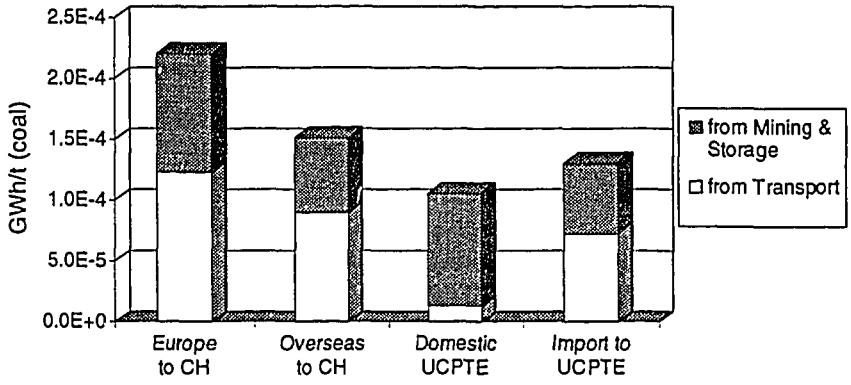

Figure 4.1.5 Electricity requirements from the upstream steps of the hard coal chain.

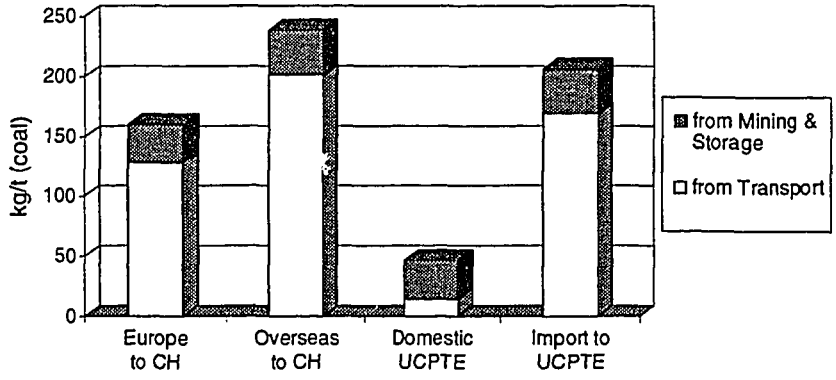

Figure 4.1.6 CO_2 emissions from the upstream steps of the hard coal chain.

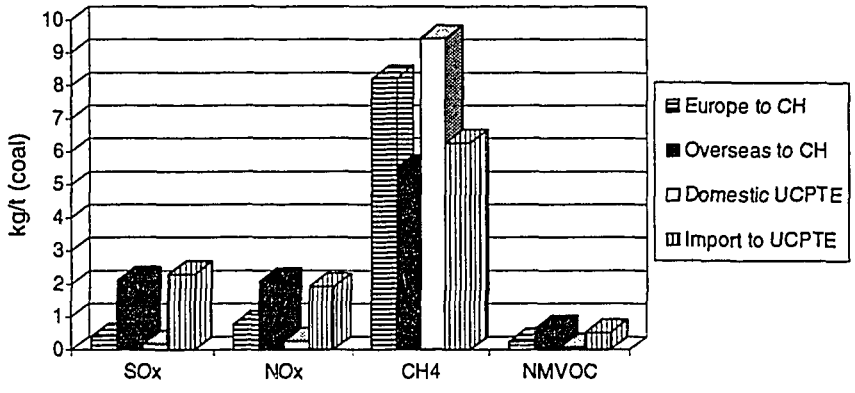

Figure 4.1.7 Selected air pollutants emissions from the upstream steps of the hard coal chain.

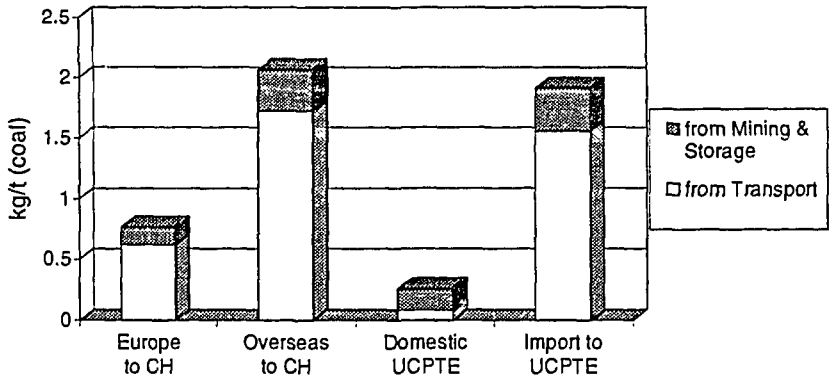

Figure 4.1.8 NO_x emissions from the upstream steps of the hard coal chain.

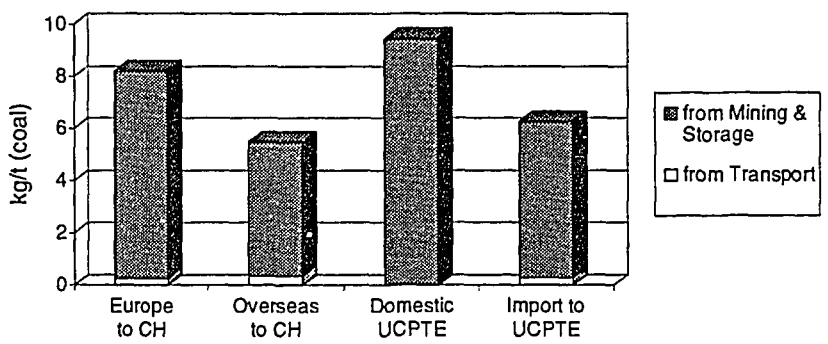

Figure 4.1.9 CH_4 emissions from the upstream steps of the hard coal chain.

4.1.5.2 Hard coal full energy chains

Figures 4.1.10 to 4.1.16 show the total requirements and emissions calculated considering the full chains. Requirements and emissions calculated for the power plants are given separately from the corresponding ones calculated for the upstream steps. The results shown for the full chains are associated with the following power plants: average UCPTE coal plants in reference year 1990 ("UCPTE 1990") as calculated in (Frischknecht et al., 1994); present generation of Austrian power plants ("A 1990"); advanced PC and PFBC plants in UCPTE in year 2010 and in Switzerland in year 2030 ("PC UCPTE 2010", "PFBC UCPTE 2010", "PC CH 2030", and "PFBC CH 2030", respectively); and, the average UCPTE coal power plant mix in year 2010 ("UCPTE 2010").

Upon closer examination of the figures it can be concluded that the upstream steps, particularly the transport of coal discussed in the previous section, clearly dominate the total material and energy requirements for the chain. In relative terms, the differences between the various types of reference hard coal plants are of minor importance.

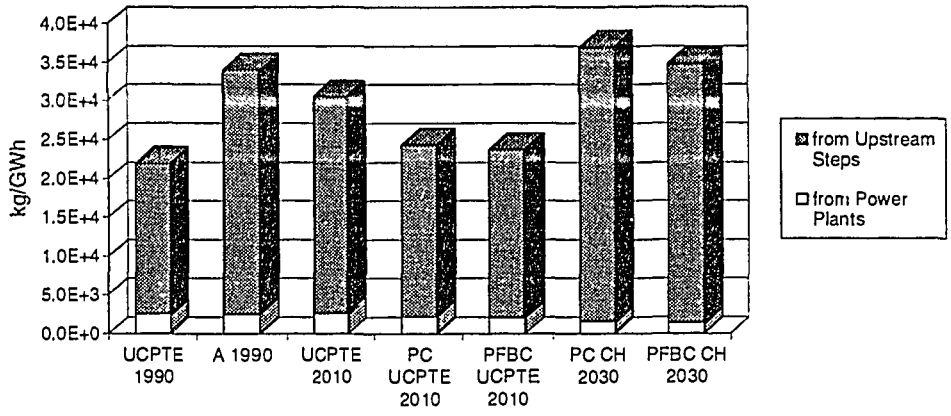

Figure 4.1.10 Total concrete requirements for different hard coal systems.

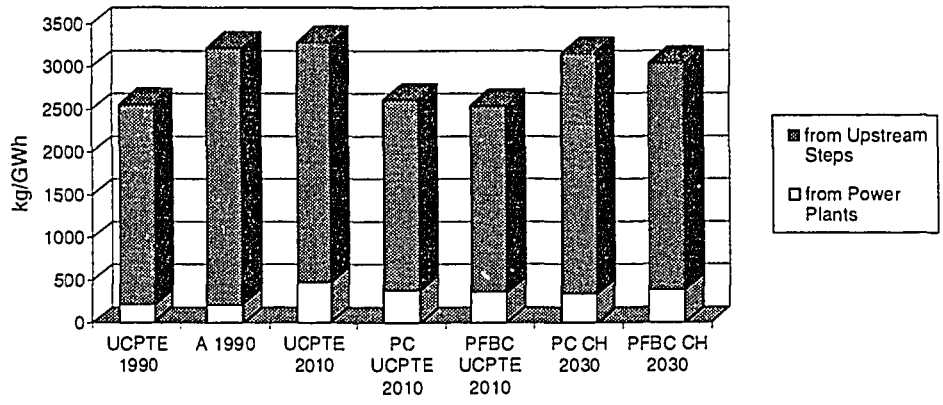

Figure 4.1.11 Total steel requirements for different hard coal systems.

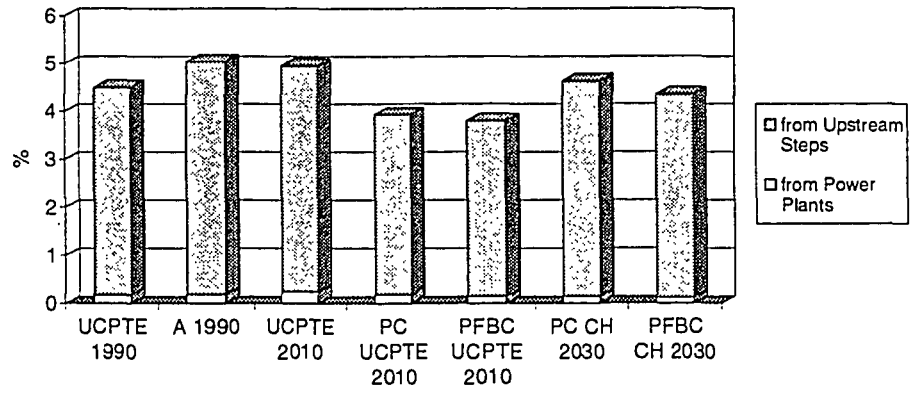

Figure 4.1.12 Electricity requirements as a fraction of the total generated by the analysed different hard coal systems.

By far the highest contribution to the total CO_2 emissions from the coal chain originates from power plant operation (Figure 4.1.13). Methane emissions are totally dominated by direct emissions in underground mining (Figure 4.1.14). As clearly shown in the pictures, both emissions normalised by the unit of energy will be reduced in the following 30 years due to the increasing plant efficiencies and, for methane, recovery potential.

The new technologies reduce significantly SO_x and NO_x emissions from the plant, as shown in Figures 4.1.15 and 4.1.16, respectively. As a consequence, the upstream steps become more important than for present systems. In PFBC plants the emissions from stack can be considered negligible compared to the other analysed coal systems. Nevertheless, it should be stressed that in the present study the transport systems have not been extrapolated to the future.

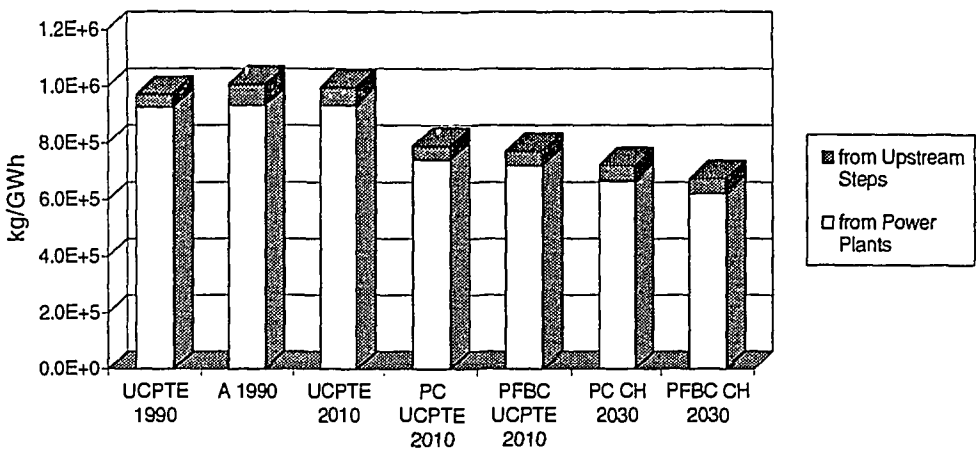

Figure 4.1.13 CO_2 emissions for different hard coal systems.

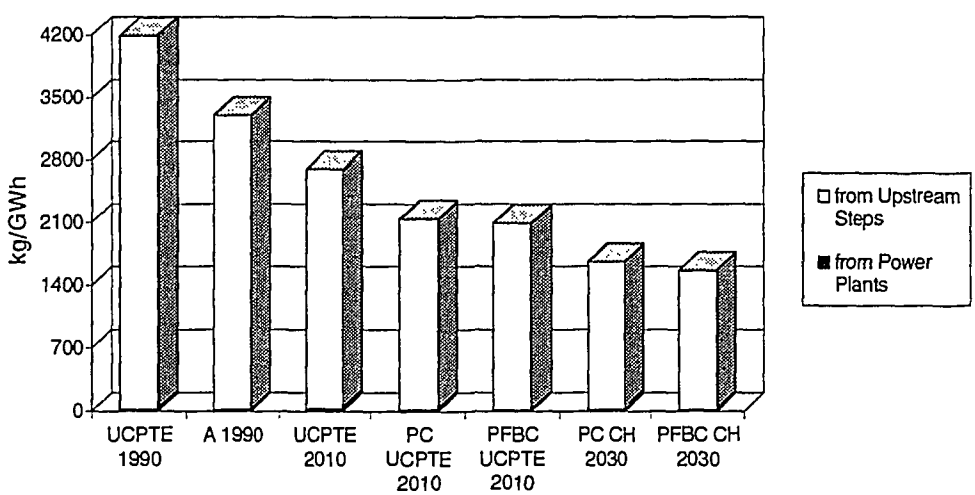

Figure 4.1.14 CH_4 emissions for different hard coal systems.

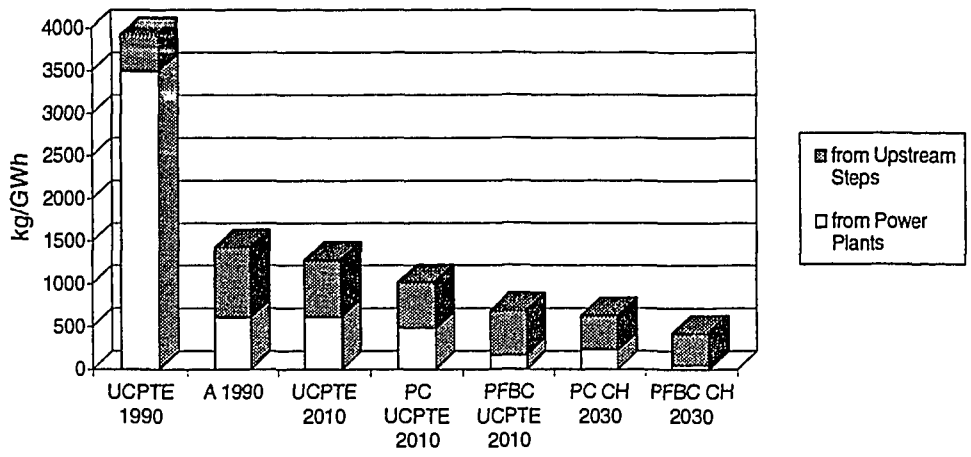

Figure 4.1.15 SO_x emissions for different hard coal systems.

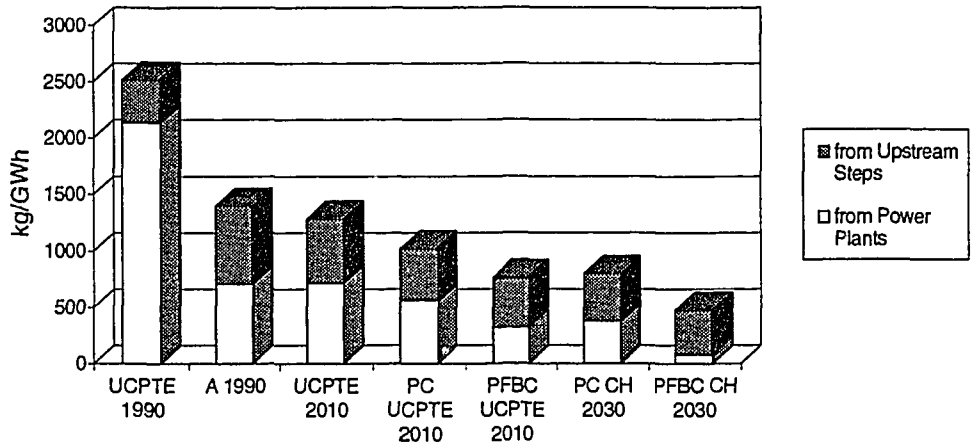

Figure 4.1.16 NO_x emissions for different hard coal systems.

It has been shown in the earlier LCA study that by far the highest contributions to the total emissions to water originate from mining and transport. It can be concluded that these emissions normalised by the unit of energy are roughly inversely proportional to the plant efficiencies (this is true for equal shares of underground to total mining and for constant transport parameters).

The amount of ashes and gypsum produced per unit of energy by advanced PC plants for Switzerland decreases when compared to the present systems because of the chosen coal quality and the increased efficiency of the power plants. PFBC plants for Switzerland also produce lower amount of ashes compared to the present systems, but the amount of gypsum increases due to the assumed high sulphur retention efficiency (higher than the efficiency of WS used in PCs). For UCPTE PFBC and PC plants the amount of ashes and gypsum is higher than the values calculated for the advanced plants for Switzerland because of the higher content of sulphur and ashes, respectively, in coal.

4.1.5.3 Hard coal mixes

In this section, the full chains associated with the hard coal power plant mixes in UCPTE and in Switzerland in year 2030 (see Section 4.1.2) are compared with the results for present systems obtained in the earlier LCA study for UCPTE countries. Austrian plants are explicitly taken into consideration because they represent the best hard coal plants nowadays. The dramatic reductions calculated for such pollutants as SO_x and NO_x for the mixes with advanced hard coal power plants as compared to UCPTE 1990 coal mix can be explained by the many old power plants without abatement technology presently in operation in UCPTE. Compared to the current emissions associated with Austrian plants, the calculated reduction is only a factor of approximately two. The mix of coal power plants UCPTE 2030 has been used for the coal-based imported electricity included in the supply option 4 and 5 (see Chapter 6).

Table 4.1.VI shows the results for the full chains associated with the coal plant mixes considered. Figures 4.1.17 to 4.1.20 show the results for selected requirements and releases to air.

Table 4.1.VI

Results for hard coal mixes (full chains).

Resources & Emissions		UCPTE 1990	A 1990	UCPTE 2030	CH 2030
Hard coal	t/GWh	605	612	421	410
Steel	t/GWh	2.6	3.2	2.3	3.1
Concrete	t/GWh	21.9	34.0	22.7	35.8
Electricity	%	4.5	5.1	3.4	4.4
CO_2	t/GWh	972	1011	734	699
SO_x	t/GWh	4.00	1.51	0.68	0.54
NO_x	t/GWh	2.52	1.40	0.72	0.65
CH_4	t/GWh	4.21	3.31	1.80	1.71
Ash	t/GWh	54.0	30.6	34.2	21.6

Coal requirements and emissions of pollutants to air decline due to the increased plant efficiencies. For Switzerland, 21.6 t/GWh of ashes would be produced which would have to be disposed of or recycled in other sectors like road construction, as discussed in (Frischknecht et al., 1994). For UCPTE countries the normalised value for ash is distinctly higher due to the inferior average coal quality and the assumed share of power plants of the present generation still in operation in year 2030. With an installed power of approximately 1.7 GW and a load factor of 0.8 (corresponding to the conditions assumed for the high-growth demand options H1 and H6), 0.25 Mt of ashes would be generated each year in Switzerland.

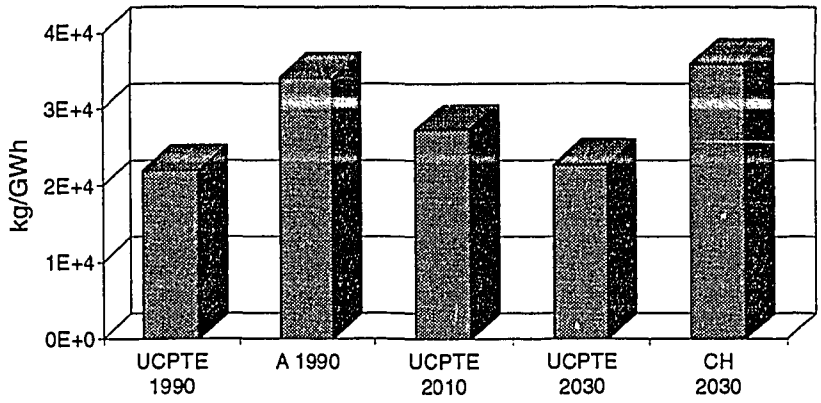

Figure 4.1.17 Concrete requirements for the full chains corresponding to the assumed hard coal power plant mixes.

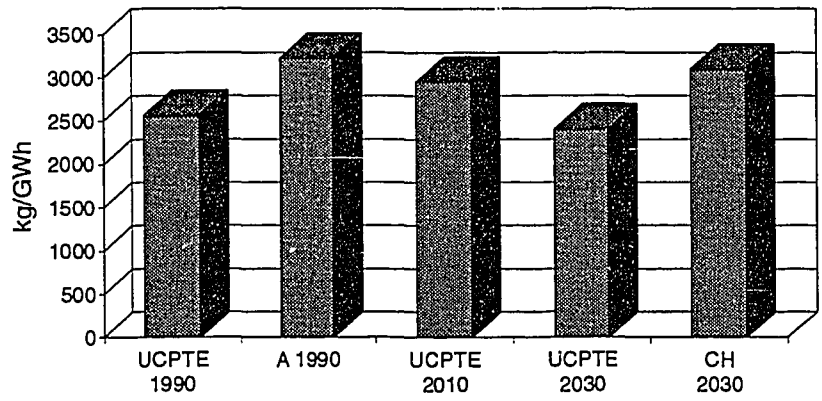

Figure 4.1.18 Steel requirements for the full chains corresponding to the assumed hard coal power plant mixes.

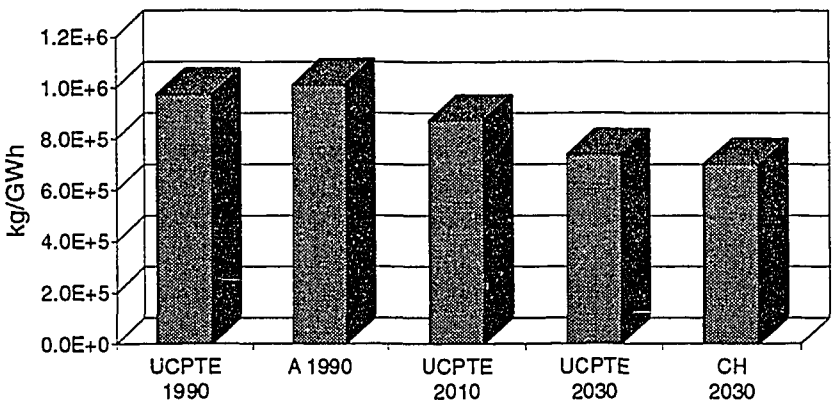

Figure 4.1.19 CO_2 emissions for the full chains corresponding to the assumed hard coal power plant mixes.

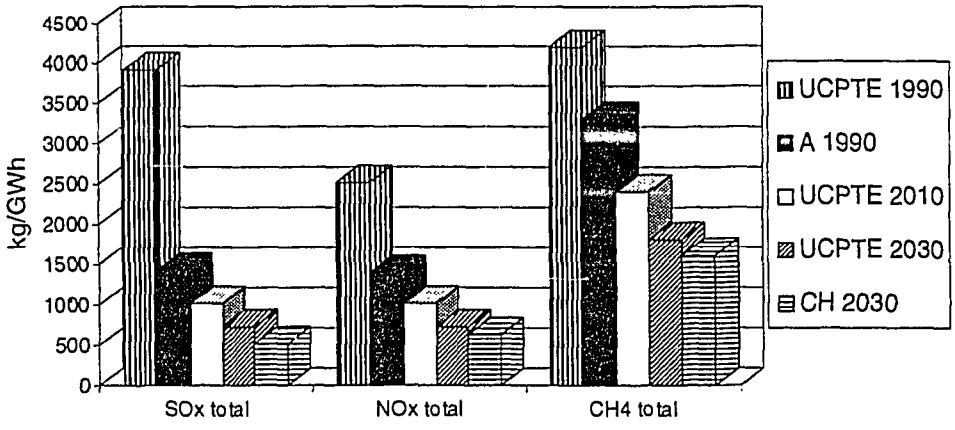

Figure 4.1.20 SO_x, NO_x and CH_4 emissions for the full chains corresponding to the assumed hard coal power plant mixes.

4.2 Natural Gas Systems

This chapter describes the assumptions, technologies and results for three various types of plants using natural gas as fuel, i.e. Gas Combined-Cycle plants (GCC, 300 MW_e), Gas Turbines (GT, 30 MW_e) and small cogenerating heating systems (160 kW_e Combined Heat and Power Plants, or CHPP). Since some of the considered electricity supply options assume the use of both gas and fuel oil in CC plants, the latter mode of operation will be presented here as well.

4.2.1 Overview

4.2.1.1 Role of natural gas

The European consumption of natural gas for electricity generation in the UCPTE grid was 1180 PJ_{th} in 1992. Power plants fed with natural gas contributed 7.8% to the total UCPTE electricity production. The share of natural gas for electricity generation will probably increase in the future due to its technological and environmental advantages in comparison to other fossil fuels. The mixing of gas fuels with air and the following burning can be engineered more easily and reliably than with liquid or solid fuels. In addition, gas turbines require a very short start-up time and can quickly adapt to demand changes. From the environmental point of view, natural gas has the lowest carbon content per unit of energy than any other fossil fuel. The release of carbon dioxide per unit of energy produced is therefore the lowest amongst fossil fuels. With its naturally low nitrogen and sulphur content natural gas is an increasingly important option for an energy market which has to meet more and more stringent environmental requirements.

On the other hand, natural gas reserves — assuming today's consumption and proven reserves — are predicted to last only about 65 years; hard coal and oil reserves are expected to last about 170 and 40 years, respectively, according to (BP, 1993). Even

though natural gas has a low potential of producing carbon dioxide, it still contributes to global warming and has to compete with less burdened non-fossil energy technologies.

Five out of the seven supply options defined by VSE as alternative means to cover the gap in future electricity supply in Switzerland in years 2020/30 include substantial shares of CC, whereas GTs and CHPPs are assumed to contribute on a relatively small scale to the base supply (see Sections 6.1 and 6.2).

4.2.1.2 General assumptions

The environmental inventories of GCC and GT are based on the earlier LCA study on current energy systems (Frischknecht et al., 1994). Changes or new data are introduced to account for important future changes. Most changes were introduced at the plant level, like increased efficiencies and improved emission performance. CHPPs, which were not assessed in the earlier study because of the small current contribution to the Swiss grid, have now been inventoried based on a modern heating plant (Bollens, 1995), with the assumption of no significant changes in the future.

It was not feasible, within this study, to adjust all the data concerning precombustion steps. The focus on the power plant is justified by the fact that changes in plant technology affect the overall inventory to a much greater extent than changes in precombustion technologies. However, the methane leakage from pipelines in the Russian Federation has been modified with respect to the previous study, due to its significance for the overall results. The origin of natural gas, i.e. the European import mix of natural gas, has been left unchanged.

The allocation of environmental burdens from cogenerating systems (i.e. systems generating electricity and heat) was done on the base of the exergy content of the products.

4.2.2 Structure of the energy chain

Various natural gas reservoirs are exploited in different countries. The produced gas is conditioned to separate unwanted components of the raw gas. The gas is transported to the consumers mainly by means of pipelines, where it is distributed by a grid of high and low pressure pipes. Figure 4.2.1 shows a simplified scheme of the natural gas energy chain.

4.2.3 Specific prioritizations and assumptions

Almost all data for gas precombustion steps are directly imported from (Frischknecht et al., 1994), where detailed relevant information can be found. The process chain for natural gas was assessed there, including gas production, conditioning, transport and distribution. The simplified treatment of precombustion is supported by the generally long life span of relevant precombustion technologies (assumed 50 years for pipelines and 30 years for raw gas exhaustion plants). Only a short, mostly qualitative summary of the precombustion steps for the European supply of natural gas is given in the following sections.

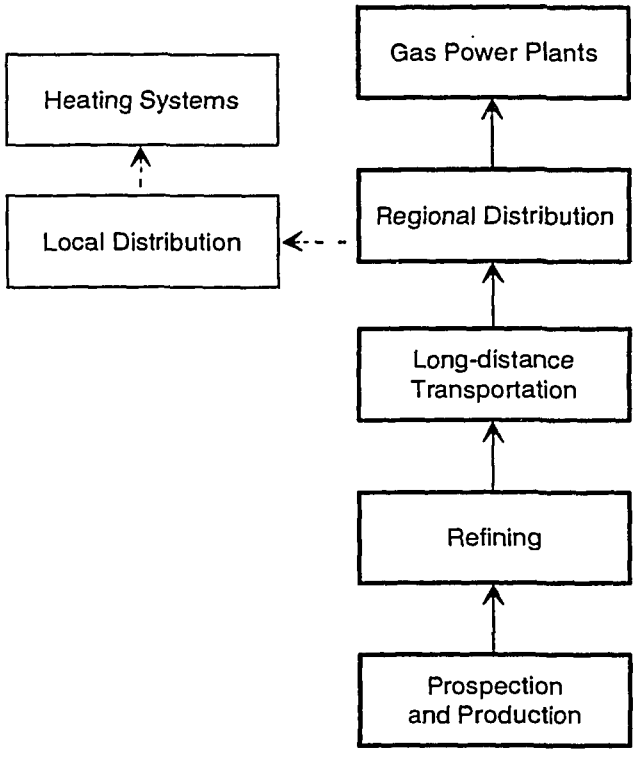

Figure 4.2.1 Major steps in the natural gas energy chain.

4.2.3.1 Gas production

The production of natural gas can be divided in two major types: on-shore and off-shore production. About 15% of the natural gas consumed in Europe stems from off-shore production, with a higher specific energy consumption than on-shore. Relevant production countries in year 1990 are listed in Table 4.2.I.

Table 4.2.I

Origin of the natural gas consumed in UCPTE and Switzerland in 1990.

Net import shares[a]	to UCPTE	to CH
from Germany	21%	13%
from the Netherlands	32%	41%
from Norway	9%	10%
from the Russian Federation	23%	32%
from Algeria	15%	4%

[a] The figures given indicate the physical origin of the gas and do not refer to direct import contracts.

Important air emissions in gas production occur during flaring of excess gas, and through gas leakages during normal use, maintenance and ventilation. The input data for this process step was not modified with respect to the previous work.

Import shares may change in the future (e.g. a higher share of imports from the Russian Federation to Germany), but detailed and reliable information for the European market are not available. The amount of polluted water released during gas prospection and production is also uncertain. Generally, higher volumes are expected. On the other hand, production water will increasingly be disposed of underground (e.g. in empty aquifers and exhausted gas fields) and not emitted to surface water, with consequent reduction of environmental burdens. This reduction, however, has not been credited, due to large uncertainties.

4.2.3.2 Gas conditioning

The composition of raw natural gas includes water, hydrogen sulphide (H_2S), higher volatile and fluid organics. Prior to transport, the raw gas has to be — at least partially — cleaned of these components. A distinction is made mainly between raw gases with high and low sulphur content. Raw gas with hydrogen sulphide content higher than 1% of the volume is called sour gas; gas having lower concentration is called sweet or lean gas. Sour gas has a higher energy demand for conditioning. Approximately 14% of the raw gas consumed in Europe is sour gas.

Natural gas contains approximately 15% of natural gas liquids (NGL) which are separated and sold as a by-product of natural gas recovery. The lower heating value was used as the criteria for the allocation of the burdens between NGLs and gas in this combined production. NGLs make an average of about 4% of the total energy content of raw gas. Therefore, 96% of all the burdens connected with the separation of NGLs are allocated to the conditioned natural gas. As for the other upstream steps, the input data for this part of the process chain have been left unchanged.

4.2.3.3 Gas transport

Natural gas transport to Europe is almost exclusively done by high pressure pipelines. Only Algeria exports about 60% of its natural gas production as liquefied natural gas (LNG). Approximately 15% of the produced gas is used for liquefaction and transportation (with freighters).

A major environmental impact adding to the burdens from the construction and disposal of pipelines are gas leakages. The average leakage loss of modern West European pipelines is about 0.02% (~1000 km length). The gas pipelines in the Russian Federation are known to be in a poor state with estimates of the 1990 leakage losses ranging between 1% and 10%. In the earlier LCA study, an average value of 2% was used. The problem of the relatively high leakage is being addressed now and replacement or mending of leaking pipelines is intended. This study assumes that already by year 2010 the losses from gas pipelines in the Russian Federation will decrease on the average down to 1%, which still is fifty times more than the losses estimated for West European pipelines in 1990.

Gas leakages need to be clearly distinguished from the use of the gas in compressor stations along the pipeline. These stations are fed directly by the flowing gas. They were inventoried based on standard 10 MW_e gas turbine units.

4.2.3.4 Gas distribution

Regional and local distribution is accomplished by a grid of high and low pressure pipelines, respectively. The 70 bar pressure in long-distance pipelines is reduced to >1 bar in the high pressure grid and to lower pressures in the low pressure grid. Environmental burdens originate from construction, maintenance, monitoring (by planes and cars) and disposal of the pipes.

Leakage in the high pressure grid is 0.07% of the transported gas; in the low pressure grid leakage goes up to 0.9%. The leakages from the Swiss low pressure grid contribute about 50% to the overall, cumulated leakage loss through the whole energy chain. It is assumed that the natural gas supplied to the Swiss power plants considered for the VSE supply options is taken directly from the high-pressure grid, whereas the gas supplied to CHPPs is taken from the low-pressure grid. Leakages from the low pressure grid are therefore not relevant for the discussion about the systems covering the future electricity gaps. The input data for gas distribution have been left unchanged with respect to the reference LCA study.

4.2.3.5 Plant technology

Information on future gas power plants have been derived from manufacturers' estimates (Mukherjee, 1995), (NZZ, 1995), (Gerber, 1995) and literature data (Booras et al., 1991), (WEC, 1988), (Lavandier et al., 1994), (Fritsche et al., 1992), (Frischknecht et al., 1994), (Bollens, 1995). The data for GCCs and GTs refer to the state-of-the-art predicted for the years 2005 and 2015, respectively.

Fairly reliable extrapolations into the future can be given for state-of-the-art in year 2005. Cautious extrapolation to year 2015 were made on the basis of figures available for year 2005. Further extrapolations are too uncertain and speculative. It is assumed that the time span for planning, building and commissioning of a plant is about five years. Hence, the state-of-the-art in year 2015 is considered to be a reasonable representation for the average of plants which will be operating in the years 2020/30. Likewise, state-of-the-art in year 2005 is used for an average new plant in year 2010. Key parameters are efficiencies and improved emissions performance.

Some reservations are in place with regard to the treatment of CHPPs in this report. First, the data concern one specific plant inventoried in a very recent report (Bollens, 1995), namely a gas engine based CHPP for residential heat production. Therefore, the results are not fully representative for other types, e.g. CHPPs with higher temperatures of the produced heat (non-residential) or CHPPs based on different types of cogenerators (e.g. fuel cells). Second, the potential for future technological improvements has not been credited in this case. While the impact of this conservatism on the total emissions is insignificant due to the low share of CHPP in the supply mixes defined by VSE (Section 6.2), the representation of CHPP at the level of systems comparison is not fully balanced. The intention is to update and extend this analysis in the future.

4.2.3.6 UCPTE gas power plants mix in year 2010.

As a part of the 2010 UCPTE electricity generation, a mix of modern GCCs and present (i.e., in year 1990) best gas power plants has been used here, as shown in Table 4.2.II.

Table 4.2.II

UCPTE mix of gas power plants in year 2010.

Gas Power Plants	Assumed share in 2010 UCPTE gas mix[a]	share of blast furnace gas in fuel gases[b]	share of coke gas in fuel gases[b]
new GCC (natural gas only)	**20%**	0%	0%
Italian gas power plant[c]	**41%**	0%	11%
German gas power plant[c]	**25%**	10.3%	13.7%
French gas power plant[c]	**9%**	63.2%	6.8%
Dutch gas power plant[c]	**5%**	6.4%	0%
Total	100%	8.6%	8.6%

a These shares are not representing anticipated shares of gas plants in the relevant UCPTE countries in 2010, but they are only used to construct a realistic mix of modern 1990's plants typical for year 2010.

b 1990's country specific shares (Frischknecht et al., 1994).

c Assuming 1990 typical modern gas power plants (Frischknecht et al., 1994).

It is assumed that GCCs fuelled with natural gas share 20% in this mix; the remaining part is covered by systems having the same performance as current Italian gas power plants[1] as described in (Frischknecht et al., 1994). The gas used at present to fire UCPTE gas power plants consists of 82% natural gas, 9% blast furnace gas, and 9% coke gas. The 2010 mix includes a slightly lower share of blast furnace gas and coke gas.

4.2.4 Technologies

4.2.4.1 Overview

Table 4.2.III lists some characteristics of the gas power plants considered in this study. These plants are shortly described in the following paragraphs.

- **Gas Turbines**

In a gas turbine the fuel is burned with pressurised air. The flue gas is forced through a turbine driving a generator. The most common fuel is natural gas, but also fuel oil can be used. The average efficiency of current GTs is about 30%. In addition, the exhaust can be used for heating purposes. This has been considered here. A turbine of 30 MW electric power has been inventoried for future plants for years 2020/30. The electric efficiency is assumed to reach 36% already by the year 2015; this value was also adopted for years 2020/30. The assumed load factor is 4500 hr/yr (or 51%) and the lifetime 25 years.

[1] In addition to the Italian plants, small shares of 1990 typical modern German, Dutch and French gas power plants are added to keep the mixture of the burned fuels constant.

Table 4.2.III

Overview of the gas power plants inventoried in this study.

	GCC		GT	CHPP
Nominal electric power, MW	300	300	30	0.16
Fuel	natural gas	fuel oil	natural gas	natural gas
Cogeneration of heat	no	no	yes	yes
Electricity to heat ratio	n.a.	n.a.	1.2	0.54
Allocation share to electricity	100%	100%	82.5%	72%
Used in Swiss supply options as:				
• plants covering deficit (years 2020/30)	yes	yes	no	no
• base plants (years 2020/30)	no	no	yes	yes
• electricity mix in year 2010	yes	no	yes	yes

n.a. = not applicable

- **Gas Combined Cycle Plant**

The temperature of the exhaust from a gas turbine can be as high as 600°C. GCC uses the flue gas to drive a steam cycle, through heat exchangers, with an additional steam turbine. The combination of these two cycles can increase the overall electric efficiency to values greater than 50% by using currently available technology. These plants can also be used as cogenerating units, but this has not been taken into account in this study. A typical GCC plant of 300 MW nominal electric power has been considered for the years 2010 and 2020/30. The assumed efficiencies are 57% and 60%, respectively. For comparison, the plant under construction in Tapada do Outeiro in Portugal, which will be fuelled with Algerian natural gas and light fuel oil, has an efficiency of about 55% (BWK 1995).

- **CHPP**

In CHPPs gas or fuel oil are used to power an engine driving an electrical generator. The waste heat is used for heating purposes. Here, only the production of electricity is of interest. Gas engine based CHPPs are a rather mature technology with modest development potential. Nevertheless, methane emissions could be lowered by means of catalytic converters. A small system of 160 kW_e operating in Basle since 1987 has been inventoried to represent a typical gas engine based CHPP. The main task of the assumed reference plant is the production of residential heat for 220 dwellings during winter. Its operational electric efficiency is approximately 27%. Since this plant is not working during summer, its load factor is approximately 4600 hr/yr (or 52.5%).

- **Other gas technologies**

Fuel cells are a further option for electricity generation. They have potential advantages of scaleable modularity and high efficiency (up to 60% in prototypes, with a theoretical limit near to 100%); on the other hand there are at present problems for achieving thermally enduring high efficiency materials. Regardless of their potentially important contribution to future power generation, fuel cells are not considered in this study.

4.2.4.2 Emissions

- **Gas combined cycle with natural gas**

GCC plants have been inventoried using a load factor of 7000 hr/yr (or 80%) and a lifetime of 25 years. Load factors in the VSE supply options range from 5100 hr/yr to 7000 hr/yr. Different emission factors due to several start-up procedures resulting from small load factors have not been considered in this study. Lower load factors would also lead to higher specific environmental burdens from construction material and energy requirements. This has not been assessed here since the influence from the construction of the gas plant is of minor importance. Table 4.2.IV lists specific emissions from future GCC plants per GWh_{th}, i.e. referring to the lower heating value of burned natural gas.

- **Gas combined cycle with fuel oil**

For supply safety and load management reasons, CCs in VSE options 1 and 6 are assumed to be partially fuelled by easily storable fuel oil (about 25% of total fuel for CCs, see Section 6.1 for options definition). Due to the different composition of the fuel oil, the emission factors for the power plant are substantially different compared to natural gas. Emission factors have been derived from elemental analysis of the used low-sulphur fuel oil and from literature data on GCCs. For VOCs the emission characteristic of oil-fuelled industrial furnaces have been used as reference.

Table 4.2.V lists specific emissions from CC plants, normalised by GWh_{th}, i.e. per GWh of burned fuel oil. Notably, oil-powered CC has higher emissions of carbon di- and monoxide as well as sulphur and nitrogen oxides than CC fuelled with natural gas. Only methane and total NMVOC emissions are smaller for oil powered plants than for gas powered plants.

For the associated oil chain the performance characteristics of current systems were adopted. However, a larger share of extra-light oil was assumed for the products from refining. The fuel oil which would burn part-time in CC plants would be in fact low-sulphur fuel oil. The demand for this type of fuel is steadily increasing ("whitening of the barrel"). Therefore, refineries will consume more and more energy for the desulphurisation of crude oil (up to about three times more than the average world-wide current practice; this upper value corresponds to the current average in US refineries).

- **Gas turbine**

The considered GT is a cogenerating unit with electricity to heat ratio of 1.2. The environmental burdens calculated for the entire plant are allocated according to the exergy content of the two products electricity and heat. In the present case, 82.5% of the burdens are allocated to the electricity generation (Table 4.2.IV; see also Table 4.2.VI).

- **Gas turbine**

The gas turbine is a cogenerating unit with an electricity to heat ratio of 1.2. The environmental burdens calculated for the whole cogenerating plant are allocated according to the exergy content of the two by-products electricity and heat. In the present case, 82.5% of the burdens have been allocated to the electricity generation (given in Table 4.2.IV; see also Table 4.2.VI).

Table 4.2.IV

Emission factors allocated to the electricity generated by gas power plants[a].

Power plant		GCC fuelled with natural gas,[b] no cogeneration		GT cogeneration	CHPP cogeneration
State-of-the-art in	year	2005	2015	2015	1995
Used for		UCPTE 2010	CH 2020/30	CH 2010/20/30	CH 2010/20/30
Electric efficiency	GWh_e/GWh_{th}	57%	60%	36%	27%
Efficiency[c]	GWh/GWh_{th}	57%	60%	43.5%	37.5%
Air emission factors					
carbon dioxide	kg/GWh_{th}	198000	198000	162000	142600
carbon monoxide		108	36	90	130
nitrogen oxides		108	72	149	50
sulphur oxides		1.8	1.8	1.4	1.4
methane		21.6	10.8	11.9	58
nitrous oxide N_2O		3.6	0.36	1.4	---
mercury		0.00018	0.00018	0.00014	---
particles		1.1	0.36	0.29	---
propane		0.7	0.7	1.8	---
butane		2.2	1.8	4.3	---
pentane		1.8	1.8	1.4	---
benzene		0.7	0.36	0.25	---
toluene		0.36	0.36	1.1	---
benzo(a)pyrene BaP		0.000036	0.000036	0.000029	---
other polyaromatics		0.018	0.018	0.014	---
formaldehyde		1.4	1.1	1.4	---
acetaldehyde		0.0025	0.0022	0.0036	---
acetic acid		0.36	0.32	0.36	---
propionic acid		0.036	0.036	0.07	---
TCDD-eq. (dioxins)		$7.6 \cdot 10^{-11}$	$6.5 \cdot 10^{-11}$	$9.0 \cdot 10^{-11}$	---
NMVOC total:		7.6	6.1	10.8	6.5
waste heat[d]	GWh/GWh_{th}	0.53	0.50	0.36	0.25

a After (Mukherjee, 1995) (NZZ, 1995) (Gerber, 1995) (Bollens, 1995) (Lavandier et al., 1994) (Frischknecht et al., 1994) (Fritsche et al., 1992) (Booras et al., 1991) (WEC, 1988).

b Emission factors for CC operating with fuel oil are given in Table 4.2.V.

c Sum of the electric and thermal efficiencies weighed with the relevant exergy.

d The waste heat is calculated using the high heating value, about 10% higher than the low value.

Table 4.2.V

Emission factors allocated to the electricity generated by oil powered CC plants[a].

Gas combined cycle (GCC) fuelled with fuel oil no cogeneration	
Efficiency	60%
Air emission factors	kg/GWh_{th}
carbon dioxide	266400
nitrogen oxides	126
sulphur oxides	252
carbon monoxide	54
nitrous oxide	2.2
particles	0.36
hydrogen fluoride	0.032
hydrogen chloride	0.34
copper	0.0025
mercury	0.0018
zinc	0.0025
formaldehyde	3.2
methane	3.6
propane	0.07
butane	1.1
pentane	0.72
benzene	0.072
toluene	0.11
benzo(a)pyrene (BaP)	0.00011
other polyaromatics	0.0018
alkanes 6+	1.73
TCDD-equiv. (dioxins)	$1.6 \cdot 10^{-9}$
other aromatics	0.11
NMVOC total	4.0
Waste heat	$0.46\ GWh_e/GWh_{th}$[b]

a References as in Table 4.2.IV.

b The waste heat is calculated using the high heating value, about 6% higher than the low value.

- **CHPP**

The electricity to heat ratio is 0.54. The temperature and hence the exergy of the produced heat are lower than the corresponding values for GT; this results in turn in a lower allocation factor to electricity of about 72%[1]. The emission factors in Table 4.2.IV are already multiplied by this allocation factor.

[1] The plant in Basle embodies a heat pump that converts part of the generated electricity into additional heat. In order to allow comparison with other electricity systems, the total electricity generated is considered here. Hence, the heat pump is assumed to be outside of the allocation boundary.

4.2.4.3 Material and energy inputs

Information on future gas power plants was taken from manufacturers' and published data (Lavandier et al., 1994), (Fritsche et al., 1992), and (Frischknecht et al., 1994). Table 4.2.VI lists the main material and energy inputs per unit of GWh_{th}.

Table 4.2.VI

Material and energy requirements for gas powered power plants allocated to the electricity generated[a].

		GCC[b] no cogeneration	GT cogeneration	CHPP cogeneration
state-of-the-art in	year	2005/2015	2005/2015	1995
electric efficiency	GWh_e/GWh_{th}	57%-60%	36%	34%
efficiency[c]	GWh/GWh_{th}	57%-60%	43.5%	37.5%
Material and energy inputs				
construction materials				
concrete	kg/GWh_{th}	108	104	61
steel high alloyed		14.4	11.5	9.4
steel unalloyed		72	61	61
aluminium		3.6	---	0.0054
copper		3.6	4.3	7.2
plastics		10.8	14.4	3.1
mineral wool		5.4	---	7.9
HCl		9.0	---	---
NaOH		7.2	---	---
energy carriers				
natural gas	GWh/GWh_{th}	1[d,e]	0.83[e]	0.72[f]
other resources				
water (de-carbonised)	kg/GWh_{th}	1800000	---	---
water, (softened)		16200	---	---
construction energy				
electricity	GWh_e/GWh_{th}	0.0001	0.000083	0.00038
diesel	GWh/GWh_{th}	0.001	0.004	---

a After (Lavandier et al., 1994) (Fritsche et al., 1992) (Frischknecht et al., 1994).
b Fuelled with natural gas or fuel oil.
c Sum of the electric and thermal efficiencies weighed with the relevant exergy.
d Natural gas or fuel oil.
e From high pressure grid.
f From low pressure grid.

4.2.5 Results

Figures 4.2.2 through 4.2.10 show selected results for gas systems, normalised by the unit of electricity. In general, reductions in almost all environmental burdens are to be expected for future GCCs with respect to other gas systems. One important reason for this is the increase of efficiency from typically 38% for current (not CC) gas power plants to 60% assumed for CC power plants in years 2020/30. Furthermore, emission abatement through primary measures, i.e. engineering of combustion, is capable to reduce some emissions like CO, NO_x, N_2O and VOCs.

The effect of the relatively low electric efficiencies assumed for the 30 MW_e GT and the 160 kW_e CHPP (36% and 27%, respectively) is reflected in the results. The normalised material requirements and emissions for these two systems are generally greater than those for larger scale 300 MW_e GCCs. Emissions of NO_x from CHPP are lower than the corresponding ones from GT because of catalytic conversion assumed for the first plant.

It has to be emphasised again that CHPP has been assessed using a reference plant with current technology. As already mentioned, improvements are possible such as in methane emission abatement. The results for CHPP should therefore be taken with some caution.

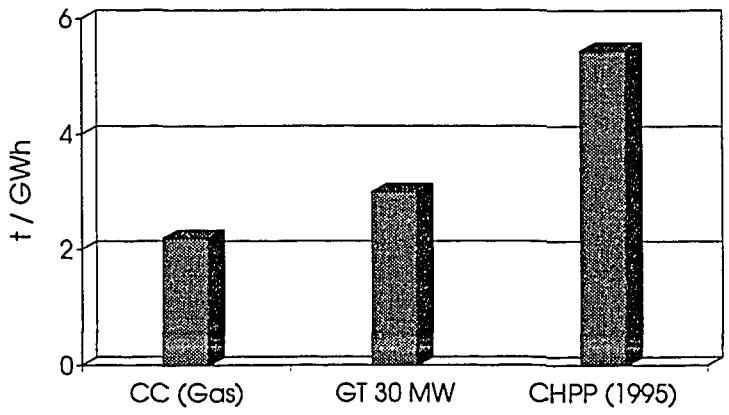

Figure 4.2.2 Concrete requirements for the gas energy chain.

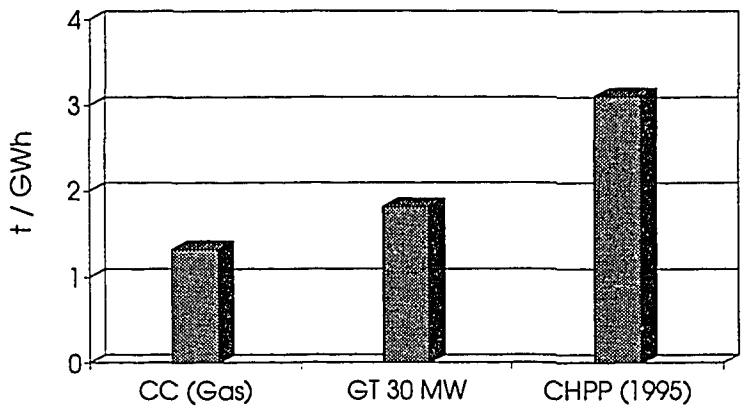

Figure 4.2.3 Steel requirements for the gas energy chain.

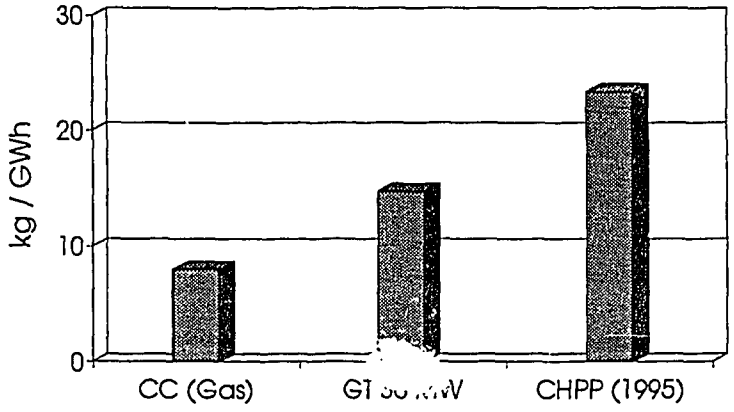

Figure 4.2.4 Copper requirements for the gas energy chain.

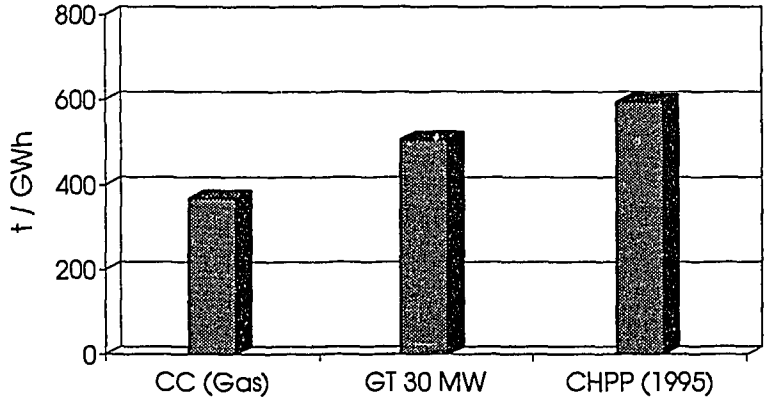

Figure 4.2.5 CO_2 emissions from the gas energy chain.

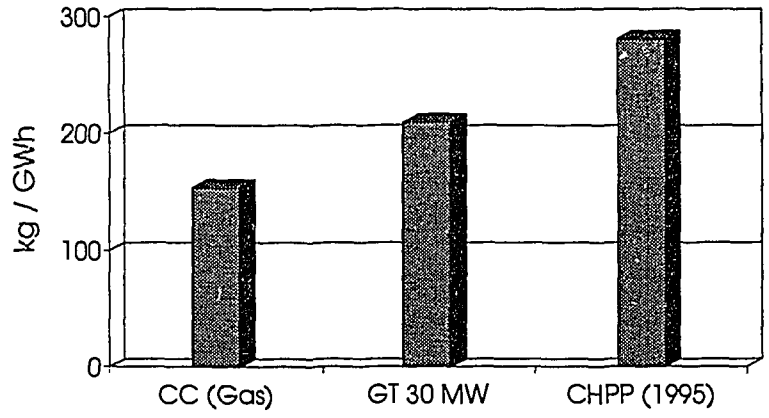

Figure 4.2.6 SO_x emissions from the gas energy chain.

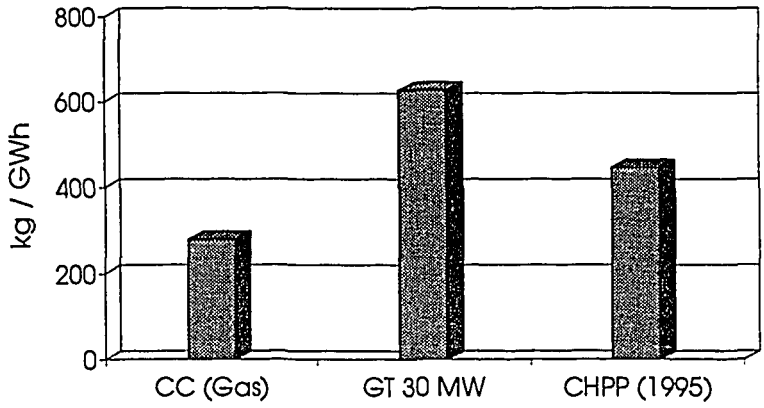

Figure 4.2.7 NO_x emissions from the gas energy chain.

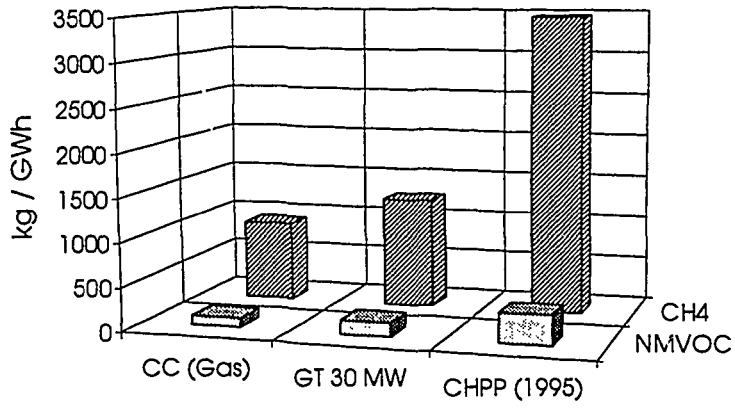

Figure 4.2.8 Methane and non-methane VOCs emissions from the gas energy chain.

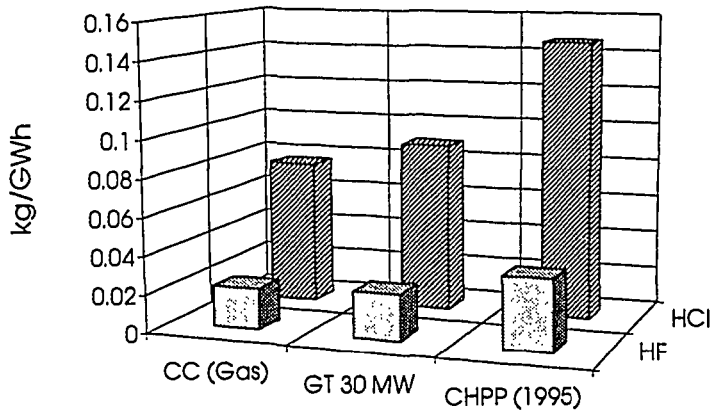

Figure 4.2.9 Halogens emissions from the gas energy chain.

A Dutch gas power plant (year 1990) has been chosen for comparison with future GCCs in Figure 4.2.10. This particular plant has an efficiency of 42% and is fuelled mostly with natural gas and some (6.4%) blast furnace gas.

The differences in CO_2 emissions are dependent on the differences in plant efficiencies (the same applies to copper requirements). NO_x emissions are dramatically reduced because of the better combustion performance in CC plants. SO_x emissions from the chain associated with the Dutch gas plant are small because of the low content of sulphur in the Dutch natural gas. CC 2030 exhibits total SO_x emission comparable with the Dutch plant because of its higher efficiency which compensates the consequences of the assumption on the origin of the natural gas imported to Switzerland (see Table 4.2.I).

Methane emissions calculated for the chain associated with the Dutch plant are the lowest because of the smaller losses[1] in the upstream part of the chain compared to the corresponding ones assumed for the gas used in Switzerland and UCPTE. The losses calculated for the gas chain relevant to CC 2030 are lower than the ones obtained for UCPTE 2010 mostly because of the assumed future reduction of leakage rate from long-distance gas transportation via pipeline in the Russian Federation[2]. Total NMVOC emissions as well as concrete, steel and electricity requirements are lower for the Dutch chain than for the UCPTE 2010 chain mostly because of the different characteristics of the upstream chain (origin of the natural gas, shorter pipelines).

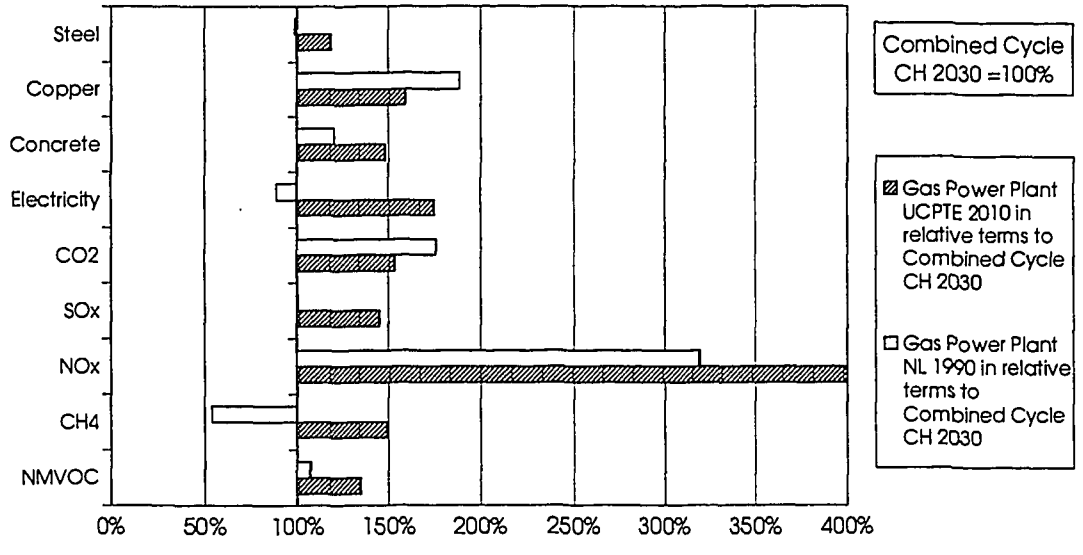

Figure 4.2.10 Comparison of selected requirements and emissions from energy chains associated with various gas power plants.

[1] Methane emissions from a gas power plant are negligible compared to the losses from upstream steps. Losses in the gas chain mainly occur at production site, processing and long-distance transportation via pipelines. The total losses for the gas chain associated with the Dutch plant are approximately 0.1%. Under present West European conditions, assumed to remain valid for the future, losses from processing are estimated approximately 10 times higher than leakages from pipelines.

[2] The assumed total losses in the gas chain in the Russian Federation for future conditions are assumed to be about 10 times higher than the total for West European conditions.

4.3 Nuclear Systems

4.3.1 Overview

The nuclear chain for LWRs is characterised by the higher number of steps, including downstream radioactive waste treatment and disposal, as compared to other energy chains. As analysed in the earlier LCA study, the various steps exhibits remarkable large differences in terms of contributions to the total calculated for the material and energy requirements as well as to the releases of pollutants and wastes to the environment. Although each step can potentially be modified in the future, the predictable changes that may have a substantial influence on the total resources and emissions can be singled out for the analysis. Nevertheless, when estimating key figures for the inventories, realistic but slightly conservative assumptions where made for systems which are expected to become commercial in the next two decades. No revolutionary designs are considered — their feasibility remains to be demonstrated.

Moreover, the main goal has not been to assess in depth the various steps of the chain or to compare different options for each step (in particular, the different types of power plants), or for the chain itself. One of the main limitations of the study is that the option of recycling of reprocessed uranium in MOX fuel elements (closed cycle) has not been included: this would require an extensive collection and organisation of the data needed for MOX fuel fabrication and for core management, to be integrated with the other steps of the chain. Nevertheless, it can be anticipated that this option would have led to the calculation of somehow smaller values for all figures of importance. However, the set of data for the nuclear system was developed consistently with the assumptions and limitations of the approach used for the other analysed electricity systems.

4.3.2 Structure of the energy chain

Figures 4.3.1 a) and b) show in a simplified manner the chains assumed for the Swiss and the UCPTE nuclear cycles for the future, based on the earlier LCA study (Frischknecht et al., 1994). In particular, the Swiss case refers to year 2030; by that time the youngest Swiss NPP (Leibstadt) will be already phased out after 40 years of operation.

Two types of power plants have been analysed, both from the family of the next Light Water Reactor (LWR) generation: the Advanced Boiling Water Reactor of GE (ABWR, 1300 MW) and a representative of a smaller size (600 MW) simplified design, the AP600 of Westinghouse. It has been assumed that the two chosen systems contribute each a half to the total electricity which has to be covered by new domestic nuclear systems in the proposed scenarios 2, 3, 5 and 7 (see Chapter 6). The domestic electricity generation from existing Swiss NPPs divided by the type of reactor is shown in Table 4.3.I for the time horizons of interest for this study.

Only very few units of the advanced types may be expected to be in operation in UCPTE countries by the year 2010. Therefore, it has been assumed for simplicity that the nuclear mix used for the UCPTE electricity mix in year 2010 for the calculation of the inventories for the infrastructures is only composed of conventional LWRs (Table 4.3.II). The values

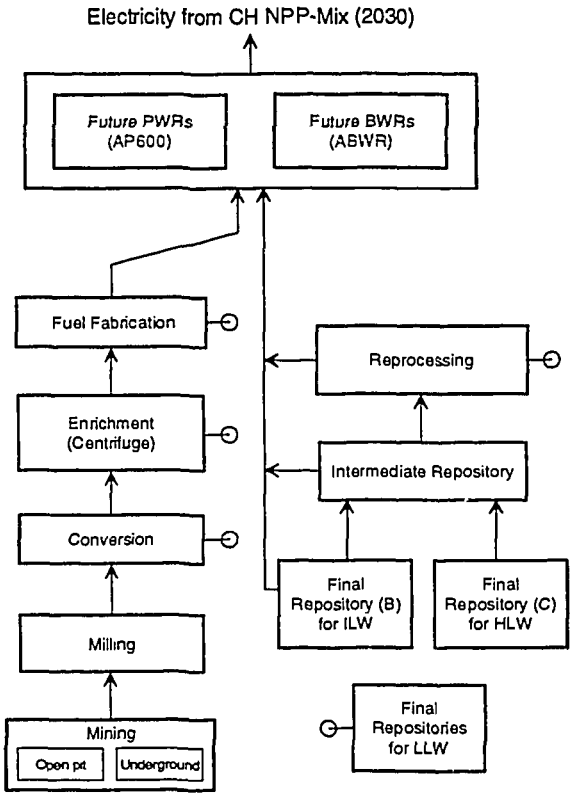

Figure 4.3.1 Assumed nuclear chains: (a) Switzerland (year 2030);
(b) UCPTE (after year 2010).

shown for years 2020 and 2030 represent assumptions on the shares of the considered types of Nuclear Power Plants (NPP) in UCPTE countries (excluding any fast breeder reactor — of the Superphenix type — or inherently safe reactors — of the PIUS type — or heavy water reactors — of the CANDU type — or gas-cooled reactors — of the AGR type — or subcritical devices fuelled by thorium, which at present do not seem to be likely to significantly contribute to the installed nuclear capacity in UCPTE in the next decades). The shares for year 2025 (averages between the two selected time horizons) have been used for the scenarios with imported electricity of nuclear origin, namely scenarios 4 and 5.

Table 4.3.I

Swiss domestic installed nuclear power.

Type of power plant	today (MWe)	2010 (MWe)	2020 (MWe)	2030 (MWe)
PWR	1690[a,b,c]	1340[b,c]	0	0
BWR	1370[d,e]	1470[d,e]	1115[e]	0

[a] Beznau I. [b] Beznau II. [c] Gösgen. [d] Mühleberg.
[e] Leibstadt; the values shown for years 2010 and 2020 include the anticipated power increase by at least 10%).

Table 4.3.II

Assumed shares for different types of LWRs in UCPTE.

Electricity from LWRs in UCPTE (for all *VSE Options*) (%)	**today**	**2010**	2020	**"2025"**	2030
existing PWR	90	90	60	**40**	20
existing BWR	10	10	5	**0**	0
future passive/simplified (e.g., AP600)	NA	0	17.5	**30**	40
future advanced (e.g., ABWR)	NA	0	17.5	**30**	40

4.3.3 Specific prioritizations and assumptions

To achieve the goal of estimating the changes that may be expected for the nuclear chain with respect to the present situation, priorities were identified on the base of the experience gained with the earlier LCA study on current energy systems. These priorities are presented in the following list.

General for the chain

- Characteristics of the fuel and fuel management: average enrichment, burnup, load factor;
- Lifetime of power plants and, to a minor extent, of other facilities;
- Control of radioactive emissions to air and water, mainly in mining/milling (especially long-term), power plant and reprocessing for future systems or future practice;
- Resources and emissions during decommissioning and reclamation of land (with state-of-the-art methods) for all nuclear facilities, in particular mines, mills, power plants and reprocessing facilities.

Other (relative to the previous LCA study):

Mining

- Material, energy and transport requirements during restoration of mines (of minor importance — not implemented, present values used).

Milling

- Management during operation and long-term of mill tailings (accomplished for the most important figures for the long-term releases).
- Re-examination of the definition of the time for 'recultivation' in the waste ponds' area, i.e., the time required for the re-establishment of the original conditions of the land before the operation of the mill — function of long-term radon emissions (not implemented here to be able to compare the long-term emissions with respect to the previous analysis on the base of same assumptions for the time horizon).

Conversion

- Operational data of European facilities (of minor importance — not implemented, present values used).
- Long-term management of waste ponds in conversion facilities (of minor importance — not implemented, present values used).

Enrichment

- Options for future technologies to use for enrichment; possible implementations by Cogema/URENCO; projected supply for the total demand of enrichment services on the European market; key parameter: electricity and fossil fuel consumption per separative work unit and associated electricity source (nuclear power plant vs. other systems or the electricity grid) (accomplished for the figures of high importance).
- Operational data of European plants for both existing industrial processes. Fewer data were available for centrifuge facilities (URENCO) in the earlier LCA study (accomplished for the figures of high importance).

Fuel Fabrication

- Requirements on materials (chemicals) during operation of the plant (of minor importance — not implemented).

Power Plant

- Modification of the data for the present average UCPTE PWRs and BWRs mix for describing the units that are expected to be still operational in the years 2010-2030 (implemented for the most important figures).

Reprocessing

- Requirements and emissions from operation, especially radioactive emissions (accomplished, using realistic assumptions for the most important figures).
- Material requirements during construction of the plant; land use; transport of chemicals; and, non-nuclear solid waste during operation (of minor importance — not implemented, present values used).

Final Repositories

- Comparison between the Swiss designs and the concepts developed by other European countries for the final repositories, and consideration of the differences in the discussion of results (of minor importance — not implemented, present approach used).
- Recalculation of data set for the Swiss final repositories to take into account scenarios different from the 240 GW·yr scenario (Nagra, 1985) assumed in the earlier LCA study (of minor importance for the chain — not implemented, present approach used[1]).
- Improvement in the description of shallow land repositories for low-radioactive solid waste (of minor importance — not implemented, present approach used).

4.3.4 Technologies

The following sections describe the major assumptions made within the present study on single steps of the nuclear chain. Steps which are not included have not been changed with respect to the reference set. Complete information on the assumptions and complete list of input data compared to the earlier LCA study are reported in (Dones, 1995).

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[1] Depending on the total amount of conditioned radioactive waste to be disposed of in the final repositories, the associated normalised requirements and emissions change. Therefore, different values would result from different nuclear scenarios. The set of environmental inventories used here, was obtained for the volume of nuclear waste that would be produced generating 240 GW·yr of electricity (approximately the double the total electricity that can be generated by the current Swiss NPPs). It is close to the sets that would result from the future nuclear-based supply mix options.

4.3.4.1 Milling

Two major issues have been identified for the assessment of future systems or future practices in uranium milling:

- Radioactive and non-radioactive emissions to air and water during operation.
- Long-term radioactive and non-radioactive emissions to air and water from restored waste ponds.

In the earlier LCA study, the post-operational emissions of radon (Rn-222) from the tailing ponds were found to dominate the emissions, because of the long duration of the release, of the order of magnitude of 10^5 years (the half life of the parent isotope Th-230, with which Rn-222 is in equilibrium, is nearly $8 \cdot 10^4$ years). In that study an assumption was taken from the literature on the time for the integration of such emission and for the calculation of the land use (defined as disturbed area times the duration of disturbance). The assumed release rate of radon was calculated on the base of the estimated long-term emission from a Canadian mine (Key Lake, at the time of the study the only reference available), weighed by the average operational radon emission rate calculated from different references (which also included Key Lake) from the late 70s and the 80s, mostly based on abandoned mill tailings.

The present simplified approach is based on the hypothesis that in the next decades most of the not yet restored tailing ponds world-wide will be fixed up[1] ; this allows to estimate the reduction that can be expected for the integrated emission of radon relative to the value used in the earlier LCA study. Therefore, no change has been made of the time for the integration of the long-term emissions of radon. For the same reason, solution uranium mining (not covered in the earlier LCA study), which in recent years has reached an important share of the uranium market (up to 19% of the uranium produced in 1993 was by in-situ leaching and 10% as by-product (UI, 1994)), has not been considered here. This can be seen as a conservative assumption with respect to the solid wastes and the long-term radon emissions. In fact, by chemical mining uranium is directly extracted from the ore; therefore the steps of crushing and grinding, which are followed by uranium leaching in the conventional milling process and which are consequently producing the bulk of the tailings, are by-passed. However, some changes in the emissions to water from uranium mining and milling may be expected when chemical mining is considered in the assessment.

According to the information available on the current practices for the management of uranium mill tailings a flux of the order of 1 Bq/m^{2}s can be assumed on the average for Rn-222 release to air from about 30 inactive mill sites in USA, Canada and Spain (IAEA 1992). Other sources (EPA 1983) report a range 10-20 Bq/m^{2}s as most common

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[1] In 1978 the US Congress issued the "Uranium Mill Radiation Control Act", where 24 sites in the States were identified as needing restoration (Matthews, 1984). DOE was designated to take the responsibility for the implementation. The deadline for the "Uranium Mill Tailings Remedial Action" Project was in year 1994. 10 tailings piles were stabilised on-site, whereas the other were moved to a different site for disposal (Fahy, 1991).

radon flux from inactive tailings in US mills, and for a typical background the value 0.037 Bq/m^{2}s.

Three reference sites are considered in (NEA, 1984): a site with a tropical monsoon climate, a site with a northern temperate climate, and a site with a semi-arid desert climate. Practices like flooding of tailings which will reduce air emissions of radon to zero have not been considered in this study.

For the first site, representative of Australian mines, a radon exhalation rate of 0.1 Bq/m^{2}s is considered for the base case (2 m rock cover), which increases to 0.4 Bq/m^{2}s after erosion of soil/rock cover. The most efficient, and at the same time the most expensive management option (5 m soil/rock cover) would reduce the radon emission by a factor of 7.5 to 0.013 Bq/m^{2}s.

For the second site, representative of locations in Northern Ontario, radon exhalation rates are assumed to drop in the base case (bare tailings) from 10 Bq/m^{2}s to 3 Bq/m^{2}s during the time interval of 10^4 yr considered in (NEA, 1984); a value of 0.5 Bq/m^{2}s is assumed under the hypothesis of reversible adsorption of Ra-226 on jarrosite and goethite. The management option which considers low permeability dam and fully saturated tailings would reduce the radon emissions to approximately 1% of the base case. The most effective management option is based on the same remedies plus removal of 90% of the radium and thorium that was dissolved in the milling processes; assuming an efficiency of the dissolution of 95%, approximately 15% of the original thorium will remain in the waste pond, which would correspond to a further decrease of the radon flux with the same proportion giving a long-term radon flux of approximately 0.005 Bq/m^{2}s.

For the third reference site, representative of mines in New Mexico, a radon exhalation rate of 10 Bq/m^{2}s is assumed for bare tailings at the end of operation of the mill. Later, the flux increases due to erosion of tailing piles. In particular, rain is assumed to erode the unprotected piles and to disperse the material in a larger area than the original. Thus, both the effects of increased flux and increased surface have to be considered to calculate the integral release over the considered time interval. The radon flux is assumed to increase up to 2.5 times after 10^4 yr in the base case, the relative area of dispersed tailings up to 1.6 times. Various options for the treatment of these tailings are considered to prevent the undesired dispersion of the waste. One group of solutions considers above-grade tailings with covers to protect from erosion. For the most efficient of this class of solutions (1 m clay with erosion protection), a reduction of radon flux to about 0.3% of the initial value (i.e., to 0.03 Bq/m^{2}s) is calculated The most protective solutions consider below-grade tailings with clay shale cover. For this second class of solutions, a reduction of radon flux down to about $3 \cdot 10^{-7}$ of the initial value can be calculated, to give $3 \cdot 10^{-6}$ Bq/m^{2}s.

For the estimation of the normalised value for long-term radon release from mill tailings that could be expected in the next decades, it can be assumed that part of the mill tailings (in already inactive mills, or mills which are today still in operation but will be closed in the near future, or future mills), will be treated using the identified solutions for the reduction of the long-term releases of radon. A simplified calculation can be made on the base of assumptions that are illustrated in Table 4.3.III. Using historical data and data on deposits to be exploited (UI 1994), it can be assumed for a first guess that 20% of total uranium production in 50 yr may be associated with tailings ponds of the first type, 40%

with the second and 40% with the third type. The minimum radon flux has been assumed consistently with the average background mentioned above.

Table 4.3.III

Assumed long-term radon fluxes from restored mill tailings.

Tailings type (NEA, 1984)	% of world uranium production 1975-2025	Tailings area m^2/kgU	Range[a] of possible average Rn flux (10^4 years) Bq/m^2s	Assumed Rn flux Bq/m^2s
1. Australia	20	0.05	0.013-0.1	0.05
2. Northern Ontario	40	0.01	0.005-3	0.01[b]
3. New Mexico	40	0.1	$3 \cdot 10^{-6}$-10	0.01[b]

[a] Maximum corresponds to the base cases; minimum to the most effective management options (NEA, 1984).

[b] As an example, the flux measured in Durango, Colorado, after restoration was 0.0071 Bq/m^2s, against 1.3-11.0 Bq/m^2s before restoration (Hamp, 1991), (NRC, 1986). The assumed value is of the same order of magnitude as the average background mentioned in the text.

Thus, an average value of $5.8 \cdot 10^{-4}$ Bq/s·kgU can be calculated. This rate integrated over $1.1 \cdot 10^5$ yr gives a post-operational long-term normalised radon release of approximately $3 \cdot 10^6$ kBq/kgU, which is 18 times lower than the corresponding value calculated in the earlier LCA study.

Adding to the above value the radon emissions during mill operation, already used to describe present conditions in (Frischknecht et al., 1994) — about $1.5 \cdot 10^5$ kBq/kgU assumed unchanged for future conditions — the total normalised release of radon would be $3.2 \cdot 10^6$ kBq/kgU, approximately 17 times lower than the total calculated for the present situation.

Table 4.3.IV shows the expected modifications (extrapolations and/or update) introduced here for some emissions to air and water with respect to the previous LCA study on present energy systems. The emissions to air of the radioactive isotopes of the decay series of U-238 have been re-calculated consistently with the previously discussed new emission rate of radon, using the set of values reported in (UNSCEAR 1988) relative to radon as the basis for the extrapolation. The radioactive and non-radioactive emissions to water have been taken from recent references regarding the Canadian mills of Rabbit Lake, Cluff Lake and Key Lake (Moffett et al., 1991), (UI, 1995). This information can be regarded as more reliable and representative than the values previously inputted, which were taken from old references. In fact, Canadian uranium production covers approximately 28% of the world total (UI, 1994). The radioactive emissions are on the average one order of magnitude lower than assumed in the earlier LCA study. Other releases of heavy metals to water, not reported in the table, are assumed to remain unchanged.

Table 4.3.IV

Updated input values for emissions from uranium mills.

Emissions		Earlier Study	Future
Radioactive to air			
U	kBq/kgU	$6.0 \cdot 10^{0}$	$5.3 \cdot 10^{0}$
U-234		---	$2.6 \cdot 10^{0}$
U-235		---	$1.2 \cdot 10^{-1}$
U-238		---	$2.6 \cdot 10^{0}$
Th-230		$3.0 \cdot 10^{0}$	$1.3 \cdot 10^{-1}$
Ra-226		$3.0 \cdot 10^{0}$	$1.3 \cdot 10^{-1}$
Po-210		---	$1.3 \cdot 10^{-1}$
Pb-210		---	$1.3 \cdot 10^{-1}$
Rn-222		$5.4 \cdot 10^{7}$	$3.2 \cdot 10^{6}$
Radioactive to Water			
U	kBq/kgU	$3.6 \cdot 10^{1}$	$7.0 \cdot 10^{0}$
U-234		---	$3.4 \cdot 10^{0}$
U-235		---	$1.7 \cdot 10^{-1}$
U-238		---	$3.4 \cdot 10^{0}$
Th-230		$1.4 \cdot 10^{3}$	$1.8 \cdot 10^{2}$
Ra-226		$3.6 \cdot 10^{0}$	$3.0 \cdot 10^{-2}$
Non radioactive to Water			
SO_4^{2-}	kg/kgU	$1.0 \cdot 10^{1}$	$3.2 \cdot 10^{0}$
NO_3^{2-}		$1.7 \cdot 10^{-2}$	$8.7 \cdot 10^{-3}$
F^-		$1.3 \cdot 10^{-3}$	$6.6 \cdot 10^{-4}$
Ca^{2+}		$1.3 \cdot 10^{-3}$	$5.4 \cdot 10^{-1}$
Cl^-		$1.4 \cdot 10^{-1}$	$5.2 \cdot 10^{-1}$
Na^+		$8.0 \cdot 10^{-2}$	$4.0 \cdot 10^{-2}$
NH_3 as N p		$1.4 \cdot 10^{-1}$	$7.2 \cdot 10^{-2}$
Phosphate		---	$2.2 \cdot 10^{-4}$
As		$3.0 \cdot 10^{-4}$	$1.6 \cdot 10^{-4}$
Ba		$6.0 \cdot 10^{-5}$	$2.2 \cdot 10^{-4}$
Mo		$2.8 \cdot 10^{-3}$	$3.8 \cdot 10^{-3}$
Ni		$4.8 \cdot 10^{-4}$	$2.0 \cdot 10^{-4}$

4.3.4.2 Enrichment

The commercial diffusion plants, which are today still covering the largest fraction of the market, started operation in the USA in the mid 50s, in France (Tricastin) in 1979. The centrifuge technology is already fully mature and is expanding in several countries including Japan and Russia. At present, the centrifuge process is the most competitive on the international market. This technology presents also the advantage, compared to diffusion, to be able to enrich separately various stocks of different origin, in particular natural from reprocessed uranium, to meet the specific requirements of different customers. Consequently, it is expected that the enrichment services in the long-term (corresponding to the time horizon for this work) will not be provided by diffusion facilities.

Two laser-based processes can be applied for uranium enrichment: the molecular route, which uses UF_6, and the atomic route, which uses elemental uranium vapour (Crocker et al. 1986). The Atomic Vapour Laser Isotope Separation (AVLIS) has been selected for further development by DOE and Cogema which believe it will be economically competitive with the centrifuge technology.

Thus, the enrichment processes which will be used in the future for the period of interest in this study (years 2010-2030) are likely to be Centrifuge and AVLIS, substituting the plants based on the gaseous diffusion process once they are phased-out.

No LCA data for a future AVLIS production plant are available. A full scale demonstration facility exists at the Lawrence Livermore National Laboratory in the USA, which includes a separator demonstration facility and a laser demonstration facility (Longenecker, 1986). On the basis of the features of the process (relatively small plant) it is assumed that material and energy requirements as well as emissions do not differ much from the centrifuge plant. Nevertheless, the total emissions from the chain should not be affected by relatively small changes in this step.

Both the centrifuge process and AVLIS need much lower energy compared to diffusion: 40-50 kWh/SWU vs. 2400 kWh/SWU. The lowest value is an estimation for the electricity needs for AVLIS (no information available at present on requirements of fuels) (Pellissier-Tanon, 1995). The present calculation uses 50 kWh/SWU which corresponds to the minimum value found in the literature for the centrifuge process (Weis, 1991), (Mohrhauer 1988). For comparison, an average electricity intensity of 75 kWh/SWU was assumed in the earlier LCA study for the centrifuge process. The centrifuge plants (fed by the UCPTE electricity network) were supposed to cover approximately only 10% of the total enrichment services for European nuclear power plants, the rest being covered by the diffusion power plant in Tricastin (fed by PWRs). General comparisons and a specific sensitivity analysis on CO_2 emissions by changing the shares of these two processes and the sources of the relevant electricity supplies can be found in (Hirschberg et al., 1994) and (Dones et al., 1994). The assumption of supply of enrichment services by centrifuge only is the central one in the frame of the analysis of future nuclear chain. In fact, the electricity needs for the cycle drop dramatically by one order of magnitude with respect to the earlier LCA study of present systems. Table 4.3.V summarises the main parameters assumed for the calculation.

(Urenco, 1994) reports for the centrifuge plants in Capenhurst a yearly loss of CFCs and HFCs based on replenishment of stocks of about 630 kg and 710 kg, respectively, without specifying the chemical species. Normalising by the annual production of 850 tSWU (1 tSWU=1000 SWU), $7.4 \cdot 10^{-4}$ kg/SWU and $8.4 \cdot 10^{-4}$ kg/SWU, respectively, are calculated. These values have been conservatively used in the calculation for future systems. Assuming that the CFCs are released to air as CFC-114 or 115[1] and assuming for the HFCs the species HFC-134a[2], a total of approximately 118 kg(CO_2-equiv.)/GWh is

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[1] GWP_{100} is 9300 for both (IPCC, 1994). The GWPs of CFCs and halocarbons considered here take into account direct effects only (IPCC, 1994). See footnote 1 in Section 5.2 for further discussion.

[2] Its GWP_{100} is equal to 1300, which represents an average value for HFCs whose GWP_{100} spans 140 through 12100 (IPCC, 1994).

calculated for the assumed future systems. This value corresponds to approximately 2% of the total greenhouse gases calculated for the nuclear chain without CFCs.

Table 4.3.V

Main parameters for the enrichment of uranium for present and future LWRs.

Parameter	PWR			BWR		
	present CH[a]	present UCPTE[a]	future	present CH[a]	present UCPTE[a]	future
Share Centrifuge(or equiv.)/Diffusion	0/100	10/90	**100/0**	50/50	90/10	**100/0**
Average enrichment %	3.5	3.5	**3.7**	3.25	3.4	**3.7**
Average enrichment of tailings %	0.28	0.28	0.28	0.28	0.28	0.28
Separative Work Unit SWU/kgU_{enr}	4.52	4.52	**4.91**	4.05	4.33	**4.91**
Electricity requirements: kWh/SWU						
for Diffusion	2400		---	2400		---
for Centrifuge (or future equiv.)	75		50	75		50
Uranium requirement kgU_{nat}/kgU_{enr}	7.49	7.49	**7.95**	6.91	7.26	**7.95**
kgU_{nat}/SWU	1.66	1.66	**1.62**	1.71	1.68	**1.62**

[a] According to (Frischknecht et al., 1994).

An estimation of CFCs emissions[1] from currently operating diffusion plants in USA was made using an American reference (Trowbridge, 1991), leading to values in the range 2900-5800 kg(CO_2-equiv.)/GWh (considering enrichment via diffusion only). Cogema has planned for its plant in Tricastin, France, the substitution of CFCs by other chemicals and water cooling, with expected reduction of total CFCs release to less than $1 \cdot 10^{-4}$ kg/SWU from unimportant uses (Pellissier-Tanon, 1995). A reduction of the use of CFCs and HFCs in centrifuge plants may be envisaged. Negligible use/release of CFCs and HCFCs can be predicted for AVLIS (Pellissier-Tanon, 1995). Therefore, it can be conservatively assumed that the total release of these gases, associated with uranium enrichment after year 2000, will be about of the same order of magnitude as the present emissions from centrifuge plants.

Some emission factors like fluoride to air and the solid wastes have been updated to the present available data for the Centrifuge plants (Urenco, 1994), with lower values than the corresponding ones used in the earlier study.

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[1] CFCs were not assessed in the earlier LCA study on current energy systems

4.3.4.3 Power Plant

To estimate the total environmental inventories for future nuclear power plants it is necessary:

- to describe the main features of typical nuclear power plants that might be built in Switzerland in 10/20 years from now;

- to extrapolate the values assessed in the earlier LCA study for European NPPs to year 2010 in order to allow the calculation of the energy mix for the infrastructure and the electricity requirements of all energy systems.

The first goal has been achieved by considering two types of nuclear power plants that may be seen at present as possible candidates for future options. These are LWRs of advanced/simplified design of the 600 MW and 1300 MW size. The models considered are the Westinghouse AP600 and the GE (with Hitachi and Toshiba) ABWR. Nevertheless, the choice of these two models does not imply in any way that these are considered by the analysts as the only potentially interesting designs for Switzerland or UCPTE. In fact, this task was not designed for comparisons of future nuclear systems but rather as an assessment of the major changes that can be expected in LCA inventories of NPPs and associated full energy chain with respect to present conditions. These two power plant types were selected mostly on the base of the amount of available information. Each can be regarded as representative of the class of reactors of the corresponding size. For these reasons, the results obtained for such systems are averaged when nuclear is compared with other electricity generating systems.

The ABWR power station consists of two units with control building, radwaste building and service buildings in common. The two first units of this type are under construction at Kashiwazaki-Kariwa site in Japan. The beginning of commercial operation is scheduled between 1996 and 1997.

The effort of the nuclear fuel industry and plant operators is towards the increase of the burn-up of fuel to decrease the costs associated with the nuclear fuel cycle. One of the main activities concerns the improvement in the material used for fuel element cladding to stabilise corrosion (Holzer et al., 1991). At the same time, it is necessary to slightly reduce the average in-core coolant temperature. Already in the past decade, the average burn-up of fuel elements in European LWRs have increased from 33 MWd/kgU to 40-45 MWd/kgU for PWRs, and from 28 MWd/kgU to 35-40 MWd/kgU for BWRs (Holzer, 1990). Table 4.3.VI shows the average value for present systems in UCPTE countries as used in the earlier LCA report on present European energy systems (Frischknecht et al., 1994). The goal of the industry is to reach average burn-ups up to or greater than 50 MWd/kgU for PWRs and up to or greater than 45 MWd/kgU for BWRs. To achieve this target, a longer in core residence time is necessary. In the present study, it has been conservatively assumed for the current NPPs a value of 45 MWd/kgU both for PWRs and BWRs for the year 2010 and beyond (Table 4.3.VI), with corresponding average enrichment of 3.7% (Table 4.3.V). This gives a 6-20% reduction on the uranium requirement.

Table 4.3.VI

Main characteristics of nuclear power plants assumed for existing systems in Switzerland and UCPTE.

Parameter	PWR				BWR			
	present CH[a]	present UCPTE[a]	future 2010	future >2010	present CH[a]	present UCPTE[a]	future 2010	future >2010
Burn-up $MW_{th}d/kg$	42	40	45	45	35	39	45	45
Net efficiency %	31	31	31	31	31	31	31	31
Uranium consumption kg/GWh	3.2	3.35	3.0	3.0	3.85	3.46	3.0	3.0

[a] According to (Frischknecht et al., 1994).

Table 4.3.VII shows some general characteristics of future LWRs (incomplete in several cases), including also the European Pressurized Water Reactor (EPR), the Advanced PWRs and the simplified BWR. Some of the figures are reported in the Utility Requirements Document worked out by EPRI and utilities, which specifies the concept for both simplified and passive designs (Douglas, 1994).

The main changes from the present generation of LWR with respect to LCA relevant parameters are: the longer lifetime (50% or more); the higher thermodynamic efficiency of the ABWR; the reduction in the solid radioactive waste in the BWRs; and, the reduced construction time (25-50% of the current values), which is a consequence of the reduction in volumes and masses of construction materials as well as of standardisation.

In particular, the strongest reduction in the construction materials requirements are for the reactors of smaller size and more simplified design, as illustrated in Table 4.3.VIII where the values for future systems are compared with the current systems as described in the earlier LCA study (naturally, only the values normalised by the unit of energy have to be compared in the context of the present study, not the absolute total masses, because of the different power of the various plants considered).

On the average, the normalised material requirements are halved with respect to the earlier input valid for 1000 MW LWRs: for the AP600 this is mainly an effect of the actual reduction of the masses and the increased lifetime; for the larger system, it is primarily a consequence of the extended lifetime and increased power (about the double total electricity can be generated during lifetime compared to current 1000 MW). More technical details can be found in the associated technical report.

Table 4.3.VII

Main parameters of future LWRs.

Parameter		PWR				BWR	
		APWR 1000	APWR 1300	AP600	EPR	ABWR	SBWR
Electrical power (net)	MW	1050[a]	1300	600	~1500	1356[b,c]	600
Core average power density	kW/l	96.2[a]	80.0[a]	78.8[a]	~107[a]	50.5[b] 50[d]	42[d]
Average burn-up	$MW_{th}d/kg$			40	55-60		
Net efficiency		0.33[a]	0.33[a]	0.31[a]	0.33[a]	0.33[b,e,c]	0.31
Construction period	yr		4.5[f]	3.5[f]		4.5[f] 4[b]	3.5[f] 2.5[d,g]
Buildings' volume reduction	%					30[b,i]	
Capacity factor	%		87[f]	87[f]		87[f]	87[f] 90[d]
Plant design life	yr		60[f]	60[f]		60[f]	60[d,f]
Total generated electricity	TWh			272		583	
Radwaste	drums/reactor·yr					100[b,i]	

a from (Nuclear News, 1992).
b Toshiba.
c Hitachi.
d GE.
e Calculated from the declared gross efficiency of 0.35.
f From the Utility Requirements Document by EPRI (Douglas, 1994).
g From pouring of first structural concrete to start of fuel loading.
h Compared to present 1100 MW reactors.
i A reduction by a factor of 8 with respect to the present conditions is claimed. Normalising the volume corresponding to 100 drums by the yearly net generated electricity, $2.02 \cdot 10^{-3}$ m³/GWh is obtained vs. 8.2 times higher value of $1.28 \cdot 10^{-3}$ m³/GWh used for Leibstadt in (Frischknecht et al., 1994).

Material requirements during operation are considered to remain constant. Transport requirements have been recalculated using the new masses and average distances for Switzerland and Europe, giving smaller values. The energy requirements have been also recalculated: for the electricity needs during the construction of future Swiss NPPs, both Swiss and UCPTE mixes in year 2010 have been used (50% each).

Table 4.3.VIII

Construction materials for present and future LWRs.

Material	PWR (1000 MW)[a]		AP600		BWR (1000 MW)[b]		ABWR (1300 MW)	
	t	kg/GWh	t[c]	kg/GWh	t	kg/GWh	t	kg/GWh
Steel:								
for components	21911	80.8	13000	47.9	20571[d]	70.7	20000[e]	34.2
for construction	5570	20.6	3500	12.6	5570	19.1	5000[f]	8.6
Reinforcing bars	33680	124.2	15700	56.5	40030	137.5	36000[f]	61.6
Copper	1472	5.4	600	2.2	1473	5.1	1500	2.6
Aluminium	200	0.8	140	0.5	200	0.7	200	0.3
Concrete (2.2 t/m^3)	372000	1372	175000	630	440000	1512	400000[f]	684
Asbestos cement	5300	19.5	3700	13.7	5300	18.2	5000	8.6
Oil	200	0.8	160	0.6	200	0.7	200	0.3
Wood (0.5 t/m^3)	3360	12.4	2600	9.7	4000	13.8	3500	6.1

a PWR KKG (Gösgen), reference PWR described in (Frischknecht et al., 1994).
b BWR KKL (Leibstadt), reference BWR described in (Frischknecht et al., 1994).
c Figures for steel and concrete have been provided as approximate data; the remaining values are qualified guesses of the analyst based on some available information on intended reductions.
d Includes titan used for the condenser.
e The mass of the vessel increases approximately 30% with respect to a 1000 MW reactor (840t), but this is about compensated by the elimination of the recirculation loops. The turbine is bigger (one more stage), the generator as well. As a first approximation the total can be assumed equal to the value for the 1000 MW reactor.
f Assuming 10% reduction

For the normalised radioactive emissions to air and water from advanced reactors the lowest present emissions have been chosen to reasonably anticipate emission rates from future NPPs. In particular, the emissions from the German newest plants with the best performance have been used (VGB, 1990-92), with the exception of emission of tritium to water for BWRs which is the one reported for the largest Swiss plants. For the UCPTE nuclear mix in year 2010, the radioactive emissions have been recalculated on the base of the previous input by considering only plants built after year 1980.

Table 4.3.IX shows the assumed values together with the current average emissions for the Swiss and UCPTE plants. From the data shown, reductions of the order of one to two orders of magnitude can be expected on the average radioactive releases, excluding tritium to water which exhibits only a small decrease. The radioactive solid wastes from the operation of the advanced BWR will decrease by approximately one order of magnitude (see Table 4.3.VII). The radioactive solid wastes from the decommissioning of the advanced LWRs will also decrease because of the longer lifetime and consequently higher total electricity generated which is used to normalise the contaminated masses.

Table 4.3.IX

Average radioactive emissions from present and future LWRs.

Radioactive emissions kBq/GWh		PWRs			
		CH present[a]	UCPTE present[a]	UCPTE 2010	PWR future
to Air	Noble gases	$2.1 \cdot 10^{6}$	$2.4 \cdot 10^{6}$	$1.9 \cdot 10^{6}$	$2.4 \cdot 10^{5}$
	Aerosols	$2.6 \cdot 10^{1}$	$1.7 \cdot 10^{1}$	$9.7 \cdot 10^{0}$	$4.0 \cdot 10^{-1}$
to Water	Tritium	$1.7 \cdot 10^{6}$	$2.2 \cdot 10^{6}$	$1.8 \cdot 10^{6}$	$1.4 \cdot 10^{6}$
	Mixed nuclides	$2.9 \cdot 10^{3}$	$2.7 \cdot 10^{3}$	$1.5 \cdot 10^{3}$	$9.0 \cdot 10^{0}$

[a] According to (Frischknecht et al., 1994).

Radioactive emissions kBq/GWh		BWRs			
		CH present[a]	UCPTE present[a]	UCPTE 2010	BWR future
to Air	Noble gases	$7.6 \cdot 10^{6}$	$1.5 \cdot 10^{6}$	$6.1 \cdot 10^{5}$	$3.2 \cdot 10^{5}$
	Aerosols	$1.8 \cdot 10^{2}$	$4.0 \cdot 10^{1}$	$3.6 \cdot 10^{1}$	$3.1 \cdot 10^{0}$
to Water	Tritium	$1.2 \cdot 10^{5}$	$1.4 \cdot 10^{5}$	$1.4 \cdot 10^{5}$	$1.0 \cdot 10^{5}$
	Mixed nuclides	$2.1 \cdot 10^{3}$	$4.0 \cdot 10^{2}$	$3.6 \cdot 10^{1}$	$1.7 \cdot 10^{1}$

[a] According to (Frischknecht et al., 1994).

4.3.4.4 Reprocessing

The two main existing commercial plants UP2/UP3 at La Hague (Cogema, France) and THORP at Sellafield (BNFL, UK) differ with respect to part of the processes, the radioactive releases and some of the conditioned waste. The option of describing the two plants separately has not been implemented because the data necessary was not available with sufficient detail. Therefore, the module describing reprocessing is still made of a mixture of data based on the available information, as was the case for the reference LCA study.

Tables 4.3.X and 4.3.XI show the radioactive emissions to air and water, respectively, from the available references. Operational releases from the French plant UP3 from (Dreicer et al., 1995) are normalised assuming 351.4 tonnes of reprocessed spent fuel with average burnup of approximately 32 MWd/kg. The latest available releases from THORP (BNFL, 1995) are still based on flowsheet calculations for the maximum throughput (1200 tU/yr) and reference burn-up of 40 MWd/kgU with 5 years cooling period. The plant has started operation in April 1994 and till March 1995 it has reprocessed only about 70 t of low-irradiated long-cooled fuel. The observed discharges are well within flowsheet

predictions (BNFL, 1995). Once available, the actual releases at full operation of the plant should be used in any LCA study for present as well as for future scenarios, because they will not change for the operational lifetime of THORP, assumed 30 years.

Table 4.3.X

Radioactive emissions to air from reprocessing plants.

Radionuclides	UP3 [a]	THORP [b]	
	Activity released (kBq/kgU)	Maximum potential discharge[c] (kBq/kgU)	Flowsheeted discharges [d] (kBq/kgU)
H-3	$1.06 \cdot 10^{4}$	$1.8 \cdot 10^{4}$	$1.8 \cdot 10^{4}$
C-14	$1.65 \cdot 10^{4}$	$3.6 \cdot 10^{2}$	$3.6 \cdot 10^{2}$
Kr-85	$1.65 \cdot 10^{8}$	$3.1 \cdot 10^{8}$	$3.1 \cdot 10^{8}$
Sr-90	---	$6.3 \cdot 10^{0}$	$3.3 \cdot 10^{0}$
Ru-106	---	$2.0 \cdot 10^{2}$ [e]	$2.0 \cdot 10^{1}$
I-129	$1.18 \cdot 10^{1}$	$2.1 \cdot 10^{1}$	$1.8 \cdot 10^{1}$
I-131	$1.64 \cdot 10^{-1}$	---	---
I-133	$7.26 \cdot 10^{-2}$	---	---
Cs-134	---	$4.3 \cdot 10^{0}$	$2.3 \cdot 10^{0}$
Cs-137	---	$8.8 \cdot 10^{0}$	$4.5 \cdot 10^{0}$
Ce-144	---	$1.3 \cdot 10^{0}$	$6.7 \cdot 10^{-1}$
U α	---	$9.4 \cdot 10^{-3}$	$9.2 \cdot 10^{-3}$
Pu-238	$2.36 \cdot 10^{-6}$	---	---
Pu-239	$5.41 \cdot 10^{-6}$	---	---
Pu α	---	$2.3 \cdot 10^{-1}$	$2.0 \cdot 10^{-1}$
Pu-241 β	---	$5.6 \cdot 10^{0}$	$5.5 \cdot 10^{0}$
Am-241	---	$6.3 \cdot 10^{-2}$ [f]	$6.3 \cdot 10^{-2}$
Cm α	---	$1.0 \cdot 10^{-1}$	$1.0 \cdot 10^{-1}$
Np-237	---	$1.6 \cdot 10^{-5}$	$3.3 \cdot 10^{-6}$
Tc-99	---	$8.1 \cdot 10^{-4}$	$1.4 \cdot 10^{-4}$
Co-60	---	$6.4 \cdot 10^{-6}$	$3.6 \cdot 10^{-6}$
Pm-147	---	$1.6 \cdot 10^{0}$	$1.7 \cdot 10^{0}$

a 1991 values, assuming 351.4 t reprocessed (Dreicer et al., 1995).

b Total from THORP plant and THORP downstream plants.

c Emission limits from (BNFL, 1992a); based on reprocessing flowsheet calculations, supplemented by R&D, for the maximum throughput of 1200 t/yr. Assumed in (Frischknecht et al. 1994).

d From (BNFL, 1995), assumed in the present study.

e Maximum potential discharge in (BNFL, 1993) is $2.0 \cdot 10^{1}$ kBq/kgU.

f Maximum potential discharge in (BNFL, 1993) is $1.6 \cdot 10^{-1}$ kBq/kgU, including Cm-242.

Table 4.3.XI

Radioactive emissions to water from reprocessing plants.

Radionuclides	UP3 [a]	THORP [b]	
	Activity released (kBq/kgU)	Maximum potential discharge[c] (kBq/kgU)	Flowsheeted discharges [d] (kBq/kgU)
H-3	$6.69 \cdot 10^{6}$	$5.8 \cdot 10^{6}$ [e]	$1.2 \cdot 10^{7}$
C-14	$1.05 \cdot 10^{4}$	$4.1 \cdot 10^{2}$	$4.2 \cdot 10^{2}$
Co-60	$2.11 \cdot 10^{3}$	$1.9 \cdot 10^{3}$	$1.8 \cdot 10^{3}$
Sr-90	$3.39 \cdot 10^{4}$	$2.4 \cdot 10^{3}$	$4.0 \cdot 10^{2}$
Tc-99	---	$2.1 \cdot 10^{2}$	$2.1 \cdot 10^{2}$
Ru-106	$2.03 \cdot 10^{4}$	$1.2 \cdot 10^{4}$	$2.0 \cdot 10^{3}$
Sb-125	$1.43 \cdot 10^{4}$	---	---
I-129	$1.59 \cdot 10^{2}$	$1.2 \cdot 10^{3}$	$1.2 \cdot 10^{3}$
Cs-134	$3.41 \cdot 10^{2}$	$9.1 \cdot 10^{2}$	$4.3 \cdot 10^{2}$
Cs-137	$3.19 \cdot 10^{3}$	$5.4 \cdot 10^{3}$	$3.9 \cdot 10^{3}$
Ce-144	---	$3.2 \cdot 10^{2}$ [f]	$1.9 \cdot 10^{2}$
Zr-95, Nb-95	---	$2.0 \cdot 10^{1}$	$1.7 \cdot 10^{1}$
Mn-54	---	$2.8 \cdot 10^{2}$	$2.8 \cdot 10^{2}$
Np-237	---	$4.5 \cdot 10^{0}$	$5.3 \cdot 10^{-1}$
U-α	$3.41 \cdot 10^{0}$ [g]	$6.9 \cdot 10^{0}$	$6.9 \cdot 10^{0}$
Pu-238	$2.09 \cdot 10^{1}$	---	---
Pu-239+240	$1.33 \cdot 10^{1}$	---	---
Pu-α	--	$1.1 \cdot 10^{2}$	$3.3 \cdot 10^{1}$
Pu-241 β	---	$3.3 \cdot 10^{3}$	$8.2 \cdot 10^{2}$
Am-241	$2.13 \cdot 10^{1}$	$6.8 \cdot 10^{0}$	$8.3 \cdot 10^{0}$
Cm-244	$1.02 \cdot 10^{1}$	$1.3 \cdot 10^{1}$	$1.1 \cdot 10^{1}$

a 1991 values, assuming 351.4 t reprocessed (Dreicer et al., 1995).
b Total from THORP plant and THORP downstream plants.
c Emission limits from (BNFL, 1992b); based on reprocessing flowsheet calculations, supplemented by R&D, for the maximum throughput of 1200 t/yr. Assumed in (Frischknecht et al. 1994).
d From (BNFL 1995), assumed in the present study.
e Maximum potential discharge in (BNFL, 1993) is $1.2 \cdot 10^{7}$ kBq/kgU.
f Maximum potential discharge in (BNFL, 1993) is $2.35 \cdot 10^{1}$ kBq/kgU.
g U-238.

This study uses the new set of radioactive emissions for THORP, which shows substantial reduction in the total discharge of aerosols to air and mixed nuclides to water, and in some of the actinides with respect to the values used in the former LCA study. The expected increase in krypton production with the higher burn-up assumed in this study, has not been considered.

Energy requirements (mainly for air conditioning and machinery) have been updated using data that are expected by the year 2010 for the total output of the reprocessing plants in La Hague, which gives slightly smaller values than previously used (Pellissier-Tanon, 1995).

Conditioned intermediate/high-level and low-level radioactive solid wastes that are predicted to be produced in the next decades have been estimated to be less or equal than $4.7 \cdot 10^{-4}$ m^3/kgU and $1.4 \cdot 10^{-3}$ m^3/kgU, respectively, including the expected increase in the average burn-up of spent fuel (Pellissier-Tanon, 1995). These volumes are about one fourth and one third, respectively, of the values used in the earlier LCA study.

Chemical requirements during operation, which were missing in the previous LCA study, have now been taken from (Dreicer et al., 1995) for UP3. These are shown in Table 4.3.XII. No major changes are calculated for the total requirements of chemicals for the full chain, which are dominated by milling and, to a minor extent, conversion.

Table 4.3.XII

Requirement of chemicals for the operation of a reprocessing plant.

Chemicals	UP3	
	Annual requirement	Normalised requirement kg/kgU
nitric acid (HNO_3)	950 m^3/a ($1.4 \cdot 10^6$ kg/yr)[a]	$4.0 \cdot 10^0$
caustic soda (NaOH)	350 m^3/a ($7.5 \cdot 10^5$ kg/yr)[b]	$2.1 \cdot 10^0$
formalin[c]	730 m^3/a ($8.0 \cdot 10^5$ kg/yr)[d]	$2.3 \cdot 10^0$
sodium nitrite ($NaNO_2$)	660 m^3/a ($1.4 \cdot 10^6$ kg/yr)[e]	$4.0 \cdot 10^0$
hydrazine hydrate	32 t/yr	$9.1 \cdot 10^{-2}$
hydroxylamine nitrate	147 t/yr	$4.2 \cdot 10^{-1}$
sodium carbonate	32 t/yr	$9.1 \cdot 10^{-2}$
oxalic acid	6 t/yr	$1.7 \cdot 10^{-2}$
liquid oxygen	no value given	---
nitrogen	no value given	---
other chemicals	NA	---
other non-chemicals	NA	---

a Density 1520 kg/m^3 100% acid.
b Density 2130 kg/m^3.
c Solution 35-40 wt% formaldeyde in water.
d Density approximately 1100 kg/m^3.
e Density 2170 kg/m^3.

4.3.5 Analysis of Results

The main findings of the analysis are discussed in this section considering the full energy chain. Results obtained in the earlier LCA study on present systems are used for comparison. In particular, total requirements and emissions calculated for the chains associated with the Swiss and the UCPTE nuclear mixes are considered here. For the

future, the European nuclear mix assumed for the decade 2020-2030 and the two analysed types of LWRs are considered. The results were normalised by the unit of electricity.

The calculated consumption of uranium per unit of electricity generated decreases by approximately 8% to 26 kg/GWh because of the assumption of higher average burn-up.

Figures 4.3.2 and 4.3.3 show the steel and concrete calculated for the chain and compared to the use in the power plant. The total steel normalised by the unit of electricity is predicted to reduce by nearly 50%, mostly because of the reduced masses and the longer lifetime of the power plants. About the same reduction is calculated for the total requirements of concrete, with the plants expected to have the strongest decrease. The lower material consumption that can be observed in the rest of the chain are mostly due to reductions in the transport needs. The differences that can be noticed between the Swiss and the European chains for the present conditions depend on the different average load factors (almost 85% for Swiss NPPs vs. 70% for UCPTE), and consequently the total energy generated during the lifetime.

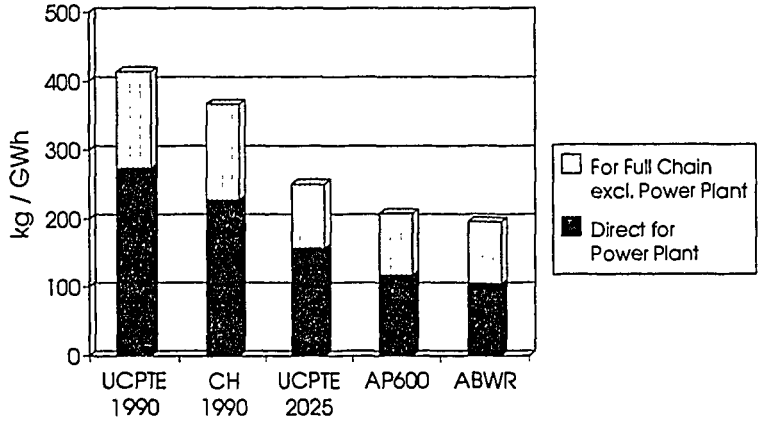

Figure 4.3.2 Steel requirements for present and future nuclear full energy chains.

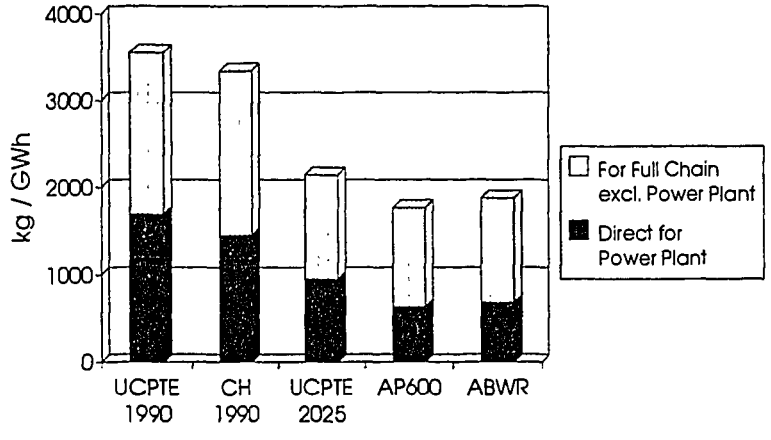

Figure 4.3.3 Concrete requirements for present and future nuclear full energy chains.

Figure 4.3.4 shows the results for the total electricity needs. The requirements for the enrichment of uranium by gaseous diffusion are currently about 80% of the total consumption of electricity. The total electricity needs should decrease from approximately 4% for the current conditions to less than 0.5% for the entire chain, mainly because of the predicted change in the processes used for enrichment.

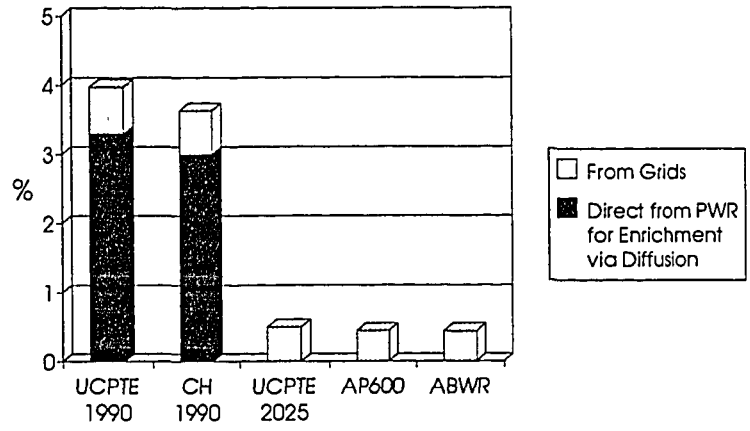

Figure 4.3.4 Electricity input requirements as a fraction of the total generated by present and future nuclear full chains.

Greenhouse gas (GHG) emissions are shown in Figure 4.3.5 in terms of CO_2-equivalent calculated with the GWP_{100} from (IPCC, 1994) considering only direct effects of halocarbons (see footnote 1 in Section 5.2). CFCs leakages at diffusion enrichment plants may at present contribute roughly 25% to the total GHG emission calculated for the nuclear chain. This contribution will nevertheless reduce during the next decade due to substitution of coolant gases, to reach negligible values for future conditions.

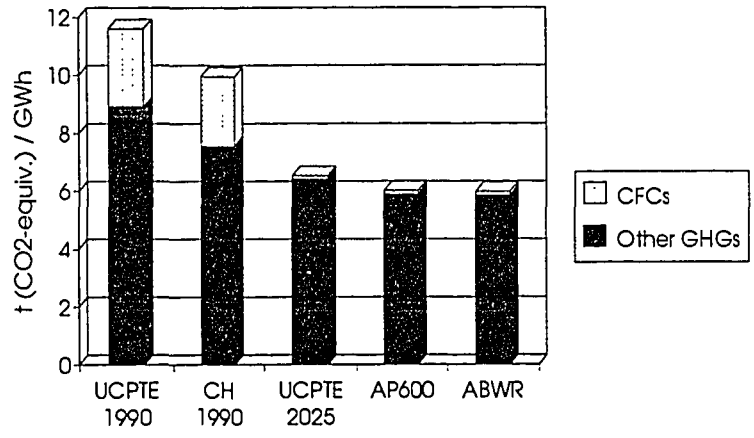

Figure 4.3.5 Greenhouse Gases (GHG) emissions to air from present and future nuclear full energy chains.

The calculated total greenhouse gases, which in the future will depend almost exclusively on the indirect contributions through the energy needs, in particular from the electricity mixes, should decrease by approximately 50% to about 6 t(CO_2-equiv.)/GWh. Other emissions to air which are typical products of combustion processes are more appropriately commented in Chapter 5 where the various energy systems are compared.

The total radioactive emissions to air and water from the entire chain are shown in Figures 4.3.6 through 4.3.9. Eight classes are considered for simplicity; the releases are again normalised by the unit of electricity. The reduction predicted for radon to air is a direct effect of the assumed restoration of the mill tailings.

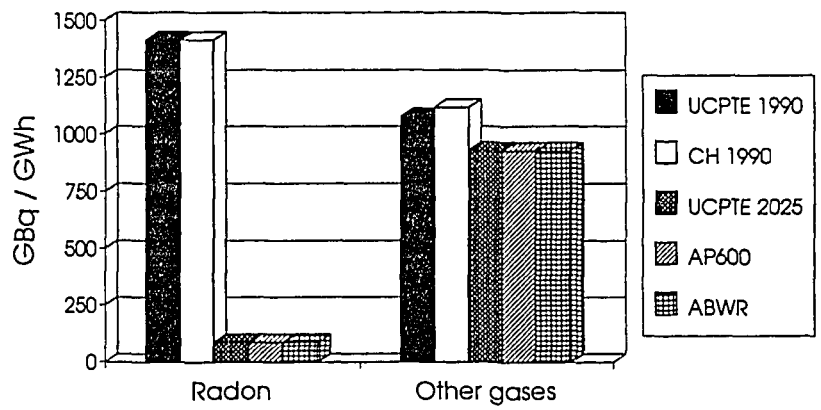

Figure 4.3.6 Radon and other radioactive gases emissions to air from present and future nuclear full energy chains.

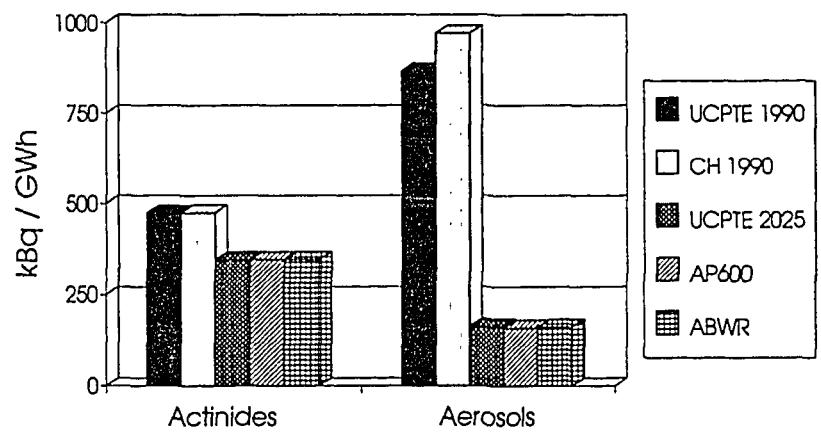

Figure 4.3.7 Radioactive aerosols and actinides emissions to air from present and future nuclear full energy chains.

By far the highest contribution to "Other gases" (Figure 4.3.6) is Kr-85 from reprocessing, which decreases because of the assumed higher burnup (i.e., less spent fuel per unit of energy generated); nevertheless, the value shown has to be taken with care, because it is based on reprocessed fuel with lower burnup (in the end, it may be expected that the total remains as high as at present). The substantial reduction in the releases of aerosols to air occurs in the reprocessing step; this also applies to the actinides (Figure 4.3.7).

The normalised value for emissions of tritium to water, mostly from reprocessing, slightly changes with the increasing burnup (Figure 4.3.8). The actinides released to water substantially decrease in the milling and reprocessing steps (Figure 4.3.9). The strong reduction in the release of mixed nuclides is a direct effect of the new input for the reprocessing step (Figure 4.3.9).

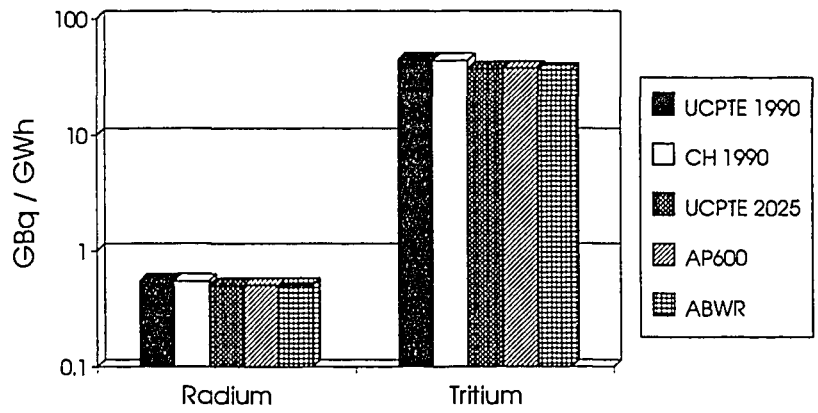

Figure 4.3.8 Radium and Tritium releases to water from present and future nuclear full energy chains.

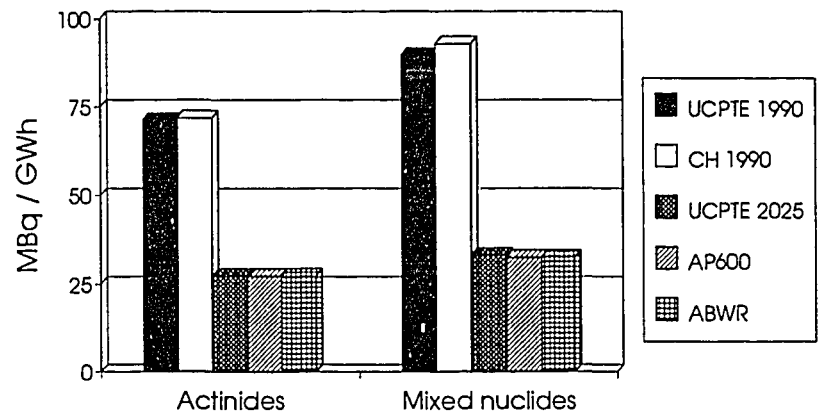

Figure 4.3.9 Radioactive actinides and mixed nuclides releases to water from present and future nuclear full energy chains.

As shown in Figure 4.3.10, which summarises the considered eight radioactive emissions classes (the four on the left-hand side: to air; the four on the right-hand side: to water), according to the estimations the future nuclear power plants (50% AP600, 50% ABWR) give negligible direct contributions to the total emissions of gases and aerosols to air as well as tritium and mixed nuclides to water, whereas there are no direct releases of isotopes of the other classes (see Table 4.3.IX).

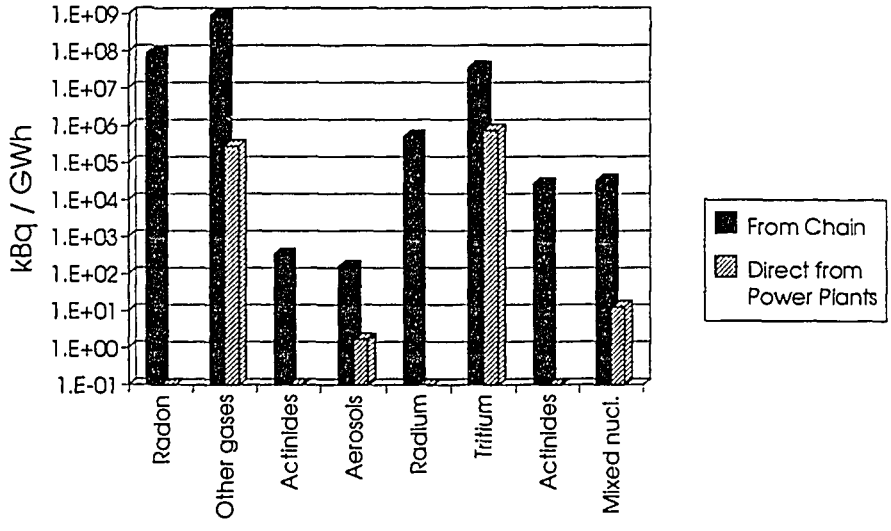

Figure 4.3.10 Radioactive releases to air and water from future nuclear full energy chains.

Figure 4.3.11 shows the conditioned solid radioactive wastes from the reprocessing of spent fuel which should be disposed of in Switzerland in the two planned final repositories for intermediate level and high level. The calculated reductions in the volumes normalised by the unit of electricity depend both on the smaller values which are expected to be attained by the operators of reprocessing plants, and the assumed higher average burnup of the fuel.

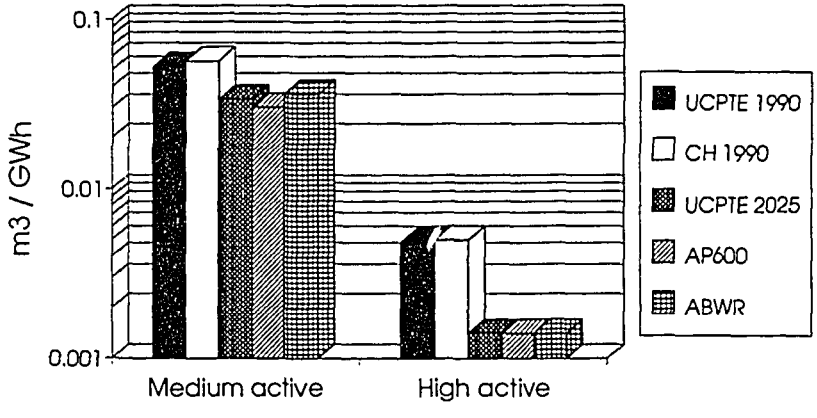

Figure 4.3.11 Conditioned radioactive solid wastes for present and future nuclear full energy chains.

4.4 Hydroelectric Systems

4.4.1 Overview

4.4.1.1 Role of hydroelectric systems

The hydroelectric production in UCPTE countries amounts to approximately 234000 GWh/yr (reference year 1990) (Frischknecht et al., 1994). The Swiss hydroelectric production in year 1992 was 32100 GWh/yr (not including the plants smaller than 300 kW, that produced an additional 190 GWh/yr). Apart from efficiency increases, the Swiss hydroelectric growth potential is very limited, with only few possible sites for big plants or extensions left. The Swiss governmental program «Energie 2000» plans to increase the hydroelectric potential by 5% until year 2000. This may be mainly achieved by efficiency increases in existing plants.

4.4.1.2 General assumptions

Almost all hydroelectric power plants are built specific to the site. Hence, inventory data on hydroelectric production is characterised by the huge ranges of values which depend on the diversity of the various sites. Average values for today's plants were established in (Frischknecht et al., 1994). For the present study it is assumed that these ranges will not change substantially in the future. There is an indication that material consumption might rise, since practically all ideal sites have been utilised and further locations are likely to be more demanding. However, this input has not been changed for this study. Changes have been implemented only for the output side, i.e. plant efficiencies have been increased according to the expected efficiency increases of future turbines. Production changes due to changes in the volume of necessary residual waters (Restwassermengen) have not been considered.

4.4.2 Structure of the energy chain

As for all renewable energy systems, there is no precombustion of the energy carrier. The environmental burdens emerge mainly from construction, operation and disposal of the converting plant. Proportional reduction of all burdens results from global increases in production efficiency.

All material and energy consumptions for construction of hydroelectric power plants have been inventoried in the earlier LCA study on present energy systems. Average values for concrete, steel, explosives, electricity and diesel consumption for three different types of plants (river, reservoir, and pumping storage plants) were established. The various life spans of different parts of the plants are heeded. The data is characteristic for alpine hydroelectric production. Emissions of global warming gases from reservoirs were therefore not considered.

4.4.3 Specific prioritizations and assumptions

As mentioned before, the only change in data are the predicted efficiency increases in hydroelectric production, thus decreasing all specific environmental burdens normalised by

the unit of electricity. Table 4.4.I shows the resulting production increases. The efficiencies of modern plants were taken from the earlier LCA study. Improvements in modern plants are due to increases of the turbine, generator and transformer efficiencies. It is assumed that the relative shares of the different types of plants are not changing in the future. Table 4.4.I shows that the use of modernised turbines could be able to increase the production of existing power plants in Switzerland up to 7.5%.

Table 4.4.I

Production and efficiency of today's Swiss hydroelectric power plants and expected increases due to modernisation.

Type of hydroelectric plant:		River	Reservoir	Pumping storage	Total for Switzerland
Average Swiss hydroelectric production	GWh/yr	15030	16410	665	32100
Efficiency of today's plants [a]	%	82 [b]	78 [b]	70 [c]	---
Efficiency of modern plants [a]	%	88 [b]	84 [b]	74 [c]	---
Production increase with modern plants	GWh/yr	1100	1260	38	2400
	%	7.3	7.7	5.7	7.5

[a] (Frischknecht et al., 1994)
[b] Efficiency defined as Electricity output / Potential energy of water.
[c] Efficiency defined as Electricity output / Electricity input.

For this study it is assumed that the existing plants are refitted with new modern equipment. Since detailed schedules of replacements are lacking, a linear approach has been used. An averaged life span of the hydro-mechanical and hydroelectric equipment of 45 years has been assumed. This figure is based on the life spans of turbines, generators and transformers given in the previous LCA study. It is assumed that within an average time of 45 years all plants existing today will have been refitted with modern equipment. For hydroelectric production in the years 2010 and 2030, a linear proportional fraction of modernised plants has been assumed. This leads to a linear mix of old and modernised plants depending on the elapsed time and to a linear increase of efficiency for the whole Swiss hydroelectric production. The average increase in production efficiency reduces the specific burdens for future conditions compared to year 1990.

4.4.4 Hydroelectric production in Switzerland in years 2010 and 2030

As shown in Table 4.4.II, the Swiss hydroelectric production by the year 2010 could increase its production efficiency by 3.3% through modernisation of the existing plants alone. This leads to a general reduction of the environmental burdens by a factor of 0.968. Therefore, all environmental burdens of the Swiss hydroelectric system in the reference year 1990 which were inventoried in (Frischknecht et al. 1994) have been multiplied by this factor to obtain the burdens of the 2010 systems. Likewise, the increase in production efficiency expected by year 2030 is 6.7%. This corresponds to a reduction of the environmental burdens by a factor of 0.938.

Table 4.4.II

Changes in efficiency and environmental burdens due to a linear modernisation scheme for existing hydroelectric plants.

Refitting time span 45 years	Time past since 1990 years	Relative efficiency	General reduction factor for burdens
Hydro 1990	0	100% (basis)	1.000
Hydro 2010	20	103.3%	0.968
Hydro 2020	30	105%	0.952
Hydro 2030	40	106.7%	0.938

4.4.5 Results

Since the only difference between the inventory of 1990's Swiss hydroelectric system and future systems is a general reduction factor for each time horizon, all burdens are reduced by this factor. These are shown in Table 4.4.II.

4.5 Photovoltaic Systems

This chapter describes the assumptions, technologies and results for two types of small photovoltaic plants, i.e. plants based on monocrystalline silicon (m-Si) cells and plants based on amorphous silicon (a-Si) thin film cells.

4.5.1 Overview

4.5.1.1 Role of photovoltaic energy

Photovoltaics (PV) is a comparatively young technology. Although the first terrestrial application (a solar radio) was devised already some 30 years ago, the first large photovoltaic power plants were built in the beginning of the 80s. An estimate for the total installed photovoltaic capacity today is approximately 300 MW_{peak}. The 1995 Swiss capacity is approximately 5 MW_{peak}.

Photovoltaics has a huge development potential globally. Most present applications are based on silicon as the photosensitive material. Alternative technologies are being developed based on other materials (copper, indium, gallium, etc.) and on other physical principles mimicking natural photosynthesis (Grätzel cells). Advancements in photovoltaics could be dependent on investments in research and development, which have not been as steady as in other energy research areas. It is not clear which solar technology will be dominant in the future. This depends on the balance between energetic efficiency and manufacture cost.

4.5.1.2 General assumptions

PV technology has been inventoried according to the anticipated trends excluding revolutionary developments. Extrapolation for PV is somewhat more difficult than for other well-established energy systems. Many parts of the process chain are not standardised operations. Substantial changes, depending on market conditions and volume of investments can still be expected in the future. Some of the inventory data used here assume a higher production volume than today's, and are therefore somewhat speculative in nature. Mainly the market shares of different technologies are quite uncertain and very difficult to extrapolate from the present situation. It has to be emphasised that the inventory presented here is not *the* definitive one for future photovoltaics. The inventory should be reassessed as soon as further developments take place.

According to the VSE definition of future supply mix options 6 and 7, photovoltaic plants are assumed to cover around year 2030 approximately 5% of the electricity gap in the cold season (which means approximately 10% of the electricity gap on a yearly basis and 4-5% of the year 2030 total electricity supply — see Sections 6.1 and 6.2). PV panels are assumed to be manufactured in Europe, i.e. using electricity from the UCPTE grid. The associated electricity mix is described in Chapter 3. Load factors are defined according to moderate Swiss climate. Only small scale, roof-top plants of $3kW_p$ are inventoried.

4.5.2 Structure of the process chain

There are no "precombustion steps" for PV systems. Solar energy is freely available and there are virtually no emissions from operation. All burdens originate from the manufacture (and disposal) of the energy converting facility, i.e. the plant itself. The process chain consists mainly of the manufacture of panels and the construction of the power plant. The process chain follows the fate of the energy converting material instead of an energy carrier. A scheme of the PV process chain for the technologies assessed in this study is shown in Figure 4.5.1.

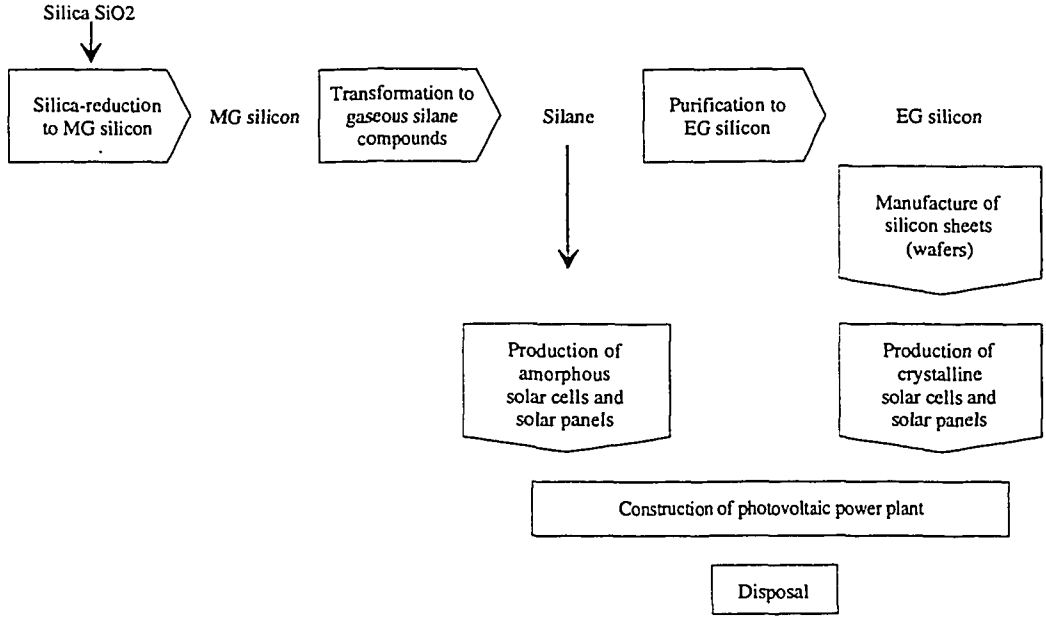

Figure 4.5.1 Photovoltaic process chain for the technologies assessed in this study.

- **Manufacture and refining of silicon**

Silicon is the most common photoactive material in today's photovoltaics. Raw or metallurgical grade silicon (MG-Si) is manufactured from silica (SiO_2) in carbothermal stoves. MG-Si is then transformed into gaseous silicon compounds, i.e. silanes. Silanes are directly used for the manufacture of amorphous silicon cells. Purified electronic grade silicon (EG-Si) from distilled silane is used for manufacture of crystalline silicon cells.

- **Cell production**

Sheets or wafers of purified electronical silicon are the basis of crystalline solar cells. For amorphous cells silane gas is deposited on a glass pane. After a series of deposition, etching and printing steps, a functional photovoltaic panels emerges.

- **Plant construction**

In this study only small scale, roof-top plants connected to the grid are considered. The PV panels are mounted on existing slanted roofs. The produced electricity is fed to the grid by means of an AC/DC converter.

- **Disposal**

Dismantling of the power plant and disposal of production wastes is considered, but on a rather uncertain basis, which calls for further assessment.

4.5.3 Specific proritizations and assumptions

- **Panel manufacture**

The starting point for this study was the database in (Frischknecht et al., 1994). The main focus of the present task was on adapting direct energy and material requirements to future processes. New information on direct production emissions to water and air was scarce. Amorphous technology was inventoried according to (van Engelenburg et al., 1993).

- **Site specific assumptions**

Compared to the value used in the earlier LCA study on energy systems, the load factor of the PV plants has been reduced from 11.4% to 10%. This is an average value for Swiss lowland locations, excluding sunny sites in Tessin and the Alps. This corresponds to a medium production of 880 kWh per kW_{peak} installed.

4.5.4 Technologies

4.5.4.1 Overview

- **Photovoltaics based on crystalline cells**

A variety of materials are used today to obtain crystalline solar cells. Crystalline solar cells from silicon are the most common type of cells in power plants. There are basically two

different types of crystalline cells: monocrystalline and polycrystalline. Differences are in manufacture costs and efficiencies. While monocrystalline cells achieve efficiencies in the range of 15—24% (upper limit obtained in laboratory conditions), they are more expensive than polycrystalline cells with efficiencies of 11—14%. Both rely on silicon wafers of roughly 300 μm thickness (today's value), and their environmental inventories are dominantly dependent on the indirect emissions connected with silicon production and the electricity consumption in panel manufacture.

- **Photovoltaics based on thin film cells**

Photovoltaic cells from amorphous silicon are much cheaper than crystalline silicon cells, but they have today a poor efficiency of about 5%. Cost reduction as compared to crystalline cells is rooted in the little use of expensive silicon. Furthermore, an automated, continuos manufacture can be achieved more easily. The thickness of the photoactive material is only a fraction of a micrometer, thus reducing the influence of the burdens of its manufacture on the environmental inventory. More dominant is the manufacture of the specially coated glass pane serving as substrate of the whole panel. As for crystalline solar cells, a variety of materials is being tested for thin film cells.

- **Other PV technologies**

Many variations and new developments of photovoltaic technologies, trying to improve cell efficiency, are continually being researched. It has become many developers additional aim to make their cells also cheap in production, thus expanding the market potential. Efforts to reduce the use of expensive cell materials compete with developments using entirely different materials like gallium, copper, indium, etc.. Different cell principles are being developed, e.g. the photochemical Grätzel cell based on titanium dioxide, mimicking natural photosynthesis. The technology choice for this study is based on the most common technologies today. This is not a vote against the potential importance of other technologies yet to reach the market. Revolutionary developments have been excluded in this study, since credible inventory data would be almost impossible to obtain. The disadvantage for photovoltaics' LCA consists in the fact that it is quite amenable of revolutionary future changes.

4.5.4.2 Systems choice and mix

A mix of basically two technologies is assumed for this inventory:

- Solar cells from monocrystalline, ribbon-pulled wafers, representing the crystalline technology. The assessed silicon production is carbothermal, although alternatives exist. Higher loads in panel production are assumed, thus reducing process energies. Wafer thickness is assumed to decrease to 150 μm. The average panel efficiency is set to 18%, thus representing a cautious extrapolation from today's values.

- Solar cells from amorphous silicon, representing the thin film technology. A triple junction cell based on data for a "best case" cell in (van Engelenburg et al., 1993) is assessed. Since the nature of the photoactive material plays a minor role in the environmental inventory of amorphous cells, this inventory represents a fair guess for other thin film technologies as well. The average panel efficiency is assumed to reach 10%. This value corresponds to the "base case" in (van Engelenburg et al., 1993). An

efficiency of 15% is the long-term goal of the Japanese photovoltaic industries, which is quite likely to be achieved within the time horizon of this study (35 years). Given the rather moderate efficiency increase credited for crystalline panels, it would appear inconsistent to assume here full implementation of drastic advancements in the a-Si technology. By year 2030 the installed PV plants will be a mixture of old and new plants. Thus, the value of 10% used in this study is believed to represent a realistic estimate for the average efficiency.

The main characteristics of the two PV types are summarised in Table 4.5.I.

Table 4.5.I

Some characteristics of the assessed PV technologies.

Assessed technology:	monocrystalline, ribbon-pulled wafers	triple-junction-cells from amorphous silicon
Represented technology:	crystalline silicon technology	thin film technology
thickness of the active layer:	150 μm m-Si	≈ 0.5 μm a-Si
total area per panel:	0.43 m^2	1 m^2
photoactive area per panel:	0.35 m^2	1 m^2
panel efficiency:	18%	10%
PV plant share in years 2020/30:	80%	20%

The relative shares of the two technologies are very speculative. Experts' opinion differs substantially about the dominant future technology, and varies between 100% crystalline and 100% amorphous. For this study it was assumed that the dominant technology today (crystalline) will have the lion's share of 80% of the installed plants. Thin film cells are believed to increase in market volume due to technology improvements and being able to reach a share of 20% of the installed plants. The environmentally more burdening crystalline technology dominates the assessment; this can be regarded as a conservative choice.

4.5.4.3 Material and energy inputs

- **Monocrystalline silicon solar panels**

The inventory of this technology is based on the data for monocrystalline panel production in (Frischknecht et al., 1994). Information on changes to account for future developments was derived from literature and expert estimates.

  * **MG silicon production**

The data for MG silicon production was unchanged compared to the previous LCA study. The carbothermal silica reduction process is quite well established and future changes are unlikely. The process is predominantly run for the electronic silicon chip manufacture.

Alternatives to carbothermal silica reduction exist. Direct production of terrestrial solar grade (TSG) silicon of satisfactory purity from pure soot and glass fibers is developed and possible, but it is waiting for a larger photovoltaic market. Ethyl Corp., Albemarle, produces TSG silicon entirely without thermal reduction of silica. This process converts fluorosilic acid from phosphate rock into silicon according to the steps shown below:

$$CaF_2 \cdot CaPO_4 \rightarrow H_2SiF_6 \rightarrow SiF_4 \rightarrow SiH_4 \rightarrow Si$$

Fluorosilic acid is an abundant and cheap by-product in the production of inorganic chemicals. The silicon produced is pure enough for electronical use and consumes only about 10 kWh/kg or 10% of the process energy usually required *to obtain EG-Si. This fact* has been reflected in the estimate for the process energy *required for* silicon purification.

* **Silicon purification**

The gain of this process has been set to 78%, which is substantially higher than in (Frischknecht et al., 1994). This judgement is rooted in the description of the Union Carbide Company (UCC) silane (SiH_4) production process from MG-Si with a gain of 98% (van Engelenburg et al., 1993). The following thermal decomposition to EG-Si has small wastes. The originally used Siemens process described in (Hagedorn et al., 1992) produces plenty of chloro silanes as by-products, leading to an EG-Si gain of only about 20%. The UCC process recycles these by-products to produce more silane; thus the MG-Si input per kilogram EG-Si output decreases to 1.28 kg. The input of HCl and hydrogen gas has been reduced proportionally to the reduction of MG-Si consumption.

A distance of 50 km was assumed for the transport of production and operational materials. Process energy was decreased from the original value of 129 kWh/kg for year 1990 to 80 kWh/kg. This reflects the fact that already 10% of today's silicon production stems from the Ethyl Corp., with a specific energy requirement of only 10 kWh/kg. Waste heat is partially used for steam production. Therefore, a share of 39% of the waste heat will not be directly emitted into the environment. According to the methodological framework of the earlier LCA study, no credits or fuel benefits are granted for this.

* **Wafer production**

Wafers are ribbon-pulled from melt with 150 µm thickness and an area of 100 cm^2. Different sizes of wafers are possible but have not been assumed, for reasons of consistency with the panel production of the original inventory (Frischknecht et al, 1994).

Wastes are assumed to be 4% melt residue, 10% in pulling and for wafer separation and 3% discarded wafers. These percentages refer to the total amount of silicon handled in the process, which is 4.3 g per wafer. Argon consumption has been reduced according to the decrease of EG-Si use. As ribbon frames 0.5 g of high alloy steel wires per wafer have been assumed. Packaging material has been left unchanged. Process energy is 0.53 kWh per wafer, estimated from today's production of Mobil Solar and Evergreen. Once more, waste heat reduction of 20% through steam production has been assumed. A distance of 50 km has been assumed for the transport of production and operational materials.

Nitrogen oxide emissions from etching have been reduced proportionally to the EG silicon use to reach a value of 0.102 mg NO_x per wafer (Hagedorn et al., 1992). Silicon and steel

wastes are disposed of in a low active chemical landfill. Emissions to water have not been reassessed, due to lack of new data.

* **Cell manufacture**

The gain in the cell production has been set to 89% according to today's gain in the Mobil Solar process. A process energy of 1.02 kWh per cell was estimated from data of the Mobil Solar and Evergreen productions. Material consumption for cell production is proportional to the area of the cell; this has been left unchanged compared to the earlier assessment. Approximately 10 kg of cooling water, 4.1 g NaOH for etching, 12.3 g of nitrogen gas, 0.5 g of phosphine, 0.38 g of silver and 6.5 g of ethylene glycol are necessary per cell.

A distance of 100 km was assumed for the transport of these materials. Direct emissions to air are 0.4 g of NMVOCs per cell from the screen printing paste. Emissions to water have been left unchanged, except for undissolved substances. This emission has been set to zero, since the process (oxide etching) which generates it is eliminated.

* **Panel manufacture**

The environmental burdens of this data module are given per kilowatt peak (kW_p) nominal power, and not per panel. The assumed panels have a nominal power of 64.8 W_p per piece. Thus, one kilowatt of power is obtained with 15.3 panels. Estimated manufacture losses in panel production are 1%. One panel contains 36 solar cells of 100 cm^2, making a total active area of 0.36 m^2. The estimated overall panel area is 0.44 m^2. The use of glass panes and lamination plastics was assessed proportionally to the total area, amounting to 69 kg of glass and 6.4 kg of EVA copolymer per kilowatt. Glass panes are 4 mm thick. Per kilowatt panels 561 solar cells are necessary. Other materials were left unchanged with respect to the earlier LCA study. No panel framing is necessary for the roof construction considered in the power plant. A process energy of 45 kWh/kW_p was derived from today's process energies in Mobil Solar and Evergreen production lines. Additionally 2.7 kWh/kg were inventoried for plastic sheeting. A distance of 200 km was assumed for the transport of production and operational materials.

- **Amorphous silicon solar panels**

* **Panel manufacture**

Unlike crystalline solar panels, a-Si solar panels are manufactured at one location. The assessed data were taken mostly from the best case analysed in (van Engelenburg et al., 1993). Manufacture losses were increased here from 1% to 4%. The most important parameter is the panel efficiency, which is assumed to be 10% (base case in the reference).

The burdens for the data module of a-Si panels are given specific to kilowatt peak (kW_p) nominal power and not per panel. The assessed solar panels have an overall area of 1 m^2 per piece, which is identical to the panels' active area. Their nominal power is 100 W_p. Hence, 10 panels give a nominal power of one kilowatt. The values given in (van Engelenburg et al., 1993) have been increased by 4% to account for the manufacture losses. The considered input data are given in Table 4.5.II.

Table 4.5.II
Input data for the production of amorphous silicon solar panels normalised to 1 kW_p.

Requirements & Emissions	Unit	Value[a]
production materials		
glass	kg/kW_p	63.
$SnCl_4$		0.049
methanol		0.0062
detergents		0.28
silane		0.0084
trimethylborane		0.0017
phosphine		0.0025
hydrogen gas		0.0035
vacuum pump oil		4.2
EVA sheet		3.4
HDPE sheet		0.17
aluminium for metallization		0.032
hydrogen fluoride HF		0.0065
methane (for deposition and scrubbing)	Nm^3/kW_p	16.6
process energy		
total energy	kWh/kW_p	230
transport of materials		
road transport	tkm/kW_p	7.1
emissions to air		
waste heat	kWh/kW_p	350
CO_2 from scrubbing	kg/kW_p	27.
emissions to water		
Zn 2+	kg/kW_p	0.0034
Cl-		0.004
F-		0.0009
wastes		
SiO_2	kg/kW_p	4.97
P_2O_5		0.0076
B_2O_3		0.0008
pump oil		4.2
aluminium (from metallization)		0.013
HDPE sheet		0.17
defective panels		1.26
wastes from used panels		
front glass pane	kg/kW_p	63.
plastic/PV material		3.65

[a] The given number of digits is not necessarily significant, being taken directly from calculation sheets.

Methane gas is not used for energy, but as a chemical agent. Approximately 99% of the methane is used for scrubbing and 1% in deposition. Direct carbon dioxide emissions in panel production originate from oxidised methane. The produced panels are not framed. The figure given for aluminium is for back layer contact sputtering. The process energy requirement is 34 kWh/m^2. Process energy for silane has been inventoried as 90.1 kWh/kg. For disposal of used[1] panels 2.8 kWh/kW$_p$ were used for separation of glass and plastic. The total energy consumption adds up to 346 kWh/kW$_p$. Waste heat originates from process energy use and oxidisation of methane.

- **Plant construction**

The same construction — a 3kW$_p$ integrated rooftop plant — is assessed for both types of solar panels (crystalline and thin film). Inventory data for construction of today's integrated plants have been used (see Table 4.5.III). The panels are framed with plastic profiles to form a solar roof tile and are mounted directly on the roof timbering of an existing slanted roof. Additional aluminium and copper profiles are used for the borders. Electricity is used for lifting materials. A distance of 200 km has been assumed for the transport of materials. For the disposal of the plant, it was assumed that bulk metal will be recycled and plastic will be deposited in a low chemical landfill.

Table 4.5.III

Input data for slant roof construction of one 3kW$_p$ solar plant with 15% efficiency.

Requirements	Unit	Value
plastic frames for solar panels	kg	87.50
aluminium	kg	8.98
copper	kg	9.81
electricity for material lift	GWh	$4.\cdot10^{-8}$
road transport	tkm	21.26

The reduced demand of area due to increases in efficiency is heeded. The data for the roof construction materials are based on a today's standard efficiency of 15%. Plants using crystalline m-Si panels with an efficiency of 18% need only 0.83 units of these roof constructions. Plants using thin film a-Si panels with an efficiency of 10% need 1.5 units. For the inventory of other parts of the plant like electronics, converter and lightning protection the data from (Frischknecht et al., 1994) has been directly used.

- **Electricity generation**

The load factor for all solar plants used in this study is 10% or 876 hr/yr. The yearly electricity production of one 3 kW$_p$ plant is therefore 2628 kWh/yr or 9.46 GJ/yr. The lifetime of the plants is 30 years, as assumed in the earlier LCA study. Hence, one plant produces approximately 78800 kWh or 0.284 TJ during its lifetime.

[1] The rate of malfunctioned panels can be considered negligible.

4.5.5 Results

Figures 4.5.2 through 4.5.9 show some selected results for the PV systems assessed in this study. For comparison the figures contain also the results for two selected PV plants from (Frischknecht et al., 1994).

Phalk 500 is a 560 kW_p power plant on Mont Soleil, Jura, which is the biggest PV power plant in Europe. Phalk 500 is not based on an existing building like the PV plants addressed in this study, but was erected on an open field. The increased burdens from construction (e.g., steel, concrete) for the Phalk plant are the main reasons for a poor environmental performance compared to other PV systems. Phalk uses m-Si solar cells and has been assessed with its site specific load factor of 13.7%. It should be emphasised that Phalk 500 is a pilot plant and has also research character. Therefore, it can not be regarded as representative for well-established, standardised plants that would be built to produce a substantial share of the Swiss electricity.

The second photovoltaic system used for comparison is a slant roof plant which was inventoried in (Frischknecht et al., 1994) extrapolating to year 1995 the data available for plants operational in year 1992. The plant is roof integrated and uses unframed solar panels with m-Si cells. Its load factor is 11.4%, representing an average Swiss site including Tessin and the Alps, slightly greater than the factor assumed in this study.

As expected, future a-Si panels have in many respects much lower environmental burdens compared to future m-Si panels. Reasons for this are the lower process energy and the smaller material consumption. The quantity of steel decreases for the future systems (Figure 4.5.3) but their copper requirements (Figure 4.5.4) show some increase in comparison with the integrated roof panels 1995. This is due to the assumption that future roof panels will be integrated solar tiles with copper profile at the border, whereas the current panels use mainly steel and aluminium frames. The tendency is to substitute metal with plastics; therefore, the total weight of future panels should be about half of the weight of current systems.

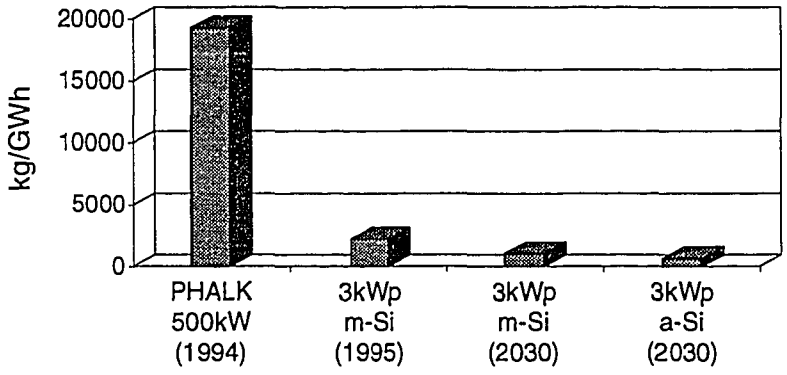

Figure 4.5.2 Concrete requirements for photovoltaic process chains.

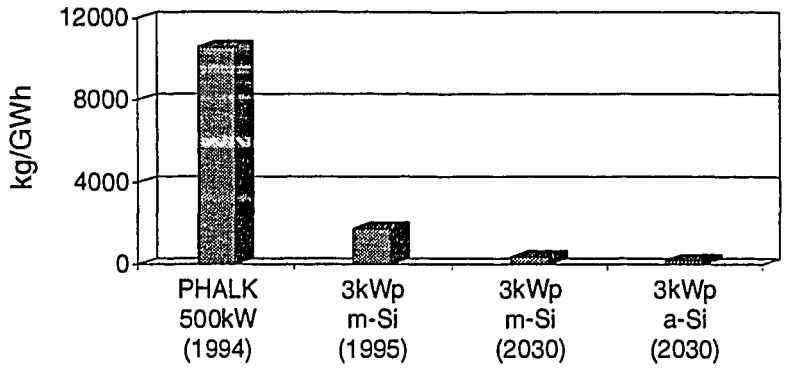

Figure 4.5.3 Steel requirements for photovoltaic process chains.

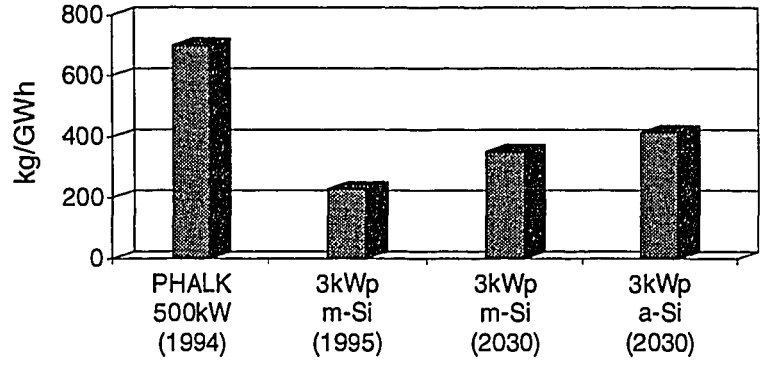

Figure 4.5.4 Copper requirements for photovoltaic process chains.

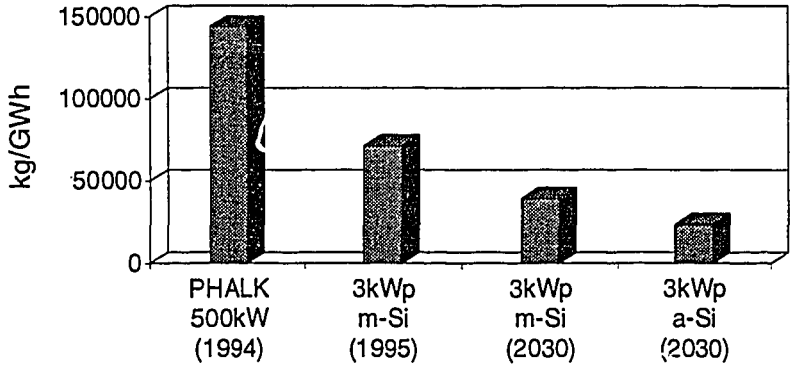

Figure 4.5.5 CO_2 emissions from photovoltaic process chains.

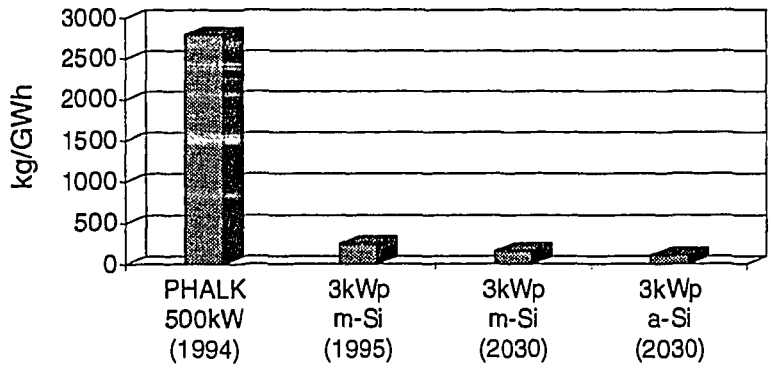

Figure 4.5.6 SO_x emissions from photovoltaic process chains.

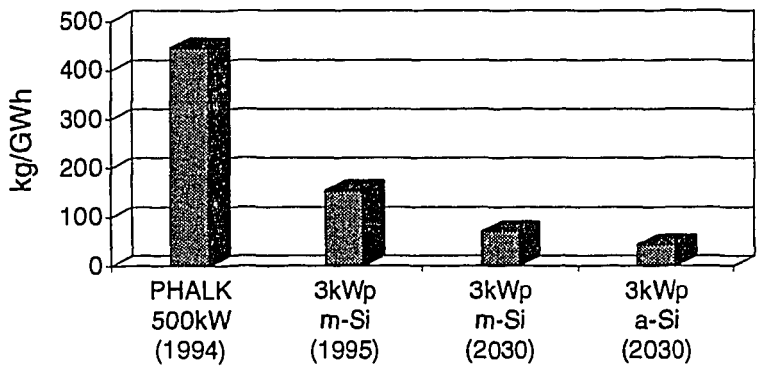

Figure 4.5.7 NO_x emissions from photovoltaic process chains.

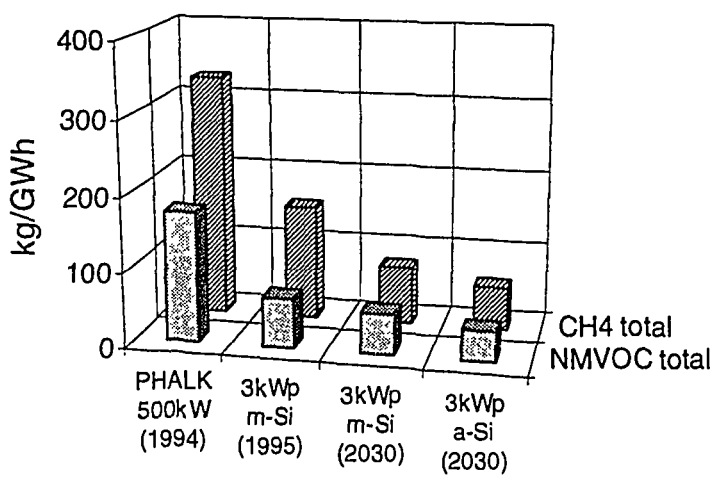

Figure 4.5.8 Methane and non-methane VOCs emissions from photovoltaic process chains.

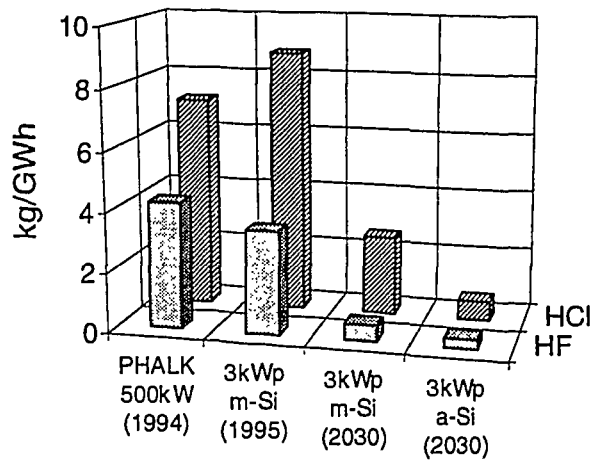

Figure 4.5.9 Halogens emissions from photovoltaic process chains.

According to this analysis, substantial improvements are possible compared to today's PV systems. It should be kept in mind that the present inventory was based on cautious extrapolations of today's trends, i.e. conservative efficiency improvements. Further improvements are likely to be achieved in the future, e.g. 15% efficiency for thin film solar panels instead of the 10% assumed here. On the other hand, a bigger PV market was assumed leading to decreases in the required process energies. The development of the PV market is an open issue and changes will have to be reassessed in the future.

5. Systems Comparisons

Systems analyses provided in the preceding chapter already contain in each of the analysed cases comparisons with the current performance characteristics. This chapter presents comparisons of the inventories (not the impacts, which are not addressed in this study) between the different systems. As a background to this comparison we refer to the overall limitations and assumptions listed in Section 3.3 and to the system-specific prioritisations and assumptions given in Sections 4.1-4.5. The main contributions to the total requirements and emissions have been described for each system in the relevant sections and they will not be repeated here.

The inventories calculated using the full chain analysis of future electricity systems are discussed and compared considering only Swiss conditions. The values shown in the figures for the systems have been normalised each by the unit of electricity produced at the busbar by the power plant (or device) of the same system. Given inclusion of distribution lines, CHPP and PV, which are delivering electricity directly to the appliances, would in comparisons to the other systems exhibit a somewhat improved environmental performance. On the other side, PV has the disadvantage of unsteady supply characteristics. CHPP is included for completeness but care should be taken in drawing conclusions for this particular system because no extrapolation to future conditions has been made.

The characteristics being compared include: selected energy and material requirements, transport requirements and selected emissions to air. The choice of the items discussed in the following sections was made on the basis of the changes introduced in the present LCA study on future electricity systems in relation to the earlier one on current energy systems (emphasis on releases to air). Although the following can not be considered a complete profile of emission inventories, the commented air pollutants are regarded as the most important for the analysed chains. A table with selected numerical results is included in Appendix D.

5.1 Material, energy and transport requirements

Figures 5.1 and 5.2 show the steel and concrete requirements, respectively, normalised by the unit of electricity. The highest steel consumption has been calculated for the hard coal systems and for the CHPP. Nuclear and renewables are in the lower range. Coal systems rank again first with respect to the use of concrete primarily due to the large transport requirements by rail (see also Figures 4.1.3 and 5.4), where large amounts of concrete are used for the infrastructure. Hydropower follows due to the great quantity of concrete used to build the dams.

Figure 5.3 shows the results for the overall electricity input requirements, including contribution from all grids (Swiss and average UCPTE) at all voltages. Among the technology chains using fossil fuels, the coal systems show the highest value for electricity input requirements, whereas the chain associated with gas combined cycle power plants shows the lowest. It has to be reminded that electricity is only one of the many energy

requirements of the chains. In particular, the gas chain uses some percent of the produced gas in turbines to drive the compressors for the long-distance transportation via pipelines (up to 20% estimated for the gas transported at present from Siberia; 2-3% for the gas from Northern Europe). Hydro exhibits the lowest electricity need, the photovoltaic panels with monocrystalline silicon cells the highest.

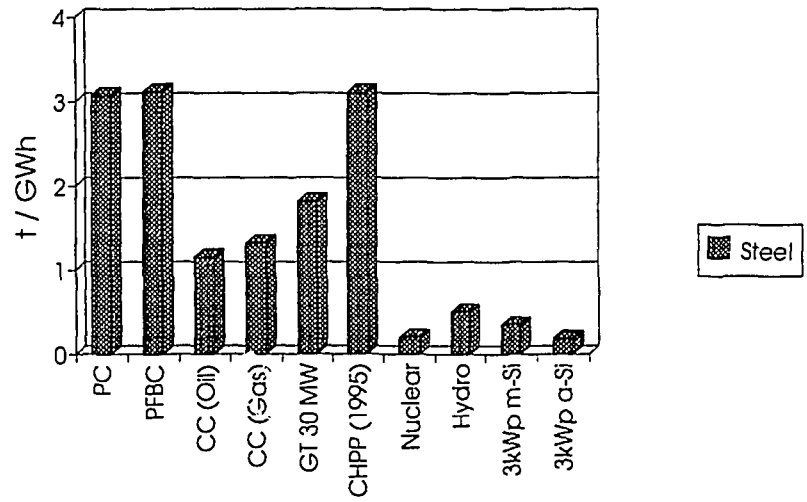

Figure 5.1 Steel requirements for the analysed full energy chains.

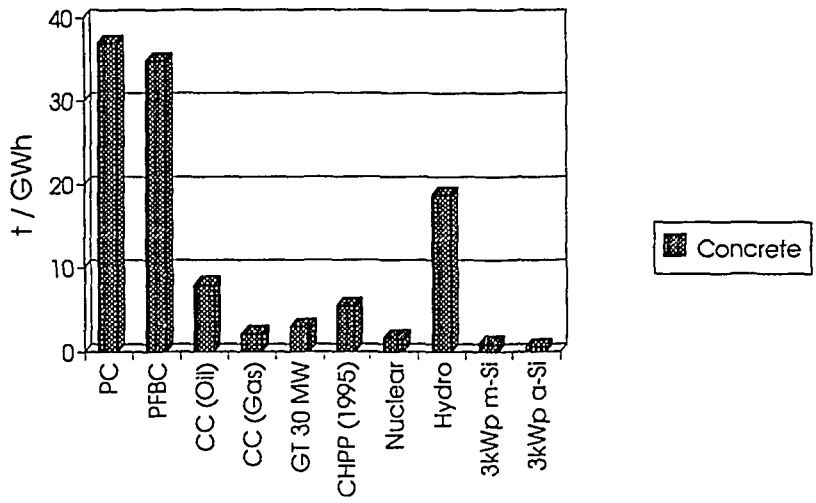

Figure 5.2 Concrete requirements for the analysed full energy chains.

Total transport requirements are illustrated in Figure 5.4, divided in transport by road, rail and ship (inland waterways and transoceanic). The coal systems have by far the largest requirements of rail and ship transports, the latter up to two order of magnitudes higher than for the other systems. Hydro and nuclear full energy chains exhibit the lowest values.

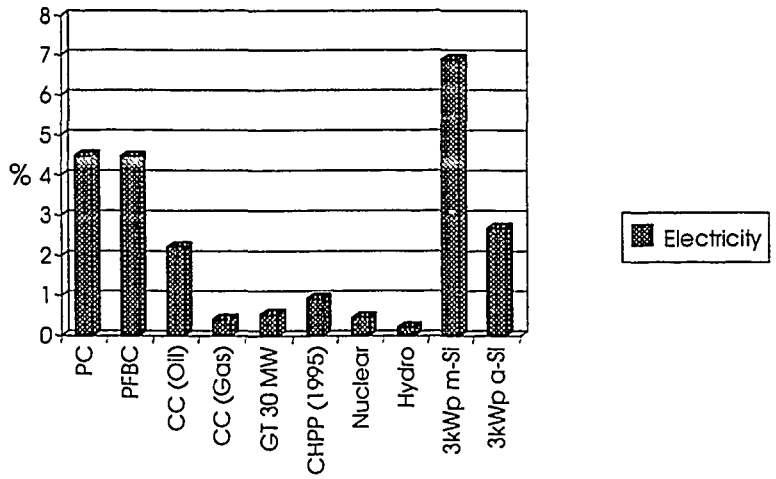

Figure 5.3 Electricity requirements as a fraction of the total generated by the analysed full energy chains.

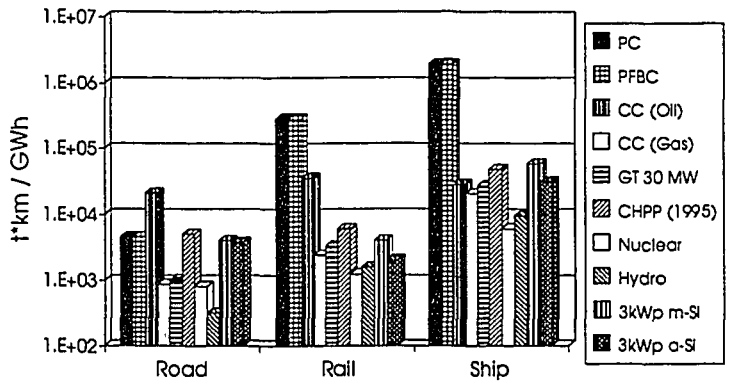

Figure 5.4 Total transport requirements for the analysed full energy chains.

5.2 Greenhouse gas emissions

Greenhouse gas (GHG) emissions are shown in Figure 5.5 in terms of tonnes of CO_2-equivalent calculated after (IPCC, 1994); they include CO_2, CH_4, N_2O, CF_4, CFCs, HCFCs, and HFCs[1]. The figure shows the direct emissions from the power plants separate from all other contributions.

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[1] The CO_2-equivalent is based on the Global Warming Potentials (GWP) relative to carbon dioxide with 100 year time horizon. In particular: CH_4 has GWP_{100} =24.5; N_2O has GWP_{100} =320; CF_4 has GWP_{100} =6300. It is assumed that CFCs are released as CFC-114 with GWP_{100} =9300; HCFCs are released as HCFC-22 with GWP_{100} =1700; and, HFCs are released as HFC-134a with GWP_{100} =1300. The GWP of CFCs and halons takes into account direct effects only. The indirect effects through stratospheric ozone depletion, which tend to strongly reduce their GWPs (IPCC, 1994), were not considered here.

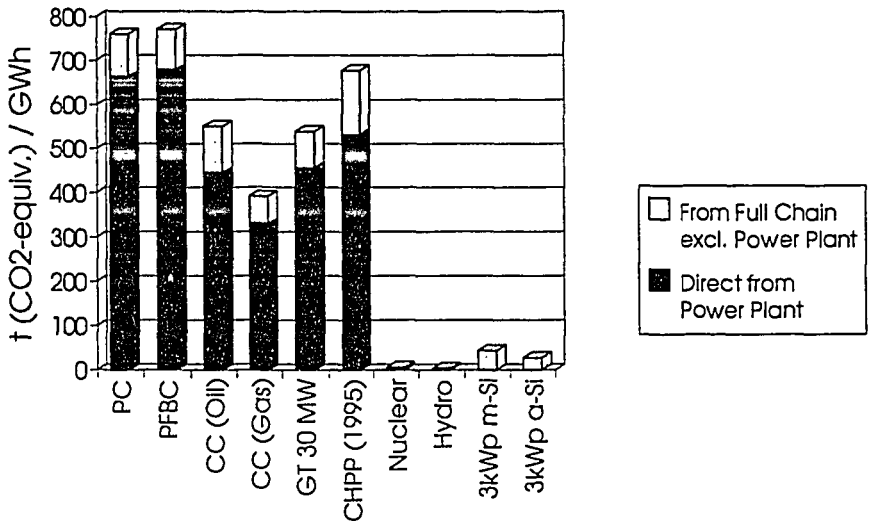

Figure 5.5 Contribution of power plants to total greenhouse gases emissions to air for the analysed full energy chains.

The fossil systems have values in the range 392-772 t(CO_2-equiv.)/GWh, where the lowest has been calculated for CC fired with gas, the highest for the coal systems. The fossil power plants are by far the highest contributors to the total (78-88 %), where the lowest share has been found for CHPP, the highest for PFBC. PFBC power plant produces directly about 680 t(CO_2-equiv.)/GWh against 330 t(CO_2-equiv.)/GWh for the CC power plant fuelled by gas. Renewable and nuclear systems show the lowest GHG emissions, which are almost entirely originating from indirect sources as well as from upstream/downstream steps and only in negligible quantities from the power plants. These systems release one to two orders of magnitude lower GHGs than the fossil systems. Figure 5.6 shows the same values for the chains but in logarithmic scale to better visualise the differences.

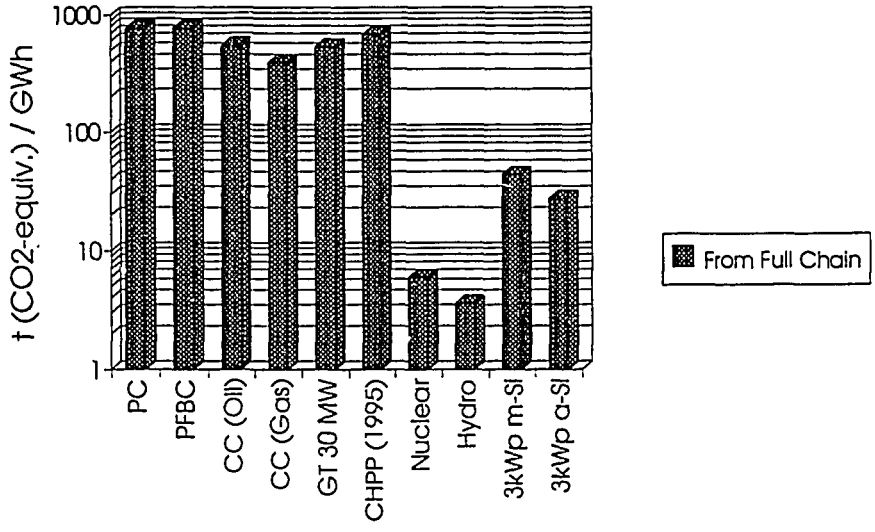

Figure 5.6 Total greenhouse gases emissions to air for the analysed full chains.

For the analysed chains, the largest contribution to total GHG emission is from carbon dioxide (range 85%-97%). The contributions from CFCs, HCFCs and HFCs are negligible. Emissions of CF_4 (from aluminium production) contribute approximately 5-9% to the total CO_2-equiv. for photovoltaic systems and are negligible for other energy systems. The highest contribution of methane to the total CO_2-equiv. from the relevant chain was calculated for CHPP (12.5%), whereas hard coal systems show a value of approximately 5%, gas systems based on turbines and CC about 6%. The only system which generates a substantial N_2O contribution relative to the total CO_2-equiv. is PFBC (approximately 7%).

Methane emissions to air are included in GHGs, but it is of interest to single them out. Figures 5.7 and 5.8 show the direct emissions from the power plants only and the total, respectively. Renewables and nuclear have no emissions at the power plant and very small calculated total values for the other parts of the energy chain. Gas fired power plants have the greatest direct methane emissions, particularly CHPPs (1995) which nevertheless have potential for improvements. All considered power plants give negligible contribution to the total, as shown in Figure 5.8.

Among gas systems, CHPPs show the highest relative contribution of the chain to total GHGs, due to the higher methane leakage rate assumed for the low-pressure grid for local gas distribution as compared to the high-pressure grid for regional distribution (cf. Section 4.2.3.4). The other gas systems have lower total methane emissions than coal systems. This depends on the values assumed for the leakages in the long-distance transportation of natural gas compared to the direct emissions from coal mines.

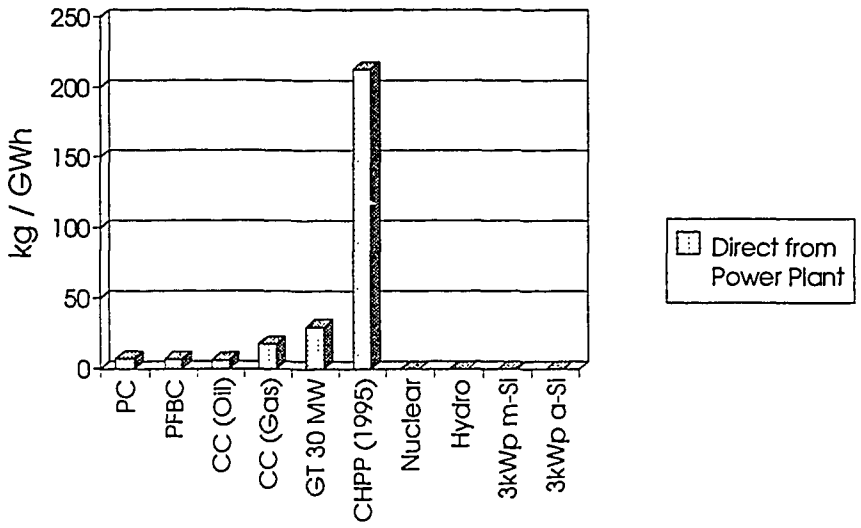

Figure 5.7 Direct emissions of methane to air from the analysed power plants.

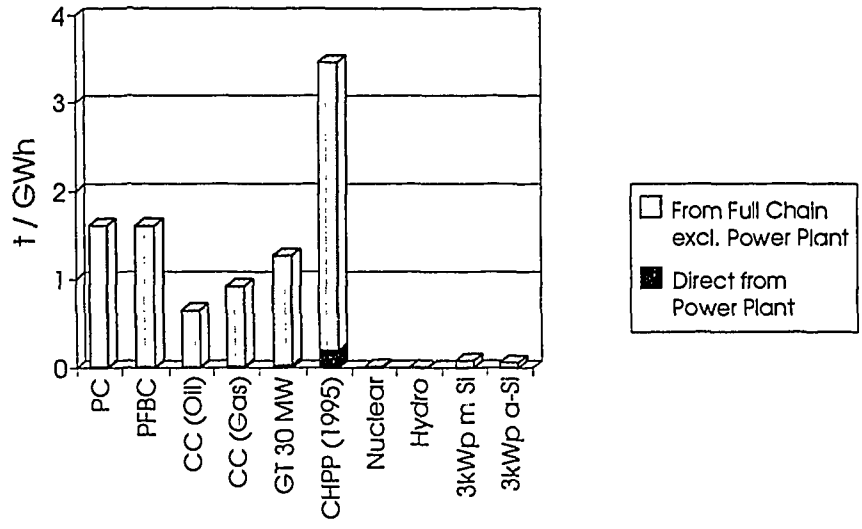

Figure 5.8 Total methane emissions to air for the analysed full energy chains.

5.3 Emission of other combustion products

Figure 5.9 shows the direct emissions of sulphur oxides at the power plants, separate from all other contributions. Emissions calculated for renewables are from indirect sources (energy requirements). As expected, CC burning oil exhibits the greatest direct emissions at the power plant (approximately 420 kg/GWh, 47% of the total) as well as from the entire associated oil chain. Coal systems and gas systems have the second and third highest emissions, respectively. As already explained in Section 4.1.4.3, PFBC has very small

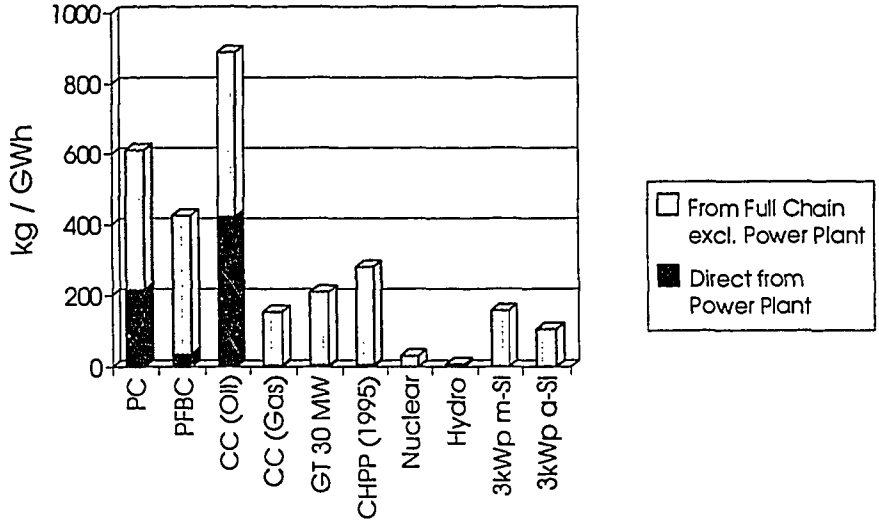

Figure 5.9 Contribution of power plants to SO_x emissions to air for the analysed full energy chains.

sulphur oxides emission at the power plant compared to the advanced PC, approximately 8% of the calculated total from the full chain. The direct emissions from the gas power plant are negligible compared to the other fossil systems (3-5 kg/GWh, only 2% of the total calculated for the gas chain).

Figure 5.10 shows the direct emissions of nitrogen oxides from the power plants, separate from all other contributions from the relevant chains. As for all the other products of combustion, the emissions calculated for renewables are from indirect sources only. PC shows the highest total emissions (about 790 kg/GWh, thereof 47% direct from the power plant), but the gas turbines have the highest normalised direct emissions of nitrogen oxides from the power plant (approximately 414 kg/GWh, i.e. 66% of the total from the chain). PFBC has the lowest nitrogen oxides emissions from the power plant compared to the other fossil power plants (approximately 68 kg/GWh, i.e. 14% of the total from the relevant full energy chain).

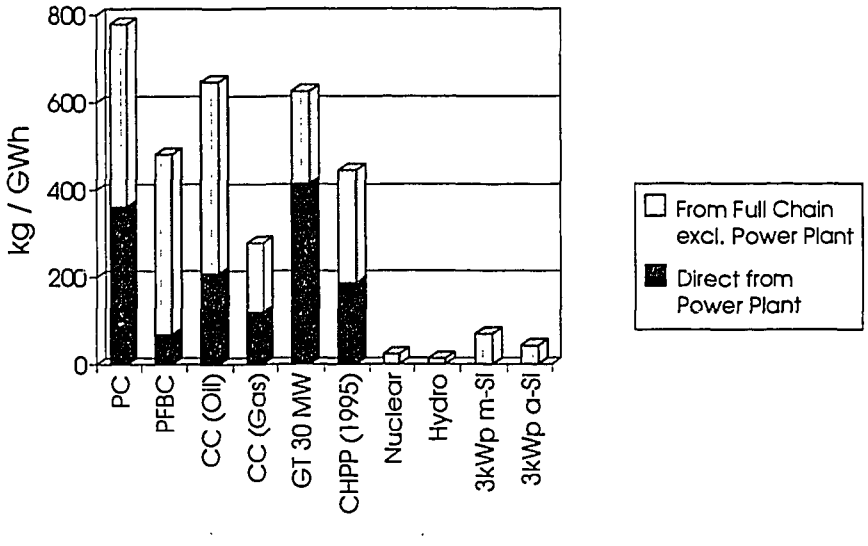

Figure 5.10 Contribution of power plants to NO_x emissions to air for the analysed full energy chains.

Among the gas systems, CC has the lowest NO_x emissions from the power plant (nearly 119 kg/GWh) as well as the lowest total from the chain (278 kg/GWh); gas turbines emit about two thirds of the total emissions from the full chain. Oil and hard coal upstream steps show contributions to total nitrogen oxides emissions comparable with the direct ones from gas turbines.

Total non-methane volatile organic compounds released to the atmosphere directly from the power plants and calculated for the entire chain are shown in Figures 5.11 and 5.12, respectively. Fossil power plants only have direct emissions, where gas turbines rank first with approximately 28 kg/GWh; to compare, coal plants discharge about 14 kg/GWh. CHPP (1995) may have potential for improvements. The various plants give negligible contributions to the total as shown in Figure 5.12, from 1% for the oil chain up to 15% for

the chain associated with the gas turbines. The oil chain has the highest total, approximately 1350 kg/GWh, mostly due to flaring and venting in the oil production step, which is about ten times higher than the relevant values calculated for the chain associated with the advanced coal power plants and CC fired with gas.

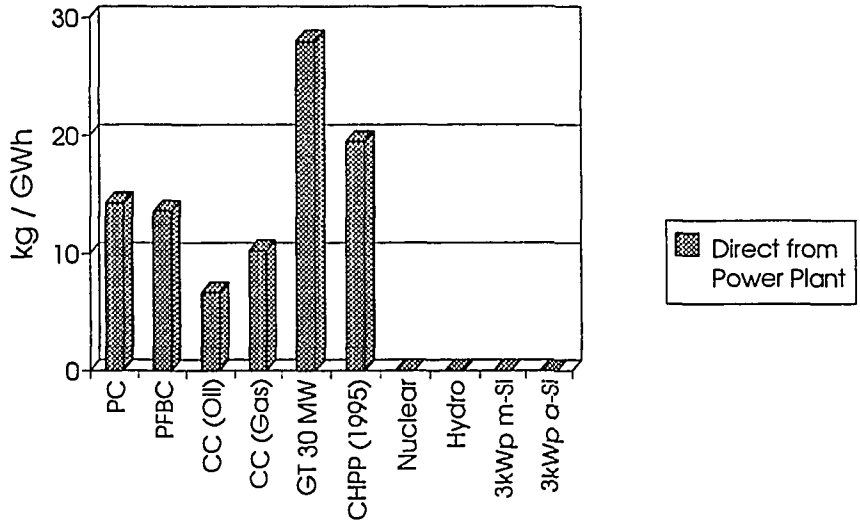

Figure 5.11 Direct emissions of NMVOC to air from the analysed power plants.

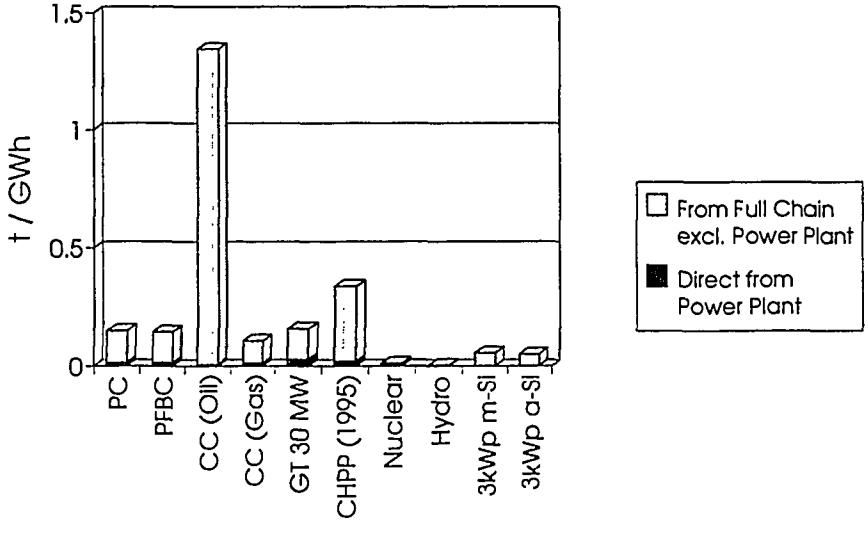

Figure 5.12 NMVOC emissions to air for the analysed future full energy chains.

Figure 5.13 shows the total VOCs, where the methane contributes the most, except for the oil chain because of the high amount of released NMVOCs.

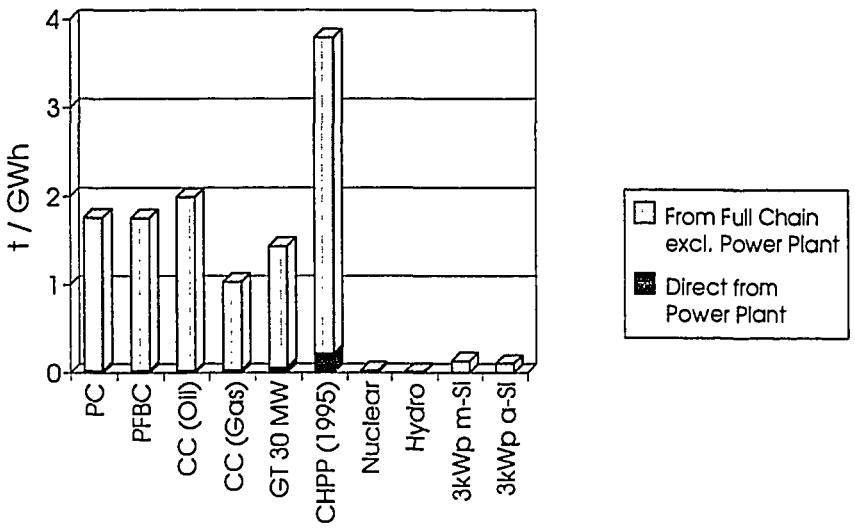

Figure 5.13 Contribution of power plants to total VOC emissions to air for the analysed full energy chains.

Total particles released to air are shown in Figure 5.14. The contribution from the power plants is negligible (2% at most for the coal chains, which corresponds to about 35 kg/GWh; less than 1% for CC when fired either with oil or gas, which corresponds to 0.6 kg/GWh). The bulk of emissions of particles from the coal chain occurs at the coal open-pit mines.

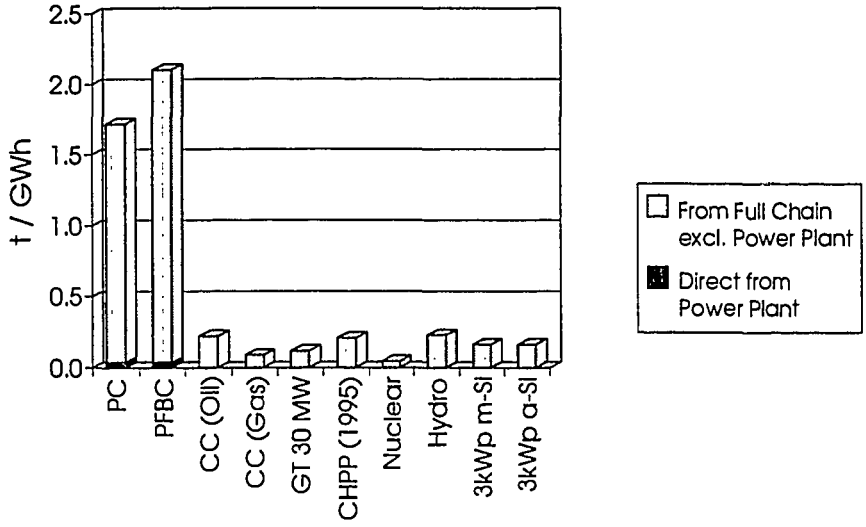

Figure 5.14 Contribution of power plants to total particle emissions to air for the analysed full energy chains.

5.4 Radioactive emissions

The total radioactive emissions to air calculated for the various chains are shown in Figures 5.15 and 5.16 aggregated into four classes. Moreover, a comparison of the direct radioactive air emissions from power plants with total from chains for the analysed hard coal and nuclear energy systems is shown in Figure 5.17.

Radon is directly emitted from the coal power plants and coal mines, but the corresponding values normalised by the unit of electricity are several orders of magnitude lower than the radon emissions at uranium mines and mills. Other noble gases and other radioactive gases originate exclusively from the nuclear chain. Therefore, all non-nuclear energy chains show for these two radioactive emission classes values of approximately two to three orders of magnitude lower than the total calculated for the nuclear chain, due to the indirect contributions through the requirements of electricity from the UCPTE grid, where about one third of the total generated electricity was assumed to be of nuclear origin (see Table 3.I).

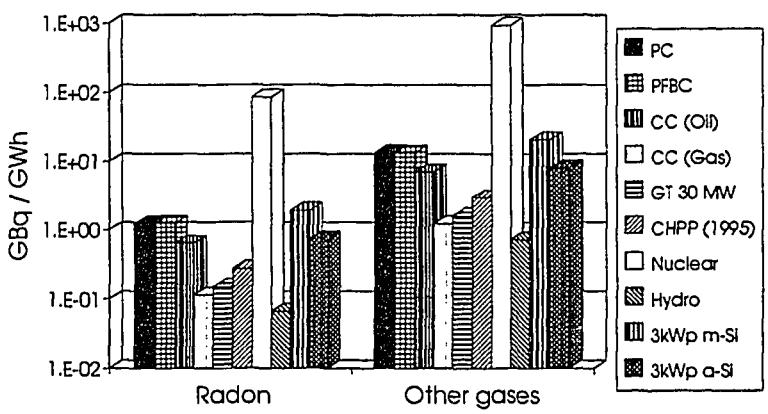

Figure 5.15 Radon and other radioactive gases emissions to air from the analysed full energy chains.

Some actinides are released to air from coal power plants, but the normalised values are approximately 35 times lower than the total assessed for the nuclear chain (mostly from uranium mining/milling and reprocessing). The total (direct plus indirect) release of actinides to air calculated for the coal chain is approximately 1.5 times higher than the release from coal power plants. The radioactive aerosols release calculated for the hard coal chain is mainly due to direct emissions at the power plant. The total release of aerosols calculated for the coal chain is lower by a factor of approximately two than the total assessed for the nuclear chain; however, the relative compositions differ drastically (natural radioactive isotopes Po-210, Pb-210 and K-40 released during hard coal combustion vs. radioactive isotopes of Cs, I, Ru, Sr mostly from reprocessing of nuclear spent fuel, and Po-210 and Pb-210 from uranium mines and mills).

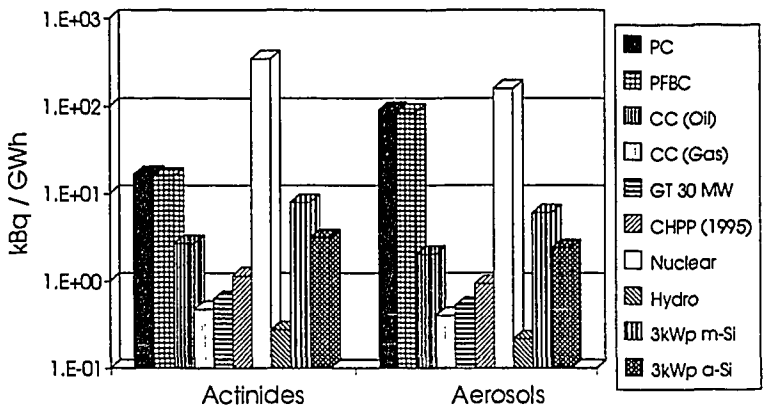

Figure 5.16 Radioactive actinides and aerosols emissions to air from the analysed full energy chains.

The highest contributors to the radioactive aerosols from the nuclear chain are the reprocessing step and mining/milling, while the power plant contributes only 1% (mostly iodine). For the same reason as given above for radon and other gases, the remaining systems show for the other two radioactive emissions classes values of approximately two to three orders of magnitude lower than the nuclear.

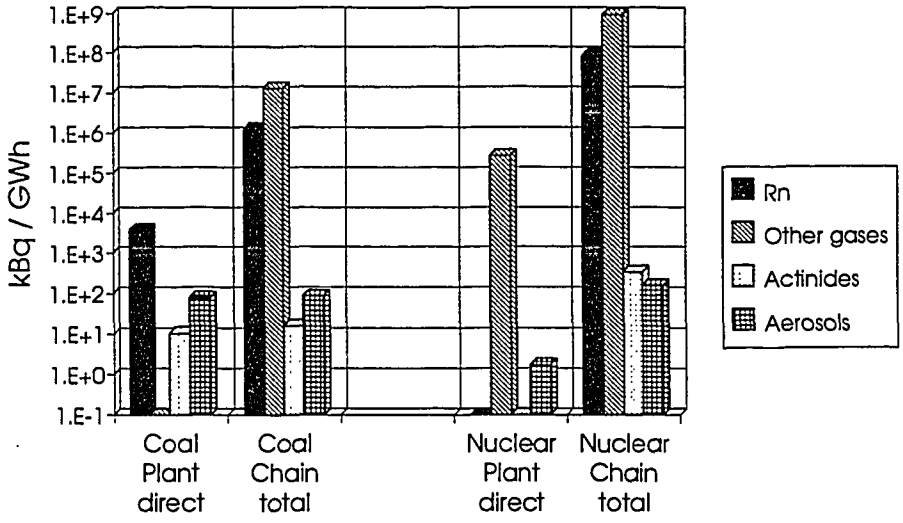

Figure 5.17 Comparison of the direct radioactive air emissions from power plants and total from full chains for the analysed hard coal and nuclear energy systems.

6. Analysis of the Supply Mix Options

6.1 Definition of the options

Two possible electricity demand level cases were postulated by VSE, without any preference given to one of them. Both cases are based on the key assumption of economic growth: a high-growth demand case corresponding to a yearly increase of 2% from year 1995 to year 2010 and 1% from year 2010 to year 2030, and a low-growth demand case corresponding to a yearly increase of 1% from year 1995 to year 2010 and 0.5% from year 2010 to year 2030[1]. These two cases were taken as input to the present work.

Furthermore, two time horizons were considered by VSE, namely years 2020 and 2030. In fact, due to the combination of projected increase of the electricity demand, the decommissioning of the currently operating Swiss nuclear power plants and the expiration of long-term electricity import contracts, a gap in the electricity supply is eventually expected to occur around year 2010. To cover this gap, VSE defined seven supply mix options for the considered demand cases and time horizons. The electricity systems which, according to VSE, are either secured (as the hydro power plants) or whose level is supposed to remain about constant at the present one (as incinerators and cogenerating systems used in industries), or are likely to grow (as CHPPs and possibly the renewables[2], in particular, photovoltaic panels), are herewith referred to as the "base" electricity systems.

The options were defined by VSE in terms of mixes of technologies with different contributions from gas, coal, nuclear and solar photovoltaic systems. The shares of these systems were established by VSE either in terms of the percentage of the total electric energy to be supplied to cover the gap in the cold season (October to March) or by fixing the installed capacity and load factors of some systems and deriving the rest, again for the cold season. During summer, power plants are assumed to operate according to marginal cost, which leads to slightly different yearly load factors for the two analysed cases. However, the LCA analysis of an electricity mix needs as an input the shares of the contributing systems in the total generated electricity (base plus gap) on a yearly basis.

Table 6.I provides a summary of the options to cover the gap in years 2020/2030 as defined by VSE. Domestic contributions are given for each system separating from imported. Only the options defined for the two cases in year 2030 were considered in this study, because this analysis bounds all other cases. Since no distinction was made between the technologies for years 2020 and 2030, the environmental inventory analysis performed for the options for the high-growth demand case in year 2030 gives the upper limits for the yearly emissions from the whole electricity sector.

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[1] Here calendar years are used for simplicity. VSE considers the hydrological years (from Fall to Summer of following year).

[2] VSE assumes a constant annual growth of electricity generated by renewables by 4 GWh per year, which is the present (1994) total generation in Switzerland.

Table 6.I

Definition of the supply mix options assumed by VSE to cover the electricity gap in years 2020/2030.

System shares in the cold season to cover the electricity gap (%)						
Options		CC (Gas)	CC (Oil)	Coal	Nuclear	PV
1	Fossil (D)	50	25	25	---	---
2	Nuclear (D)	---	---	---	100	---
3	Nuclear & Gas (D)	gap minus nuclear share	---	---	present installed capacity	---
4	Nuclear & Fossil 100% (I)	10	---	30	60	---
5	50% Nuclear & Gas (D); 50% Nuclear & Fossil (I)	25 (D)	---	10 (I)	25 (D) 40 (I)	---
6	Fossil & Photovoltaic (D)[a]	47.5	23.75	23.75	---	5
7	Nuclear & Gas & Photovoltaic (D)[b]	as opt. 3 minus 5% (PV) for H	---	---	as opt. 3 for H	5
		as opt. 3 minus 2.5% (PV) for L			as opt. 3 minus 2.5% (PV) for L	

D = domestic; I = imported; H = high-growth demand; L = low-growth demand.

a Option 1 modified with photovoltaics substituting domestic fossil systems.

b Option 3 modified with photovoltaics substituting domestic nuclear and gas systems.

Table 6.II gives the shares of the various systems covering the gap for the high- and low-growth demand options in year 2030 on a yearly basis. These values were used as input to the calculations. Minor differences between the shares of the systems covering the gap in options 1, 4, 5 and 6 of the high- and low-growth demand cases, respectively, were ignored for simplicity of calculation, i.e. the same load factors were assumed for the two cases.

Table 6.II

System shares for the supply options assumed to cover the gap in year 2030.

System shares (%)						
Options		CC (Gas)	CC (Oil)	Coal	Nuclear	PV
1	Fossil (D)	54.5	17.5	28	---	---
2	Nuclear (D)	---	---	---	100	---
3	Nuclear & Gas (D)	54.7 H 23.1 L	---	---	45.3 H 76.9 L	---
4	Nuclear & Fossil 100% (I)	6.5	---	28.5	65	---
5	50% Nuclear & Gas (D); 50% Nuclear & Fossil (I)	18 (D)	---	 10 (I)	27 (D) 45 (I)	---
6	Fossil & Photovoltaic (D)	49	15	26.5	---	9.5
7	Nuclear & Gas & Photovoltaic (D)	45.6 H 17.6 L	---	---	45.3 H 72.5 L	9.1 H 9.9 L

D = domestic; I = imported; H = high-growth demand; L = low-growth demand.

6.2 Assumptions

As already mentioned, the following analysis and discussion address the cases in year 2030 only. The total electricity demand assumed by VSE and used for the LCA calculation is approximately 84.5 TWh/yr in the case of the high-growth demand options and 65.6 TWh/yr in the case of the low-growth demand options.

The shares of the different systems within the base electricity supply were provided by VSE for year 2030. The base supply (excluding incinerators) contributes nearly 38.4 TWh/yr, i.e. 45.4% and 58.5% of the total in the cases of high- and low-growth demand, respectively. According to the values given by VSE, the base supply is dominated by hydro power plants (87.4%) with much smaller contributions from CHPPs (5.1%), small gas turbines (2.7%), what remains at that time of the already secured contracts with foreign utilities (nuclear plants, 4.5%), and photovoltaics and other renewables (0.4%).

Communal incinerators are expected to marginally contribute to the electricity generation in Switzerland, 0.6 TWh/yr additional to the values given above. They have not been included because they generate electricity as a by-product and LCA-based emissions should be allocated to the origin of the wastes rather than to electricity. Moreover, small

amounts of electricity that may be delivered by part of the reserve turbines which are supposedly working at low load factors have not been included in the calculation.

Imported nuclear electricity is assumed to be generated by a mix of power plants of the present (40%) and future (30% by simplified and 30% by advanced LWRs) generations. Electricity generated by UCPTE hard coal plants is a mix of approximately 17% of present PC plants, 44% of advanced PC and 39% of PFBC. The imported electricity by gas systems is from combined cycle power plants, assuming the same characteristics as for the Swiss plants.

Given the above assumptions, the breakdown into contributions from specific electricity supply systems can be established for the seven supply mix options considered. This is shown in Table 6.III for the high-growth demand case (labelled H1-H7) and in Table 6.IV for the low-growth demand case (labelled L1-L7); all values are rounded to the first decimal. Flowcharts describing in detail the structure assumed for the calculation of the environmental inventories with ECOINVENT are included in Appendix B.

Table 6.III

System shares for the total supply for the high-growth demand case in year 2030.

System share (%)							
System	H1	H2	H3	H4	H5	H6	H7
CC Gas (D)	29.8	---	29.9	---	9.8	26.8	24.9
CC Gas (I)	---	---	---	3.5	---	---	---
CC Oil (D)	9.6	---	---	---	---	8.2	---
GT 30 MW (D) [a]	1.2	1.2	1.2	1.2	1.2	1.2	1.2
CHPP (D) [a]	2.3	2.3	2.3	2.3	2.3	2.3	2.3
Coal (D)	15.3	---	---	---	---	14.5	---
Coal (I)	---	---	---	15.6	5.5	---	---
Total Fossil	*58.2*	*3.5*	*33.4*	*22.6*	*18.8*	*53.0*	*28.4*
Nuclear (D)	---	54.6	24.7	---	14.7	---	24.7
Nuclear (I) [b]	2.0	2.0	2.0	37.5	26.6	2.0	2.0
Total Nuclear	*2.0*	*56.6*	*26.7*	*37.5*	*41.3*	*2.0*	*26.7*
Hydro (D) [a]	39.7	39.7	39.7	39.7	39.7	39.7	39.7
Photovoltaic (D) [c]	0.2	0.2	0.2	0.2	0.2	5.4	5.2

D = domestic; I = imported.

[a] Base supply only.

[b] 2.0% is from base supply.

[c] 0.2% (rounded) is the contribution of renewables to the base supply; here only photovoltaic has been assumed for simplicity.

Table 6.IV

System shares for the total supply for the low-growth demand case in year 2030.

System share (%)							
System	L1	L2	L3	L4	L5	L6	L7
CC Gas (D)	22.6	---	9.6	---	7.5	20.3	7.3
CC Gas (I)	---	---	---	2.7	---	---	---
CC Oil (D)	7.3	---	---	---	---	6.2	---
GT 30 MW (D) [a]	1.6	1.6	1.6	1.6	1.6	1.6	1.6
CHPP (D) [a]	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Coal (D)	11.6	---	---	---	---	11.0	---
Coal (I)	---	---	---	11.8	4.2	---	---
Total Fossil	*46.1*	*4.6*	*14.2*	*19.1*	*16.3*	*42.1*	*11.9*
Nuclear (D)	---	41.5	31.9	---	11.2	---	30.1
Nuclear (I) [b]	2.6	2.6	2.6	29.6	21.3	2.6	2.6
Total Nuclear	*2.6*	*44.1*	*34.5*	*29.6*	*32.5*	*2.6*	*32.7*
Hydro (D) [a]	51.1	51.1	51.1	51.1	51.1	51.1	51.1
Photovoltaic (D) [c]	0.2	0.2	0.2	0.2	0.2	4.1	4.3

D = domestic; I = imported.
[a] Base supply only.
[b] 2.6% is from base supply.
[c] 0.2% (rounded) is the contribution of renewables to the base supply; here only photovoltaic has been assumed for simplicity.

6.3 Results

Figures 6.1 through 6.12 show selected total[1] emissions to air resulting from each of the seven options in year 2030 for the high-growth demand case; figures 6.13 through 6.24 show the same set for the low-growth demand case. The discussion is focused on the high-growth demand case. The overall picture is in the qualitative sense with one exception identical for the low-growth demand case although the emissions from the systems covering the gap are reduced, reflecting their lower share (see Section 6.3.4). A table with selected results for air emissions is included in Appendix E.

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[1] These are based on the lumped emissions calculated for the various full energy chains and discussed in the previous chapters. A separation of the total emissions into domestic and external to Switzerland is not included in this report but will be carried out in the future.

In general, considering the full energy chains, the options with fossil systems show the highest releases of typical combustion gases while the options with nuclear systems present the lowest. On the other side, the nuclear options exhibit the highest emissions of radioactivity.

6.3.1 Greenhouse gas emissions

Greenhouse gas emissions calculated for the high-growth demand electricity options are shown in Figure 6.1. H1 exhibits the highest total yearly production of greenhouse gases, expressed in CO_2-equivalent, that originate from the entire chains of the various fossil systems considered. Approximately 26.2 Mt(CO_2-equiv.)/yr are emitted, thereof 92% from the systems covering the gap; 84% of the total emissions are directly produced by the power plants. H2 shows the lowest total yearly production of greenhouse gases from the relevant whole chains. Approximately 2.3 Mt(CO_2-equiv.)/yr are produced in this option, thereof merely 12% (or 0.28 Mt(CO_2-equiv.)/yr) are from the nuclear energy chain covering the gap.

The mixed options have intermediate values included in the range 9.2 to 24.3 Mt(CO_2-equiv.)/yr (or 35% to 93% of the value calculated for H1). For these intermediate options, the contribution of the gap to the total (including the base) varies between 78% and 92%. Direct contribution from the fossil power plants to the total greenhouse gas emissions from all the relevant chains is between 65% and 84% for the different high-growth demand options, as shown in Figure 6.2 (see systems comparison for greenhouse gases in Figure 5.5).

Relative contribution of methane to total CO_2-equiv. is 5.5-9.5% for the various high-growth demand options. Relative contribution of N_2O to the total CO_2-equiv. is 0.1-2.4%. Emissions of CF_4 have a negligible impact on the option-specific results because they contribute only with a small share to the total CO_2-equiv. for photovoltaic systems.

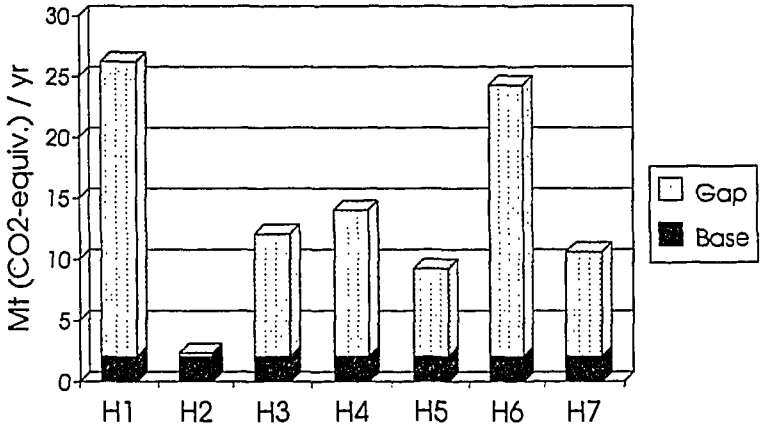

Figure 6.1 Emissions of greenhouse gases to air for the high-growth demand case and different supply mix options (year 2030).

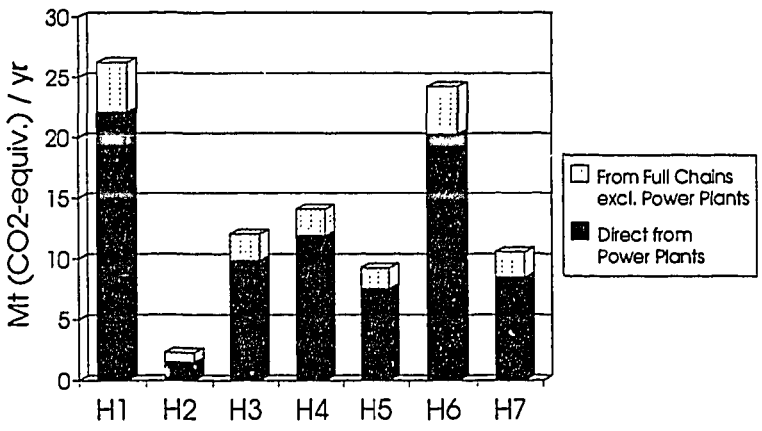

Figure 6.2 Contribution of power plants to total greenhouse gases emissions to air for the high-growth demand case and different supply mix options (year 2030).

In particular, the results for total methane emissions (Figure 6.3) show the highest total value of 57500 t/yr for option H1, the lowest of 8900 t/yr for the nuclear option H2. The base contributes 8300 t/yr from the chains of CHPPs and gas turbines, corresponding to 95% of the total calculated for the nuclear option and only 14% of the total for the option based on domestic fossil systems. For all options, the contribution from the fossil power plants to the total methane emissions is one to two orders of magnitude lower than the values calculated considering the full chains.

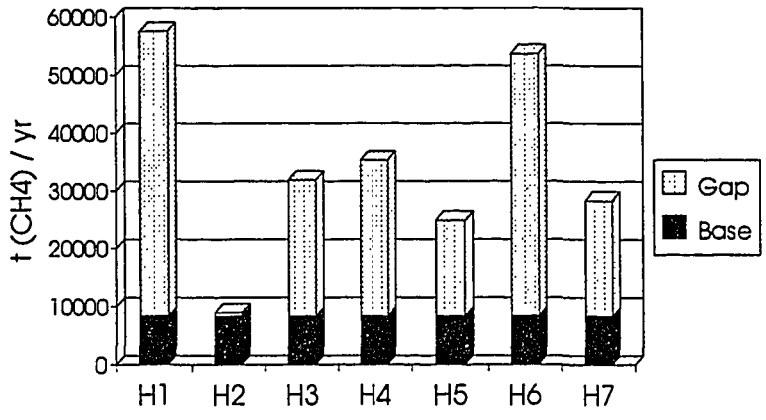

Figure 6.3 Methane emissions to air for the high-growth demand case and different supply mix options (year 2030).

To put in perspective the calculated total greenhouse gas emissions from the electricity sector, the various options can be compared with the corresponding present inventories for Switzerland. The total greenhouse gas emissions calculated using the same methodology for the Swiss electricity mix in (Frischknecht et al., 1994) for the reference year 1990 are nearly 0.9 Mt(CO_2-equiv.)/yr, thereof about 63% is from the energy chain associated with oil power plant in Vouvry, which contributes about 1.2% to the total electricity generated.

The total emission inventory of greenhouse gases in Switzerland was estimated for the reference year 1988 as 66.2 Mt(CO_2-equiv.)/yr in terms of CO_2-equiv. based on IPCC 1992 GWPs (BUWAL, 1994 a, b). Using for consistency IPCC 1994 GWPs, the total changes to approximately 72.2 Mt(CO_2-equiv.)/yr. Therefore, the total GHG that would be emitted from the electricity sector (including full chains, inside and outside Switzerland) in the case of the "fossil" option H1 in 2030 corresponds to about 36% of the current total Swiss domestic GHG inventory. The highest share of the present inventory is from carbon dioxide, 68% or 49.1 Mt(CO_2)/yr. Halocarbons represent the second largest contributor at level of about 19% (approximately 14 Mt(CO_2-equiv.)/yr), but there is a trend towards substituting them in the near future with other substances that do not harm the stratospheric ozone layer and whose warming potential should be lower. Methane contributes 8%, N_2O 5% of the total (5.8 and 3.4 Mt(CO_2-equiv.)/yr, respectively).

The CO_2 emissions originate primarily from energy sources (91% or 44.6 Mt(CO_2)/yr); the remaining contributions are from waste incineration (4%) and cement industry (5%). For the energy sources, 37% (16.5 Mt(CO_2)/yr) stems from for the transport sector, 28% (12.5 Mt(CO_2)/yr) from households, 15% (6.7 Mt(CO_2)/yr) from services and 14% (6.2 Mt(CO_2)/yr) from the manufacturing industry (BUWAL, 1994 a).

6.3.2 Other combustion products

The results for total SO_x and NO_x emissions (Figures 6.4 and 6.5) exhibit a pattern similar to the ones obtained for carbon dioxide. H1 shows the highest total yearly production of SO_x of approximately 18800 t/yr, thereof 94% originates from the systems covering the gap and only 27% is directly produced by the power plants. H2 shows the lowest total yearly production of sulphur oxides, approximately 2500 t/yr, of which barely 0.6% (or approximately 15 t/yr) is directly emitted from the fossil power plants of the base supply systems, which only have insignificant direct sulphur emissions. H1 exhibits also the highest total yearly production of NO_x of approximately 22400 t/yr of which 91% is from

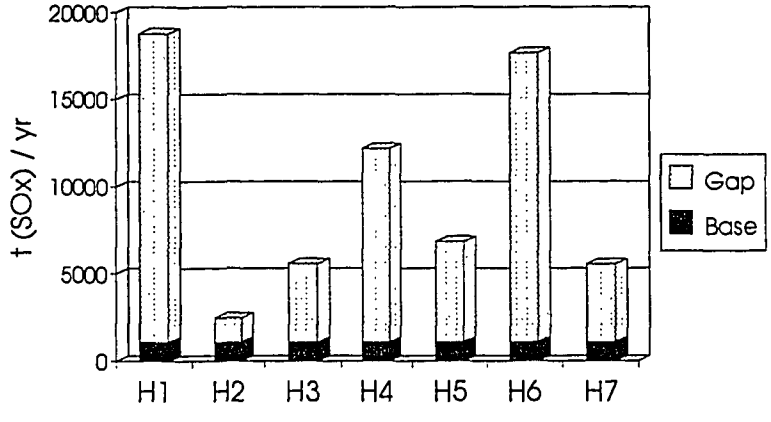

Figure 6.4 SO_x emissions to air for the high-growth demand case and different supply mix options (year 2030).

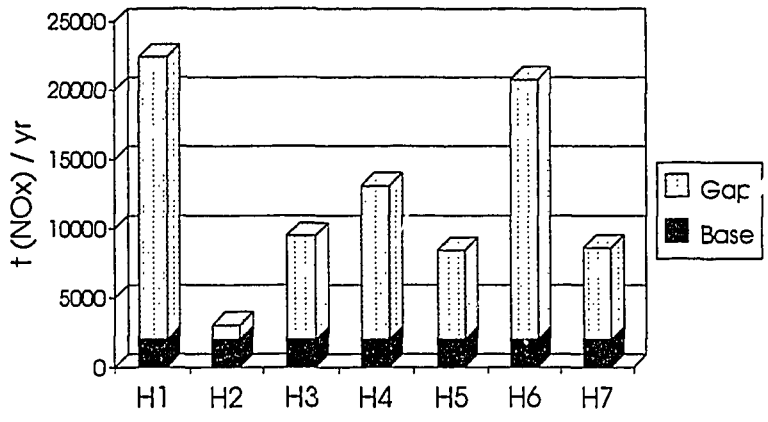

Figure 6.5 NO_x emissions to air for the high-growth demand case and different supply mix options (year 2030).

the systems covering the gap, and 37% is directly produced by the power plants. H2 shows the lowest total yearly production of nitrogen oxides, approximately 3000 t/yr, of which 26% (800 t/yr) is directly emitted from the gas turbines and CHPPs of the base supply systems.

The emissions of sulphur oxides and nitrogen oxides calculated for the other options are between the two extremes represented by options H1 and H2. In particular, photovoltaic systems which in H6 substitute for a part of fossil share (corresponding to 9% of the electricity gap or approximately 5% of total electricity demand), reduce these emissions by about 7-8% compared to H1.

SO_x emissions are for options 3-7 in the range 5600-17600 t/yr (30-93% of the value calculated for H1); NO_x emissions between 8400-20800 t/yr (38-93% of the value calculated for H1). For these intermediate options, the contribution of the gap to the total (including the base) varies between 81% and 94% for SO_x and between 76% and 90% for NO_x.

The direct contribution from the fossil power plants to the total from all the relevant chains and for all the high-growth demand options is for sulphur oxides between 0.6% for the domestic nuclear option H2, as previously discussed, and 27% for the fossil option H1; for nitrogen oxides the corresponding range is between 26% for the nuclear option H2 (practically only from the gas systems of the base) and 40% for the option H4 because of the relatively high imported electricity from European coal power plants, which include also some remaining plants of the present generation. These contributions are shown in Figures 6.6 and 6.7, respectively (see systems comparison for SO_x and NO_x emissions in Figures 5.9 and 5.10, respectively).

For comparison, the total SO_x and NO_x emissions calculated using the same methodology for the Swiss electricity mix in (Frischknecht et al., 1994) for the reference year 1990 are nearly 3500 t/yr and 1900 t/yr, respectively, thereof about 58% and 42%, respectively, are from the energy chain associated with the oil power plant.

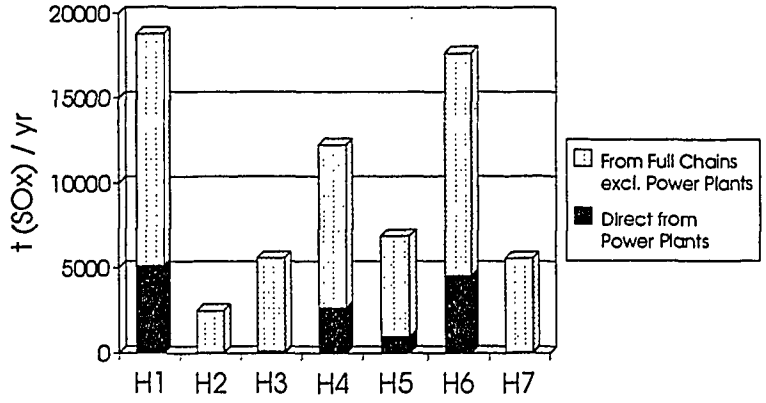

Figure 6.6 Contribution of power plants to total SO_x emissions to air for the high-growth demand case and different supply mix options (year 2030).

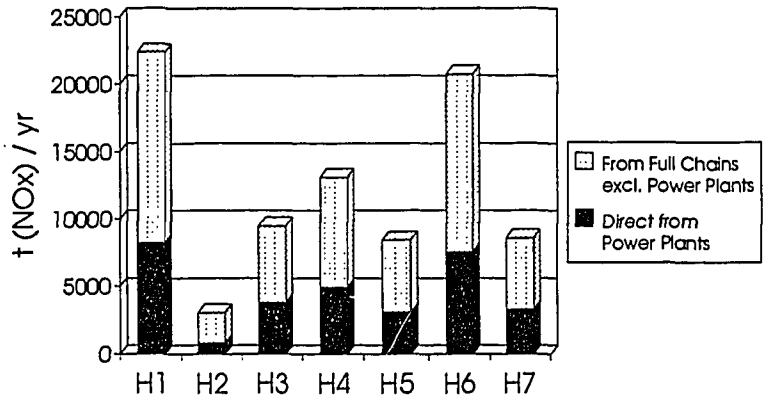

Figure 6.7 Contribution of power plants to total NO_x emissions to air for the high-growth demand case and different supply mix options (year 2030).

Moreover, the yearly emissions of SO_x and NO_x in Switzerland from industry, household and traffic are provided here for comparison for years 1995 and 2000 (based on extrapolations from the past; BUWAL, 1994). The total SO_x inventory for year 1995 is approximately 55000 t/yr (a peak of 135000 t/yr was recorded in year 1965), of which 70% from industry, 27% from households and barely 3% from traffic; the total is expected to increase slightly by year 2000 to approximately 57000 t/yr. Therefore, SO_x emissions calculated for the domestic fossil option H1, including all possible contributions, would approximately equal 34% of the present inventory in Switzerland, while the base would give nearly 2%.

The total NO_x emissions for year 1995 are approximately 128000 t/yr (against a peak of 215000 t/yr around year 1985) thereof 33% from industry, 6% from households and 61% from traffic; the total is expected to further decrease by year 2000 by about 20% to approximately 101000 t/yr because of the application of the Clear Air Ordinance

(Luftreinhalte-Verordnung) in the industry and transport sectors. Therefore, the total NO_x emissions calculated for the fossil domestic supply option H1 would equal approximately 16% of the present inventory in Switzerland, while the base would give less than 2%.

The results for total NMVOC emissions (Figure 6.8) show the highest total values for options H1 and H6 (16400 t/yr and 14700 t/yr, respectively), because they include combined cycle systems fuelled by oil with releases of NMVOCs approximately one order of magnitude higher than from the other analysed energy chains. However, the combined cycle power plant fuelled by oil releases directly less than 1% of the total NMVOC calculated for the chain. The systems of the base contribute with approximately 960 t/yr to the total. Therefore, the systems covering the gap contribute in the case of H1 about 94% to the total from the relevant mix. The lowest NMVOC emitting option is H2, with only 1400 t/yr. For all options, the contribution to total NMVOCs from the fossil power plants is one order of magnitude lower than the calculated total considering full energy chains. Total VOC emissions (which include NMVOCs and methane) are shown in Figure 6.9.

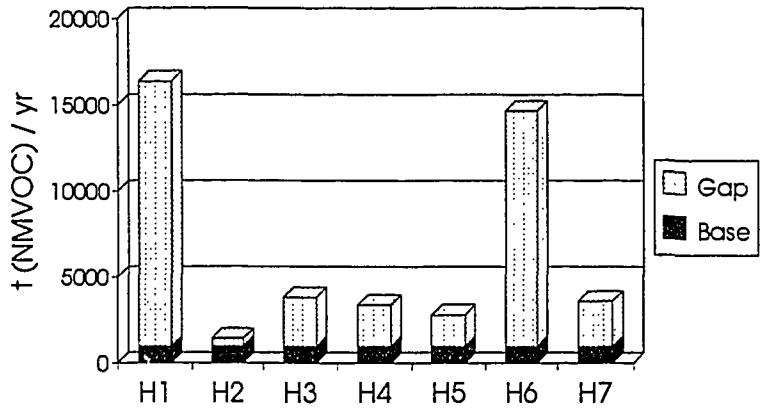

Figure 6.8 Total NMVOC emissions to air for the high-growth demand case and different supply mix options (year 2030).

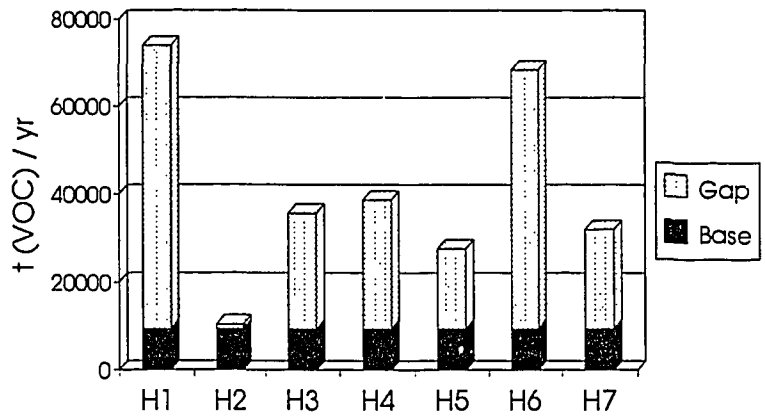

Figure 6.9 Total VOC emissions to air for the high-growth demand case and different supply mix options (year 2030).

For comparison, the total NMVOC emissions calculated for the Swiss electricity mix in (Frischknecht et al., 1994) for the reference year 1990 are roughly 1800 t/yr, thereof about 76% are from the energy chain associated with the oil power plant. Moreover, the yearly emissions of VOCs expected in Switzerland from the industry, household and traffic sectors in year 1995 (BUWAL, 1994) is approximately 241000 t/yr, against a peak of 349000 t/yr around year 1985) thereof 65% from industry, 19% from households and 16% from traffic.

The total emissions of VOCs are expected to increase by year 2000 in the industrial (5%) and household (15%) sectors and decrease in the transport (-25%) to give a total of approximately 246000 t/yr (+2%). Therefore, the total VOC emissions that are calculated including all contributions to the relevant chains constituting the domestic fossil option H1 (approximately 73900 t/yr) would equal about 31% of the present inventory in Switzerland.

The options including coal systems (H1, H4 and H6) show the highest total values for emissions of particles to air, approximately 37000 t/yr (Figure 6.10). About 1700-2000 kg/GWh of particles are released to air from the analysed coal chains, thereof merely 35 kg/GWh from the power plants (see systems comparison for particles in Figure 5.14). Other systems show one to two order of magnitude lower particle emission from the relevant full energy chain; fossil power plants other than the coal-based show values in the range 17-25% compared to hard coal power plants, while hydro systems, photovoltaic panels and nuclear power plants do not produce any particles during operation. The lowest value has been calculated for the nuclear option H2, 10500 t/yr, thereof 20% from the nuclear chain supplying the electricity for the gap. The base contributes with 8300 t/yr from the chains of CHPPs and gas turbines (22% to the total calculated for the option with highest contribution of coal systems).

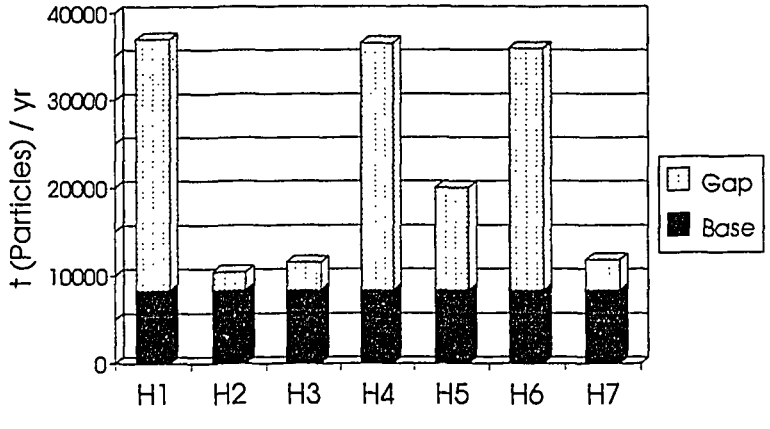

Figure 6.10 Total particle emissions to air for the high-growth demand case and different supply mix options (year 2030).

6.3.3 Radioactivity

Radioactive isotopes released to air have been categorised in four classes to facilitate the discussion, namely: radon, which includes also radium; other gases, which includes other noble gases, C-14 and tritium; actinides, which includes natural isotopes as well as isotopes of actinides generated in the operation of the nuclear reactor (e.g., isotopes of uranium and plutonium); and, the aerosols (e.g., iodine and caesium). The activities within these categories have been calculated by summing up all contributions without any inclusion of weighting factors. Thus, no estimation of health consequences can be made by direct use of these classes. Nevertheless, they are useful to compare the options and the systems with respect to the total emissions.

Figures 6.11 and 6.12 show the values calculated for the different classes of radioactive emissions to air for the high-growth demand options. To make it more transparent, the classes of radioactive emissions are shown on the x-axis.

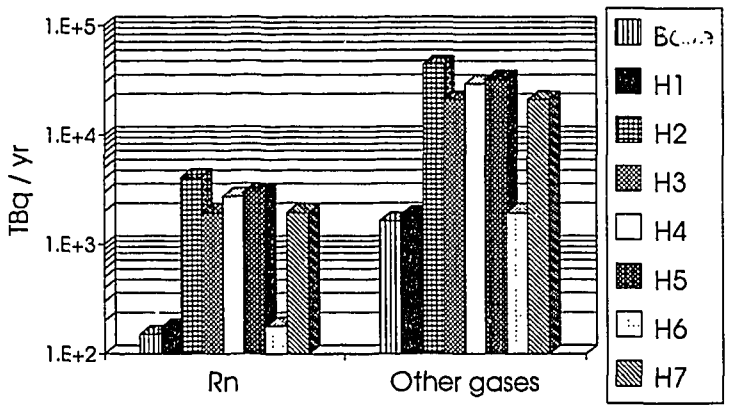

Figure 6.11 Emissions of radon and other radioactive gases to air from the base supply and the supply mix options (including the base) for the high-growth demand case (year 2030).

Generally, options which include electricity generated by nuclear power plants either domestic or abroad (H2-5 and H7) present one order of magnitude higher radioactive emission values within each class. The same behaviour can be observed in the radioactive emissions to water (not included here). The emissions are roughly proportional to the share of electricity of nuclear origin to the total. In particular, the maximum calculated emissions apply to H2 with 56.6% of the total electricity supplied by nuclear plants; the lowest total radioactive emissions are calculated for H1 and H6, with only 2% of imported electricity of nuclear origin considered in the base supply.

To explain the differences calculated for the various options, the origins of the main contributors to the total have to be pointed out. Among the four classes, the aerosols show the lowest spread in the results calculated for the seven options, because of the contribution of the direct emissions from coal power plants, as shown in the systems comparisons. The nuclear option differs only by a factor of about 5 from the options with

only fossil or fossil plus photovoltaic. Moreover, option H3 which preserves the presently installed nuclear capacity, has a few times higher total aerosols emissions compared to the fossil options. As already shown in Section 4.3.5, the highest contributor to the radioactive aerosols from the nuclear chain are the reprocessing step and mining/milling, while the power plant contributes only 1% (mostly iodine).

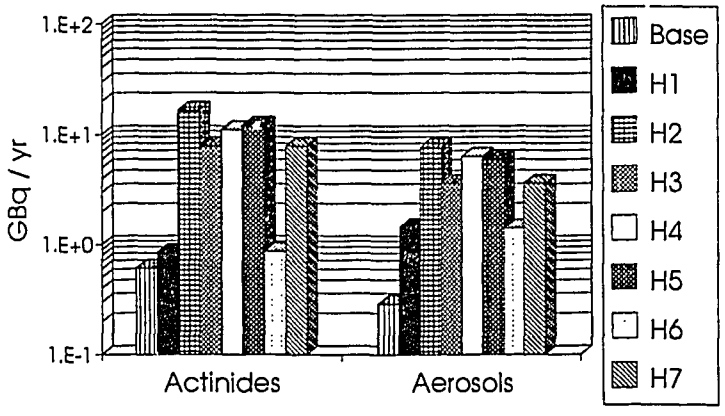

Figure 6.12 Emissions of radioactive actinides and aerosols to air from the base supply and the supply mix options (including the base) for the high-growth demand case (year 2030).

The nuclear energy chain shows by far the highest values for the other classes of radioactive emissions, due to direct releases to air mostly from reprocessing and mining/milling. These emissions are one to two orders of magnitude higher than the corresponding values calculated for the other non-nuclear energy chains, which instead are indirectly imported via the various electricity requirements supplied by the grid. Therefore, these calculated radioactive releases are strongly dependent by the assumed contribution of nuclear power plants to the Swiss and UCPTE electricity mixes that supply the electricity required by the infrastructures (i.e., material production, transport, etc.) of future systems (48% and 32%, respectively, assumed for year 2010).

As already shown in Section 4.3.5, apart from aerosols the nuclear power plants directly discharge to air some radioactive isotopes of noble gases, such as krypton and xenon, but the contribution to the total calculated for the chain is less than 1‰, the remaining being released at the reprocessing plant.

For comparison, the radioactive emissions to air of the classes radon, other gases, actinides and aerosols calculated for the current Swiss-relevant nuclear full energy chain in (Frischknecht et al., 1994) and normalised to the unit of electricity generated by nuclear power plants, are about 16, 1.2, 1.4 and 6 times higher, respectively, than the corresponding factors assessed in this study for future nuclear systems (see Section 4.3.5).

6.3.4 Results for the low-growth demand case options

Figures 6.13 through 6.24 show selected results for the options for the low-growth demand case in year 2030. With the exception of L3, the ranking of the low-growth demand case options does not change as compared to the corresponding high-growth demand case. Option L3 exhibits for typical emissions from the fossil chains lower values than the corresponding ones for option L5, whereas for the radioactive emissions from the nuclear chain the values associated with option L3 are higher. This depends on the shares of nuclear and gas systems to cover the gap in L3 which differ from the corresponding ones in H3 (see Tables 6.I and 6.II). This fact derives in turn from the definition of the option number three, where it is assumed that in both low- and high-growth demand cases the presently installed total nuclear capacity is maintained, i.e. future nuclear domestic systems supply on the yearly basis the same total electricity as generated yearly by the current Swiss nuclear power plants. In fact, the yearly radioactive emissions calculated for L3 are identical to the ones associated with H3.

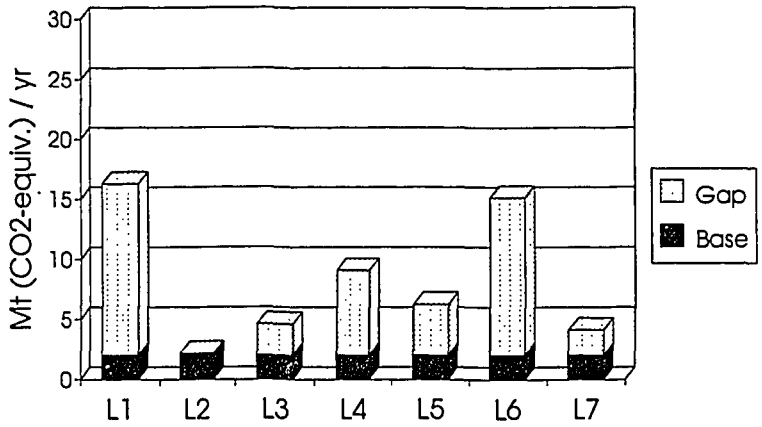

Figure 6.13 Greenhouse gases emissions to air for the low-growth demand case and different supply mix options (year 2030).

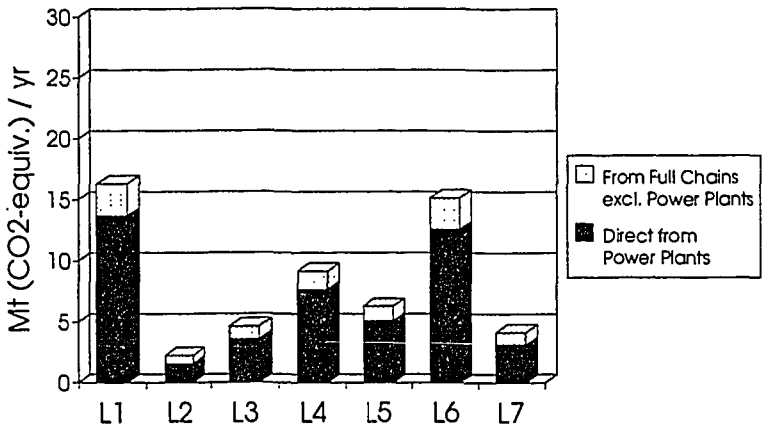

Figure 6.14 Contribution of power plants to total greenhouse gases emissions to air for the low-growth demand case and different supply mix options (year 2030).

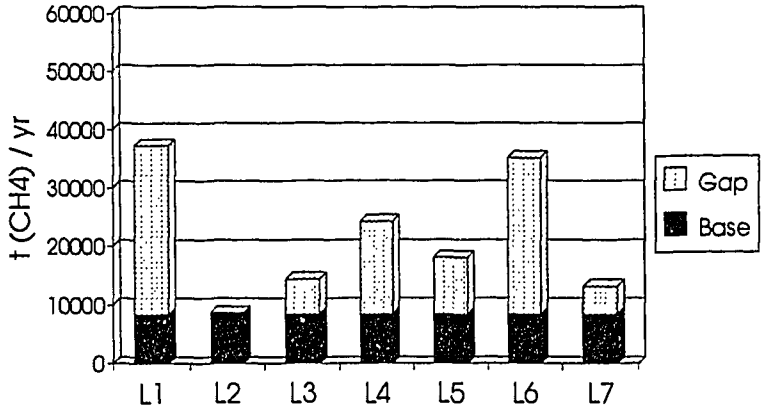

Figure 6.15 Methane emissions to air for the low-growth demand case and different supply mix options (year 2030).

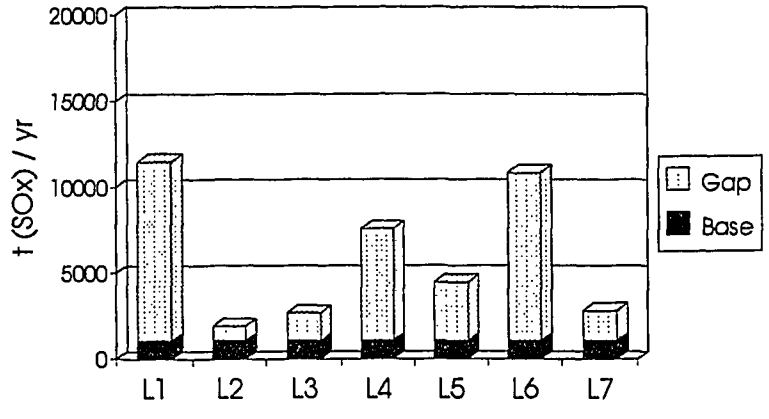

Figure 6.16 SO_x emissions to air for the low-growth demand case and different supply mix options (year 2030).

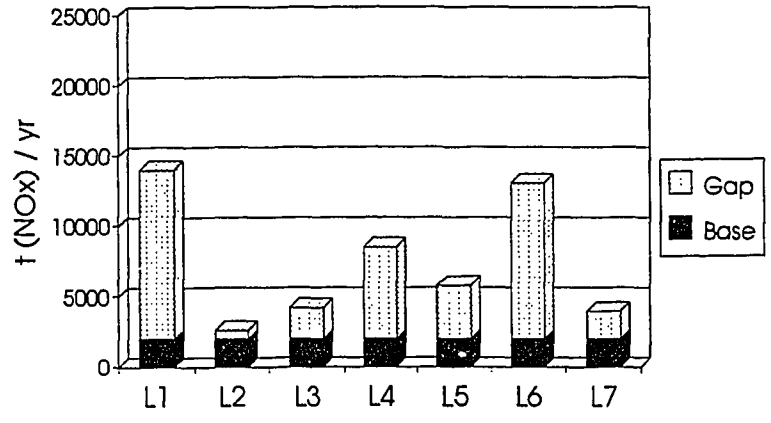

Figure 6.17 NO_x emissions to air for the low-growth demand case and different supply mix options (year 2030).

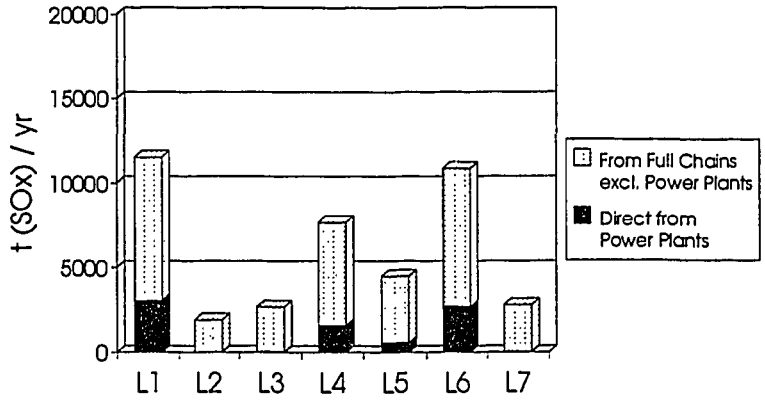

Figure 6.18 Contribution of power plants to total SO_x emissions to air for the low-growth demand case and different supply mix options (year 2030).

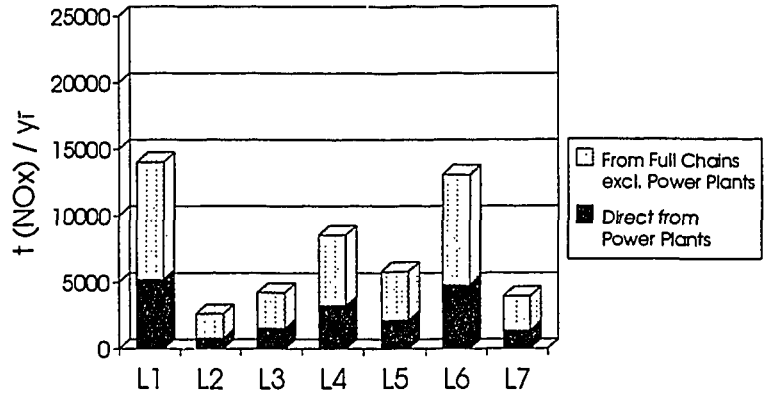

Figure 6.19 Contribution of power plants to total NO_x emissions to air for the low-growth demand case and different supply mix options (year 2030).

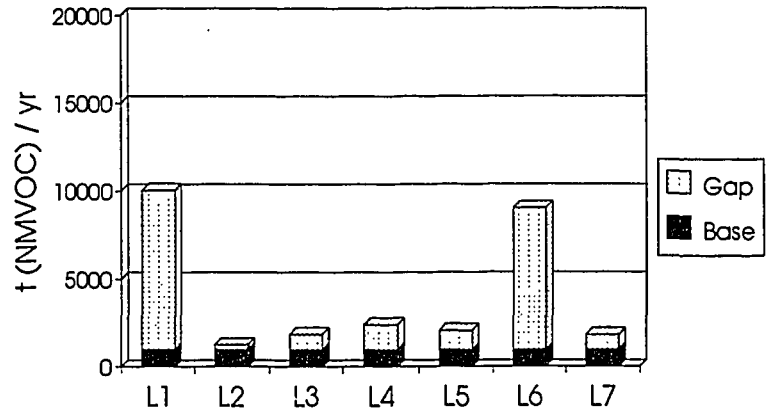

Figure 6.20 Total NMVOC emissions to air for the low-growth demand case and different supply mix options (year 2030).

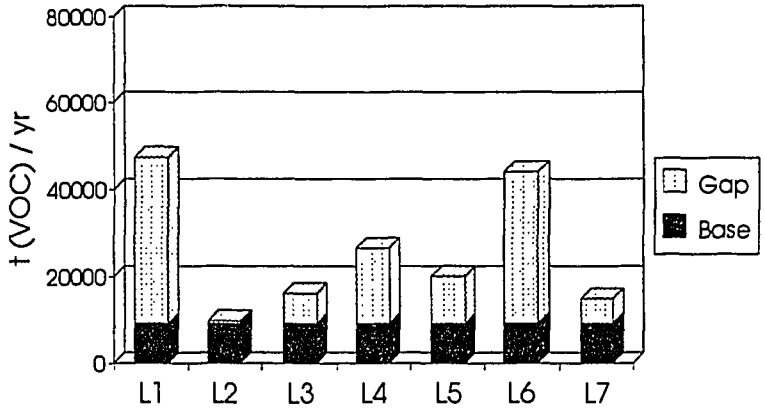

Figure 6.21 Total VOC emissions to air for the low-growth demand case and different supply mix options (year 2030).

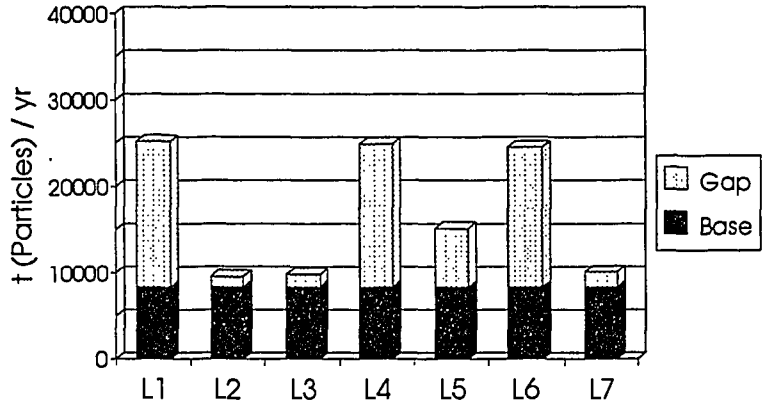

Figure 6.22 Total particle emissions to air for the low-growth demand case and different supply mix options (year 2030).

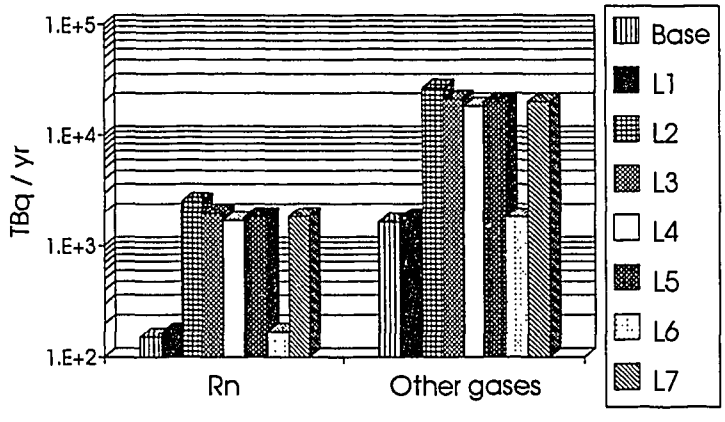

Figure 6.23 Emissions of radon and other radioactive gases to air from the base supply and the supply mix options (including the base) for the low-growth demand case (year 2030).

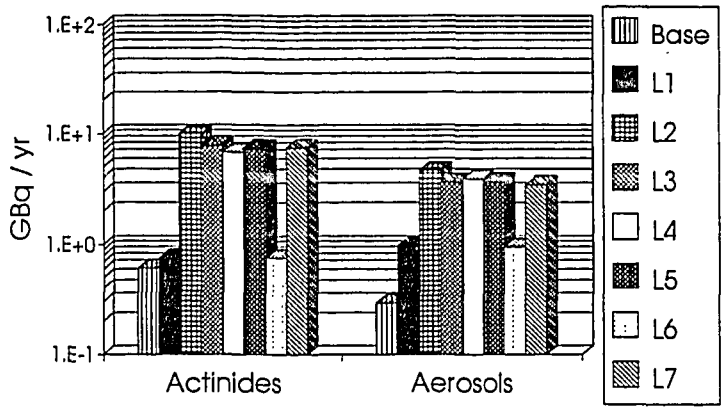

Figure 6.24 Emissions of radioactive actinides and aerosols to air from the base supply and the supply mix options (including the base) for the low-growth demand case (year 2030).

7. Conclusions and Suggestions for Further Developments

Chapters 4, 5 and 6 provide the detailed results concerning specific systems, systems comparisons and comparisons of supply mix options. These specific results will not be repeated here. The following observations summarise the insights from the present work.

- The feasibility of applying Life Cycle Analysis (LCA) to the electricity supply options for the future has been demonstrated. Clearly, any analysis of technology systems that might be implemented in the next 30 years is a subject to more serious limitations and larger uncertainties than a corresponding analysis of currently operating systems. In the detailed bottom-up analysis applied here the difficulties are numerous and concern, for example: scope (e.g. choice of the most representative systems), appropriate and balanced accounting for technological advancements, modelling of structural changes (e.g. electricity mixes, infrastructure, sources of fuel supply). In spite of these problems the LCA approach is attractive. In comparison with the traditional focus on the electricity generating plant itself it provides a much more complete picture of the emissions and residuals associated with the different options, and gives a more balanced perspective on the relative importance of the direct emissions from the power plant.

- The LCA approach is process-oriented with an explicit representation of all technologies of interest. The previous analyses of energy systems currently in operation (Frischknecht et al., 1994), combined with the information on the development trends, allowed to focus the present work on parts of the fuel cycles which are the most significant contributors to emissions and/or are being subject to major changes. These are:

Gas systems:	gas transport and power plant
Coal systems:	mining, coal transport and power plant
Nuclear systems:	mining/milling, enrichment, power plant, and reprocessing
Hydro systems:	power plant
Photovoltaic systems:	manufacturing of solar cells

- For the different fuel cycles the most important changes (in terms of the impact on the results of the present analysis) in relation to the existing analysis of currently operating systems are:

Gas systems:	reduction of gas leakage, improvements of power plant burner performance characteristics and of power plant efficiency.
Coal systems:	partial CH_4 recovery in underground mining, improvements in power plant abatement technology and of power plant efficiency.
Nuclear systems:	reductions of long-term radon emissions from mining/milling tailings, reductions of electricity consumption and CFC emissions in enrichment by replacement of diffusion by centrifuges or laser technologies, power plant improvements (particularly life time extension and increased burn-up), use of actual emissions from a modern reprocessing facility, reduced volume of radioactive solid wastes.
Hydro systems:	power plant efficiency improvements (turbine).
PV systems:	improvements in the manufacturing of m-Si and a-Si solar cells (yield, electricity consumption) and in cell efficiencies.

- The results of the analysis of future systems show that due to the advancements in power plant technologies, the relative importance of other steps in the fossil and nuclear fuel chains, as well as of the contributions from transportation and material production, significantly increases. This insight emphasises the role of the LCA approach. As expected, for all systems analysed the overall emissions of major pollutants are significantly reduced in the absolute sense.

- The overall analysis has a certain conservative bias. First, analysis of revolutionary technologies was beyond the scope of this work. Second, in cases where no reliable information on expected future developments was available and/or when the information was unreliable and/or when the overall impact of a particular contribution was low, mostly conservative data (frequently representative for the current situation) were selected; for photovoltaic systems, which represent a young technology, the performance parameters are however, somewhat more speculative than for the other systems. Third, no advancements in the processes for material production and in transportation have been credited. This is perhaps the most serious conservatism, although the assessed increased relative importance of these types of contributions is quite certain. Furthermore, with respect to the major pollutants that have been analysed, the "ranking" of the different systems is not believed to be distorted by this particular conservatism.

- As expected, fossil-based systems exhibit the largest emissions of combustion products. Among them, the chain associated with gas combined cycle plants is clearly the best performer. Use of oil as a fuel in this type of plant results in a quite dramatic increase of SO_x emissions from the power plant itself as well as from the associated oil chain, while emissions of such pollutants as CO_2 and NO_x increase to levels comparable with those from the hard coal fuel chain. Generally, the clearly dominant contributor to total GHG emission from fossil chains is the CO_2 released at the power plant. Considering the improvements of fossil power plant technologies, the relative importance of these plants as contributors to the total fuel chain emission of other combustion products decreases when compared with the present situation. As with current systems, hydropower exhibits the smallest emissions of combustion products, followed by nuclear and solar. The improvements in photovoltaic systems in relation to the performance of present commercially available technologies are assumed to be significant; of particular importance are the reduced electricity requirements in the cell manufacturing processes, leading to the corresponding reductions of "grey" emissions. The radioactive emissions are naturally highest for the nuclear fuel cycle; however, the relative contribution of the power plant is in this context very small.

- The results of the systems analyses are clearly reflected in the findings for the considered options. Options which include a significant share of fossil systems (either as a domestic source or as a source of imported electricity) lead to substantial increases of the emissions of combustion products in comparison with the current (1990) situation. Nuclear-based options are much more favourable in this respect. Substitution of a share of fossil fuels by photovoltaic leads to some reductions of pollution levels. With respect to emitted radioactivity the nuclear-based options exhibit LCA-results that are one order of magnitude higher than the ones associated with the other options.

In view of the limitations of the present analysis the following LCA-specific extensions are recommended for further research:

1. Overall and continuous database improvements, reflecting availability of new information and technology developments.

2. Scope extensions:

    - coverage of emissions to water, of solid wastes and land use for all systems;
    - consideration of possible further changes in the upstream steps of fossil chains;
    - consideration of some additional energy sources (e.g. wind, biomass) and technologies (e.g. fuel cells); inclusion of revolutionary processes (e.g. CO_2 storage);
    - analyses of additional scenarios.

3. Improvements of existing systems analyses, e.g.:

    - extension and enhancement of analysis of cogenerating systems, particularly CHPPs;
    - consideration of MOX fuel in the nuclear fuel cycle;
    - detailed treatment of solar cell manufacturing processes.

4. Consideration of future advancements in material production and transportation.

5. Further disaggregation of results for energy chains (direct versus grey emissions, Swiss-specific emissions versus emissions external to Switzerland).

6. Impact assessment according to environmental impact classes; possibly valuation of impacts.

The present report only addresses the basic two steps in LCA (goal definition and inventorisation). Apart from the LCA-specific scope extensions suggested under point 6 above (see also (Heijungs et al., 1992)), other activities within the Project GaBE "Ganzheitliche Betrachtung von Energiesystemen" — "Comprehensive Assessment of Energy Systems"* — aim to provide a multi-disciplinary perspective on the energy planning for Switzerland. This includes:

- Scenario-based simulation of environmental impacts (primarily for fossil systems)
- Health effects of normal operation
- Impacts associated with severe accidents
- Economic consequences of environmental policies
- Overall integration/decision support.

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* See for example (Hirschberg, 1995) for the overview of the current status and results of this project.

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List of Abbreviations

ABB	Asea Brown Boveri
ABWR	Advanced Boiling Water Reactor
AGR	Advanced Gas-Cooled (Nuclear) Reactor
AVLIS	Atomic Vapour Laser Isotope Separation
APWR	Advanced Pressurized Water Reactor
a-Si	Amorphous Silicon
BaP	Benzo(a)pyrene
BNFL	British Nuclear Fuels Limited
BUWAL	Bundesamt für Umwelt, Wald und Landschaft (Swiss Federal Office of Environment, Forests and Landscape)
BWR	Boiling Water Reactor
CANDU	Canadian Deuterium (Nuclear Reactor)
CC	Combined-Cycle Plant
CFC	Chloro-Fluoro-Carbon
CHPP	Combined Heat and Power Plant
DOE	US Department of Energy
EG-Si	Electronic Grade Silicium
EPR	European Pressurized Water Reactor
EPRI	Electric Power Research Institute (USA)
ETHZ	Eidgenössische Technische Hochschule Zürich (Swiss Federal Institute of Technology Zurich)
EVA	Ethyl-Vynil-Acetate
GaBE	Ganzheitliche Betrachtung von Energiesystemen (Comprehensive Assessment of Energy Systems)
GCC	Gas Combined-Cycle Plant
GE	General Electric
GHG	Greenhouse Gases
GT	Gas Turbine
GWP	Global Warming Potential (of greenhouse gases)
HCFC	Hydro-Chloro-Fluoro-Carbon
HDPE	Hochdruck-Polyethylen
HFC	Hydro-Fluoro-Carbon

IGCC	Fully Integrated Coal Gasification Combined Cycle plant
IPCC	Intergovernmental Panel on Climate Change
KKG/KKL	Kernkraftwerk (Nuclear Power Plant) Gösgen/Leibstadt
LCA	Life Cycle Analysis
LNG	Liquified Natural Gas
LWR	Light Water Reactor
MG-Si	Metallurgical Grade Silicium
MOX	Mixed-Oxides Fuel
m-Si	Monocrystalline Silicon
NGL	Natural Gas Liquids
NMVOC	Non Methane Volatile Organic Compounds
NPP	Nuclear Power Plant
PC	Pulverized Coal Combustion plant
PFBC	Pressurized Fluidized Bed Combustion plant
PIUS	Process Inherent Ultimate Safety (Nuclear Reactor, ABB Atom)
PSI	Paul Scherrer Institut
PV	Photovoltaic
PWR	Pressurized Water Reactor
SBWR	Simplified Boiling Water Reactor
SCR	Selective Catalytic Reduction (for NO_x)
SWU	Separative Work Unit
TCDD	Tetrachloro di-benzo-p-dioxins
THORP	Thermal Oxide Reprocessing Plant (BNFL, UK)
TSG-Si	Terrestrial Solar Grade Silicon
UCC	Union Carbide Company
UCPTE	Union pour la coordination de la production et du transport de l'électricité
VOC	Volatile Organic Compounds
VSE	Verband Schweizerischer Elektrizitätswerke (Swiss Association of Producers and Distributors of Electricity)
WS	Limestone Wet Scrubbing (for SO_x)

Appendices

Appendix A

Swiss and UCPTE Electricity Mixes in Year 1990 (Frischknecht et al., 1994).

Electricity Mix	Electricity Supply System	Share %
CH mix 1990	Hydro	56.7
	Nuclear (domestic)	41.2
	Oil	1.2
	Other [a]	0.9
UCPTE mix 1990	Lignite	10.5
	Hard coal	18.3
	Oil	9.6
	Gas [b]	9.5
	Nuclear	36.2
	Hydro	15.2
	Other [c]	0.7

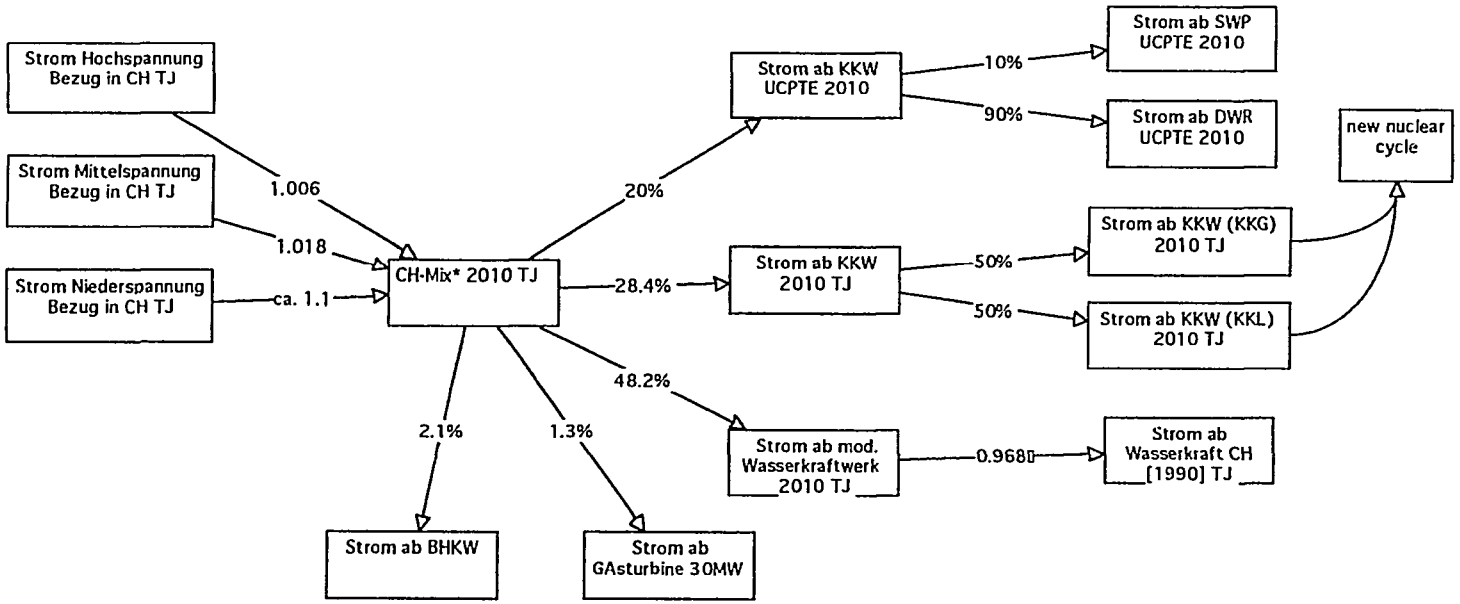
a Including combined heat and power plants, and incinerators.
b Fuelled with 84% natural gas, 8% coke gas, and 8% blast-furnace gas.
c Including geothermal, wind, tidal energy, wave energy, and solar.

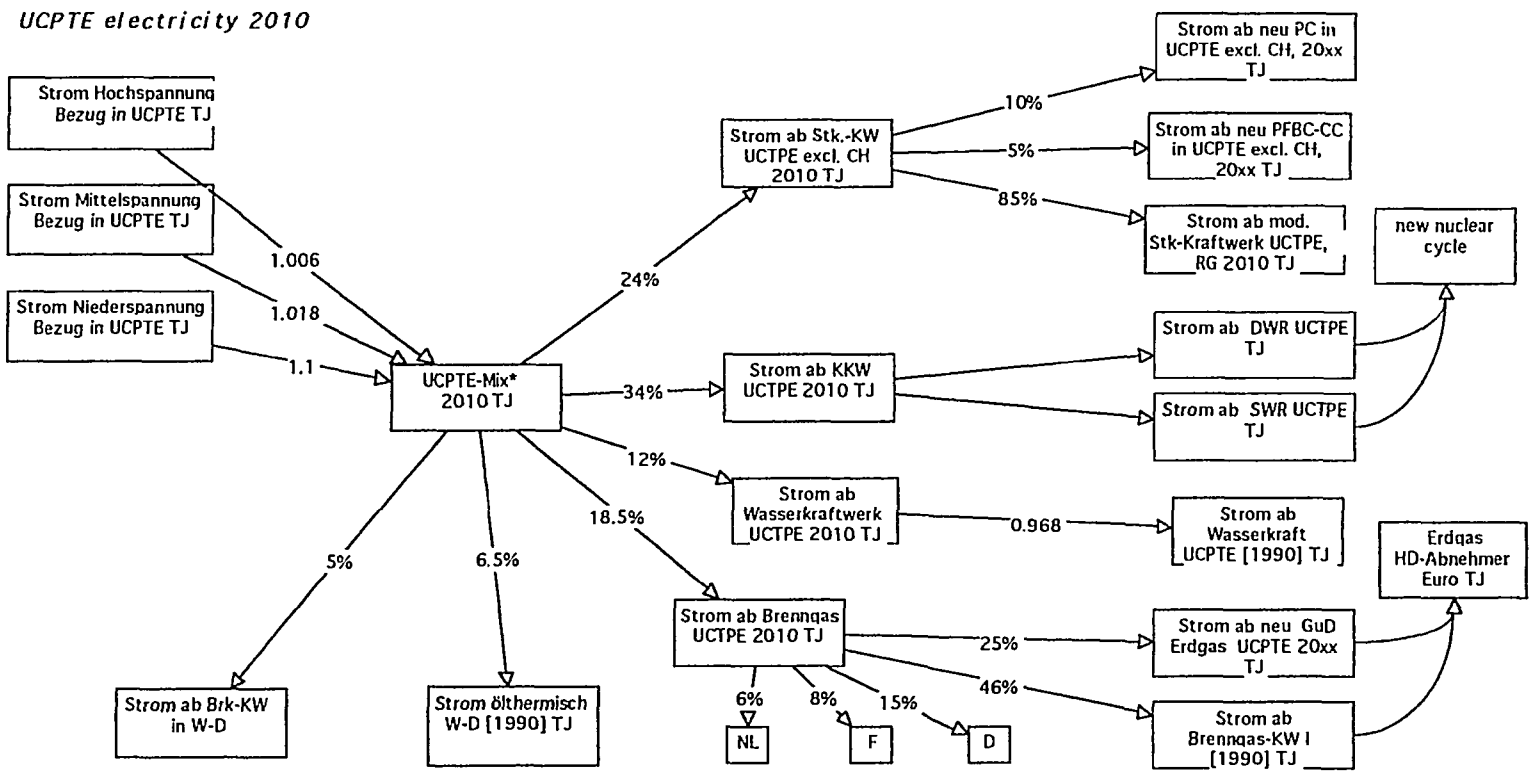
Appendix B

Structure used in ECOINVENT for the assumed electricity mixes for Switzerland and UCPTE in year 2010, for calculation of environmental inventories associated with the infrastructure*.

* The names of the modules are in German (original used in the database). The three modules in the upper left-hand side corner represent the high-, medium- and low-voltage Swiss/UCPTE grids. The factors shown in the arrows includes the losses (the factor would be 1 without losses). The other factors are the relative shares of the considered electricity systems as described in the report. In particular, the value for the module identifying the hydropower plants ("Strom ab Wasserkraft") corresponds to the reduction factor for the associated burdens indicated in Table 4.4.II for year 2030.

Swiss electricity 2010




UCPTE electricity 2010
Strom Hochspannung Bezug in UCPTE TJ
Strom Mittelspannung Bezug in UCPTE TJ
Strom Niederspannung Bezug in UCPTE TJ
1.006
1.018
1.1
UCPTE-Mix* 2010 TJ
24%
34%
12%
18.5%
5%
6.5%
Strom ab Stk.-KW UCTPE excl. CH 2010 TJ
Strom ab KKW UCTPE 2010 TJ
Strom ab Wasserkraftwerk UCTPE 2010 TJ
Strom ab Brennqas UCTPE 2010 TJ
Strom ab Brk-KW in W-D
Strom ölthermisch W-D [1990] TJ
10%
5%
85%
6%
8%
15%
NL
F
D
Strom ab neu PC in UCPTE excl. CH, 20xx TJ
Strom ab neu PFBC-CC in UCPTE excl. CH, 20xx TJ
Strom ab mod. Stk-Kraftwerk UCTPE, RG 2010 TJ
Strom ab DWR UCTPE TJ
Strom ab SWR UCTPE TJ
0.968
Strom ab Wasserkraft UCPTE [1990] TJ
25%
46%
Strom ab neu GuD Erdgas UCPTE 20xx TJ
Strom ab Brennqas-KW I [1990] TJ
new nuclear cycle
Erdqas HD-Abnehmer Euro TJ

Appendix C

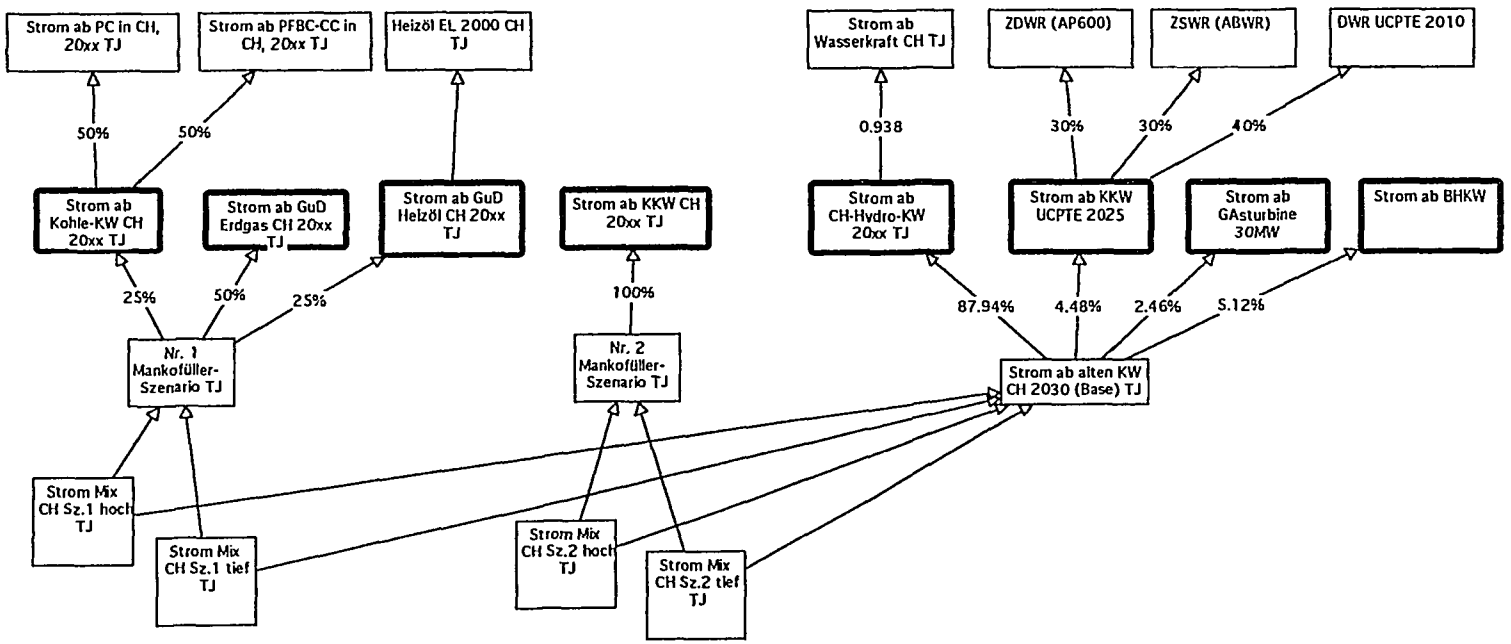
Structure used in ECOINVENT for the assumed electricity mixes for Switzerland and UCPTE for the deficit scenarios in year 2030*.

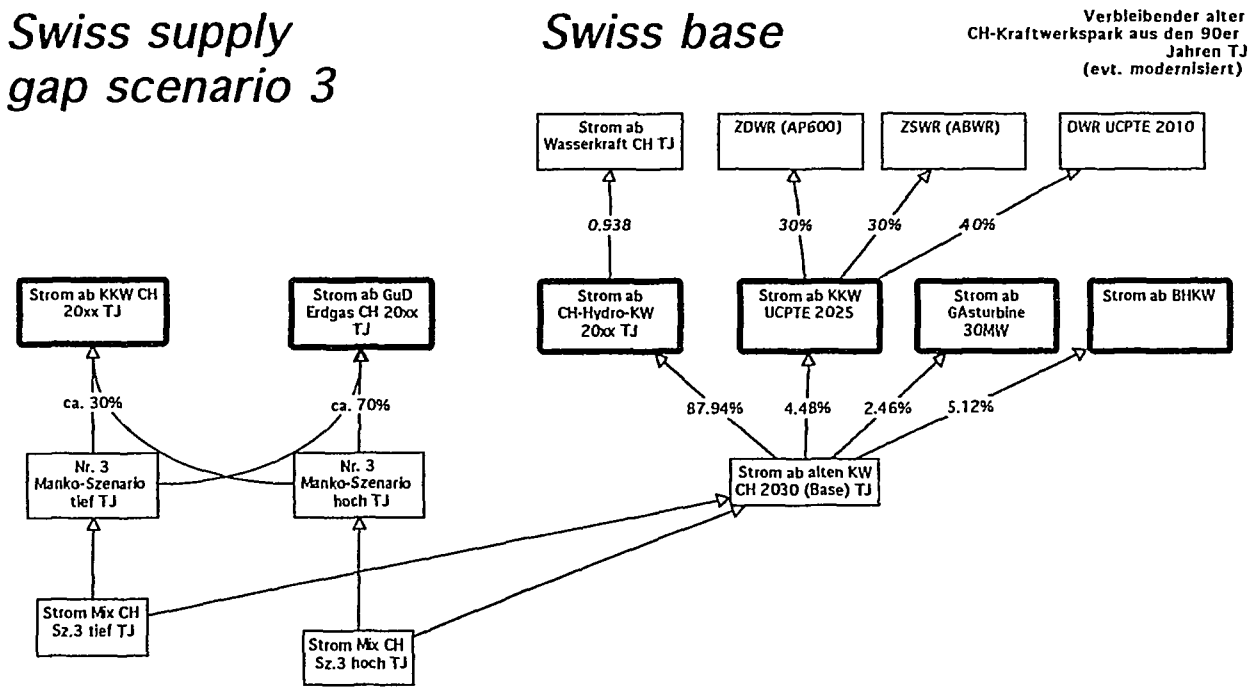
* The names of the modules are in German (original used in the database). The other factors are the relative shares of the considered electricity systems as described in the report. In particular, the value for the module identifying the hydropower plants ("Strom ab Wasserkraft") corresponds to the reduction factor for the associated burdens indicated in Table 4.4.II for year 2030.

Swiss supply gap scenario 1 & 2

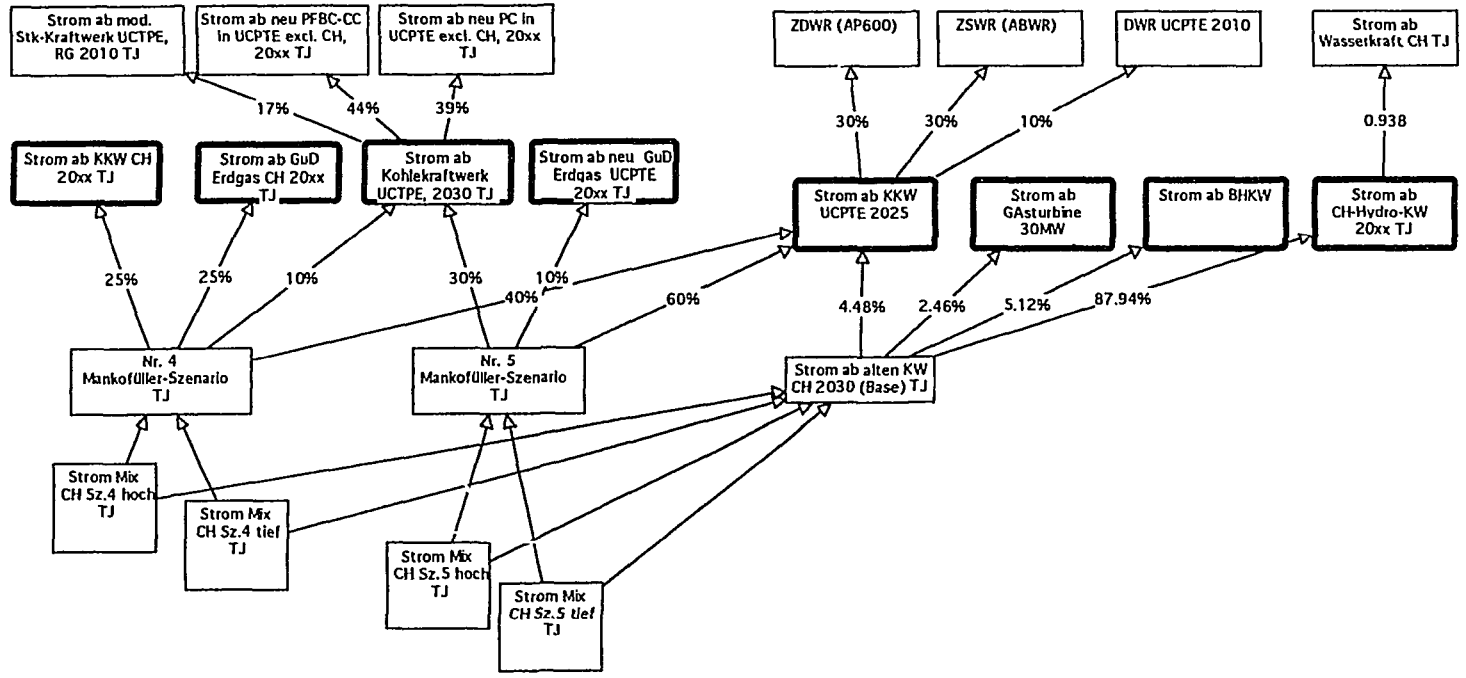
Swiss base

Verbleibender alter CH-Kraftwerkspark aus den 90er Jahren TJ (evt. modernisiert)



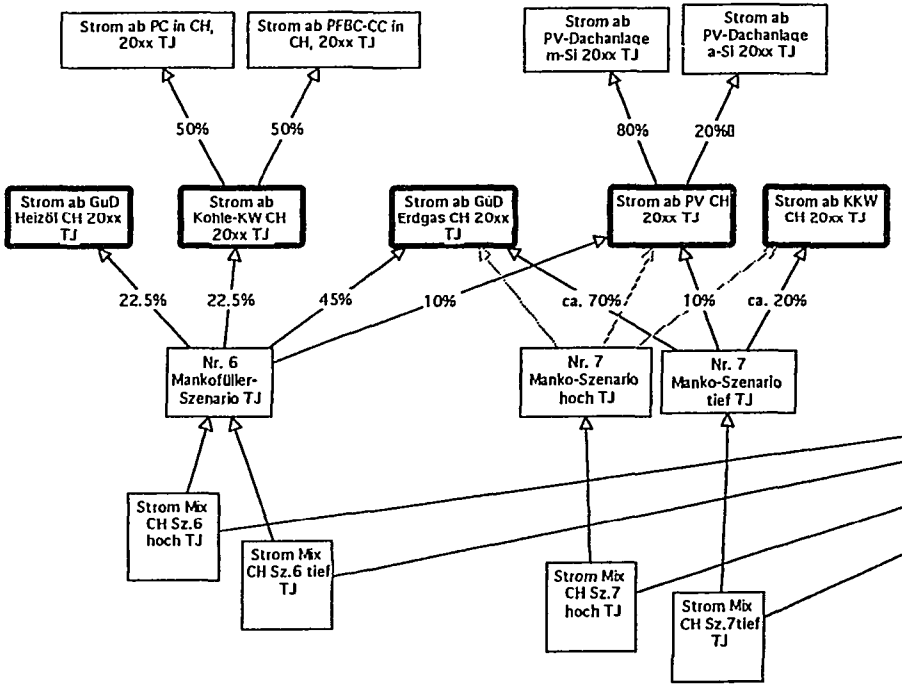

Swiss supply gap scenario 3
Swiss base
Verbleibender alter CH-Kraftwerkspark aus den 90er Jahren TJ (evt. modernisiert)
Strom ab Wasserkraft CH TJ
ZDWR (AP600)
ZSWR (ABWR)
DWR UCPTE 2010
0.938
30%
30%
40%
Strom ab KKW CH 20xx TJ
Strom ab GuD Erdgas CH 20xx TJ
Strom ab CH-Hydro-KW 20xx TJ
Strom ab KKW UCPTE 2025
Strom ab GAsturbine 30MW
Strom ab BHKW
ca. 30%
ca. 70%
87.94%
4.48%
2.46%
5.12%
Nr. 3 Manko-Szenario tief TJ
Nr. 3 Manko-Szenario hoch TJ
Strom ab alten KW CH 2030 (Base) TJ
Strom Mix CH Sz.3 tief TJ
Strom Mix CH Sz.3 hoch TJ

Swiss supply gap scenario 4 & 5

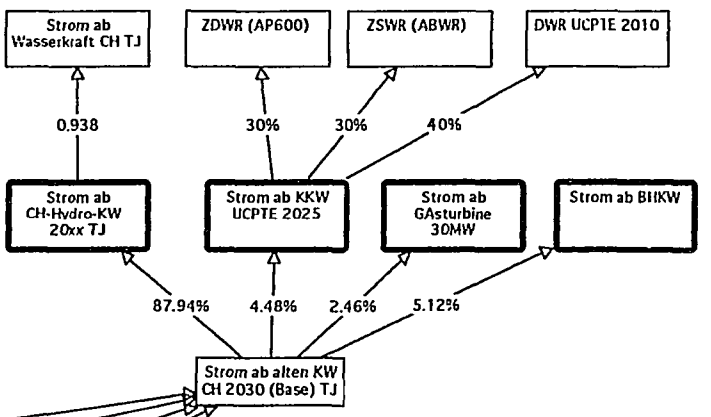


Swiss base

Swiss supply gap scenario 6 & 7



Swiss base



Appendix D

Selected Emissions to Air from Future Electricity Supply Systems included in VSE Supply Mix Options for Switzerland.

Pollutant / Group	Electricity System	PC	PFBC	CC (Oil)	CC (Gas)	GT 30MW	CHPP (1995)	Nuclear	Hydro	PV 3kWp m-Si	PV 3kWp a-Si
SO_x (kg/GWh)	direct from PP	216	34	421	3	4	5	0	0	0	0
	full chain	611	425	888	153	209	281	31	7	157	104
NO_x (kg/GWh)	direct from PP	360	68	209	119	414	186	0	0	0	0
	full chain	780	482	648	278	626	445	23	13	69	42
CO_2-equiv. ($t(CO_2\text{-eq.})/GWh$)	direct from PP	664	679	445	331	456	532	0	0	0	0
	full chain	762	771	551	392	540	679	6	4	44	28
CH_4[a] (kg/GWh)	direct from PP	7	7	6	18	32	216	0	0	0	0
	full chain	1612	1608	645	921	1275	3460	12	7	78	57
NMVOC (kg/GWh)	direct from PP	14.3	13.6	6.6	10.2	28	19.5	0	0	0	0
	full chain	148.6	143.4	1347.1	105.0	158.0	335.3	10.3	3.4	53.9	47.7
Particles (kg/GWh)	direct from PP	36	34	1	1	1	0	0	0	0	0
	full chain	1719	2103	221	88	119	207	46	229	164	0.164
Radioactivity[b] (GBq/GWh)	direct from PP	0.004	0.004	0	0	0	0	0.280	0	0	0
	full chain	14.6	14.6	7.6	1.3	1.8	3.3	1014.1	0.8	22.5	8.8

PP = Power Plant.

[a] CH_4 is also included in CO_2-equivalent.

[b] Total, obtained adding up the radioactive emissions without weighing factors.

Appendix E

Selected results for the Yearly Emissions to Air associated with the VSE-defined Options for Year 2030 (including Full Chains).

Pollutant / Group	Emissions from the Base Supply	Emissions from the Supply Mix Options							
		Analysed Demand Cases	① Fossil (D)	② Nuclear (D)	③ Nuclear & Gas (D)	④ Nuclear & Fossil 100% (I)	⑤ 50% Nuclear & Gas (D); 50% Nuclear & Fossil (I)	⑥ Fossil & Photovoltaic (D)	⑦ Nuclear & Gas & Photovoltaic (D)
SO_x (1000 t/yr)	1.1	high-growth	17.7	1.4	4.5	11.1	5.8	16.6	4.5
		low-growth	10.4	0.8	1.6	6.5	3.4	9.8	1.7
NO_x (1000 t/yr)	2.0	high-growth	20.4	1.0	7.5	11.1	6.4	18.8	6.6
		low-growth	12.0	0.6	2.2	6.5	3.8	11.1	1.9
CO_2-equiv. (Mt/yr)	2.0	high	24.2	0.3	10.0	12.0	7.2	22.2	8.5
		low	14.3	0.2	2.6	7.1	4.2	13.1	2.1
CH_4 [a] (1000 t/yr)	8.3	high-growth	49.2	0.5	23.5	26.9	16.4	45.3	20.0
		low-growth	29.0	0.3	6.0	15.9	9.7	26.7	4.8
NMVOC (1000 t/yr)	1.0	high-growth	15.4	0.5	2.9	2.4	1.8	13.7	2.6
		low-growth	9.1	0.3	0.9	1.4	1.1	8.1	0.8
Particles (1000 t/yr)	8.3	high-growth	28.7	2.1	3.2	28.3	11.7	27.6	3.5
		low-growth	16.9	1.2	1.5	16.7	6.9	16.3	1.8
Radioactivity [b] (1000 TBq/yr)	1.8	high-growth	0.3	46.9	21.2	30.5	33.8	0.3	21.3
		low-growth	0.2	27.6	21.2	18.0	19.9	0.2	20.0

D = domestic; I = imported [a] CH_4 is also included in CO_2-equivalent. [b] Total, obtained adding up the radioactive emissions without weighing factors.