# GREENHOUSE GAS EMISSION INVENTORY BASED ON FULL ENERGY CHAIN ANALYSIS

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**Abstract**

Methodology, characteristics, features and results obtained for greenhouse gases within the recent Swiss LCA study 'Environmental Life-Cycle Inventories of Energy Systems' are presented. The focus of the study is on existing average Full Energy Chains (FENCHs) in the electricity generation mixes in Europe and in Switzerland. The systems, including coal (hard coal and lignite), oil, natural gas, nuclear and hydro, are discussed one by one as well as part of the electricity mixes. Photovoltaic systems are covered separately since they are not included in the electricity mixes. A sensitivity analysis on methane leakage during long-range transport via pipeline is shown. Whilst within the current study emissions are not attributed to specific countries, the main sectors contributing to the total GHGs emissions calculated for the various FENCHs are specified.

## 1. INTRODUCTION

Detailed environmental inventories for major energy systems have been generated within a co-operation project of the Swiss Federal Institute of Technology (ETHZ) and the Paul Scherrer Institute (PSI). The aim of this work was to analyze environmental inventories of present energy systems in Europe using the Life-Cycle Assessment (LCA) methodology, and to develop a comprehensive database for applications by LCA practitioners in the industry and other fields, and for comparative assessment of energy systems to support the Swiss energy policy.

The work started in 1990 and involved approximately 14 persons-years. The final report was issued in March 1994 [1]. The resulting database contains detailed inventories of resource requirements and emissions for energy systems and energy products in use in Switzerland and in Western Europe. In particular, the European situation is described using average values applicable to UCPTE. The UCPTE (Union pour la coordination de la production et du transport de l'électricité) is the European association of electricity generating and transmission companies and includes Austria, Belgium, France, Germany, Greece, Italy, Luxembourg, the Netherlands, Portugal, Spain, Switzerland, and ex-Yugoslavia.

Table I describes the energy systems and relevant products considered in the study. The established LCA-based inventories form an important input to the ongoing Swiss multidisciplinary research project on 'Comprehensive Assessment of Energy Systems' (GaBE, from the German 'Ganzheitliche Betrachtung von Energiesystemen'),which covers health effects, environmental impacts and economic aspects associated with different energy systems [2]. The objective of this project is to develop, implement and use a comprehensive methodology for the consistent and detailed assessment of energy sources of interest under Swiss conditions and thereby provide scientific support to the decision-making process concerning future configuration of the Swiss energy system. Global Warming Potential associated with emission inventories is considered to be one of the important characteristics of the different energy chains and will to some extent affect these decisions. The present paper provides a detailed comparative assessment of Full-Energy-Chain (FENCH) Greenhouse Gas (GHG) inventories for major electricity generation systems; the corresponding comparison of heating systems is under way and will be reported in the near future. Overall comparison of LCA-based inventories has recently been reported [3].

TABLE I. ENERGY SYSTEMS AND RELEVANT PRODUCTS CONSIDERED IN THIS STUDY

| 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 pressurized 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 are treated separately from other electricity generating systems since they contribute only marginally to the present electricity mixes.

## 2. METHODOLOGY

Full-energy-chains (FENCHs) are considered in the study; their scope ranges from exploration and extraction of energy resources through processing and their final use, to dismantling of infrastructures and disposal of waste. The environmental inventories were developed for average existing systems, using 1990 as the reference year. The main features of the study are described in the following. Inventories have been developed for different energy products and systems. The inventories include energy and non-energy related resource depletion categories (approximately fifty). They also include land depreciation, waste heat, gaseous and liquid emissions (more than 200), and solid waste. The inventories of greenhouse gases constitute only one important sub-set of the emissions considered.

Resource depletion and emissions are given in physical units without further valuation or aggregation. Resource depletion and emission factors have been categorized at the most detailed and disaggregated level possible (i.e. single chemical substances). Nevertheless, when only aggregated information was available (i.e. classes of substances), it was included as such in the study. To avoid double counting, each data point for resource depletion or emission is counted either as a single substance (or environmental intervention, if applicable), or as part of an emission category (or an environmental category). In particular, gaseous emissions by transportation systems have been considered separately from emissions originating from other diffused sources and from stacks. This allows the separation of the contribution from transport systems from the total calculated for the whole systems.

Each energy system has been subdivided into several processes. Each process is in turn characterized by its product (e.g., electricity in the case of a power plant), and has been described with one module which includes the energy and non-energy resource requirements, material requirements, transport needs, requirements of products from other processes, and emissions to air and water as well as solid waste, all normalized by the unit product. Approximately 500 sub-processes have been developed, of which about 100 are strongly interconnected and 400 have few linkages. A bottom-up process chain methodology was used for the calculation of the energy and material balances for these systems and products. Therefore, all possible interactions between the various parts of different energy systems were considered (e.g., mining of coal has also an input of electricity from coal power plants).

The following energy resources are considered: gas from combined oil and gas fields; natural gas; gas from coal mines; crude oil; lignite and hard coal in their natural state; natural uranium in uranium ore; potential energy of water; wood from forests. All processes are described on a "cradle-to-grave" basis. All stages in the life of each step of an energy system have been included: construction, operation and maintenance, and dismantling. Infrastructures, downstream processes, and production of materials are covered, highlighting the requirements of natural resources and energy.

A set of standards was established for the definition of systems boundaries to achieve a high level of consistency and detail throughout the energy systems. In particular, service modules for material production, transportation, construction and disposal services have been developed in order to be uniformly used by all energy systems. Data for these service modules were taken from literature, dating as far back as the early 80s, mainly from German and Swiss sources; however, it was also necessary to use a vast array of references from other west European countries.

Materials used in large amounts in energy systems (concrete, steel, aluminum) and materials with associated highly toxic emissions during their production, use and disposal (e.g. platinum) were analyzed with greater accuracy than ones used in lesser amounts. The service modules are simpler than the modules describing the main processes in the energy chains. Road transportation systems (trucks and cars), average rail transportation systems for west-European conditions, inland waterway and sea transportation systems (ships and tankers) are considered. To avoid arbitrariness, a set of standard transportation distances was defined for most important materials. The load factor for road and rail transportation is set at an average of 50%. Construction and materials for road and rail infrastructures are included. It is shown that road and rail infrastructures account for an important share of the environmental impact of transportation. A set of disposal systems was defined, including sanitary landfills, chemical landfills, industrial and communal incinerators. Also the requirements of energy products for all the considered processes are consistently treated throughout the study by using specifically developed modules.
Thus, the boundaries of the systems are defined by the steps of the energy chains, by the stages in the life cycle of the facilities and by the common modules describing supply of services and material production.

Details on system boundaries and allocation criteria for multi-input and multi-output processes are explicitly mentioned in the report for each energy system. Energy and material inputs to the processes are followed upstream regardless of geographic or political boundaries, up to the extraction of resources from the environment. The effluents are followed downstream to the final point of emission into the environment. The above means that also liquid and solid waste treatment, as well as other downstream processes are included in the analysis. The calculation of the energy chains is made from the perspective of both the average Swiss and European final uses. At the stage of final use, typical modern heating systems available on the Swiss and European markets were considered, but no specification has been given for heating systems installed in specific regions. Iterative loops are established among systems due to the tree structures defined by the complex interconnections of the modules describing the various processes. All electricity requirements outside Switzerland are inventoried using the average UCPTE electricity mix.

A static approach is used in the study: requirements/emissions are considered to be independent of the time. In particular, it has been assumed that material production occurs entirely at present. For example, dams built decades ago but still in operation are accounted with concrete produced now and today's energy-mix; the materials and the energy used for the final repositories of conditioned nuclear waste are supposed to have the characteristics of the current ones, even if these facilities have not been yet built and will be in operation for many decades.

Multi-output processes are included in many energy systems (e.g., cogeneration of heat and electricity; combined production of oil and gas on offshore platforms). Therefore, criteria for the allocation of environmental burdens to the different products had to be defined. Explicit allocation criteria based on the physical properties of the products are always applied instead of 'credits' based on some reference system. In most cases a criterion based on the heating value of the products is used, but criteria based on mass, weight, and exergy were also defined in some cases. No additional credits were given to systems producing recycling materials.

The system of equations describing the balances of resources and emissions is solved using an algorithm based on the algebraic inversion of the input/output matrix that represents the interconnected subsystems. With this first step, the total cumulated inputs to the systems are calculated (sum of the first order, second order, third order, etc. contributions from all processes associated with a specific energy system). Final step is the calculation of the total cumulated emissions and total cumulated resource depletion by multiplying the inverted matrix with the matrix of the environmental interventions at the process level. A CONVEX computer was used to perform the calculation.

## 3. ELECTRICITY SYSTEMS

In the following sub-sections, the analyzed chains for electricity generation are briefly described. Data for the following GHGs has been collected: carbon dioxide, methane, CFCs, $N_2O$, etc. However, the paper presents mainly results obtained for $CO_2$ and $CH_4$ emissions because the contribution from the other species to the total $CO_2$-equivalent is generally very small. The $CO_2$-equivalent used is based on the IPCC 1992 global warming potentials (GWP) relative to carbon dioxide with 100 year time horizon [4]. $CO_2$ and $CH_4$ are shown separately as well as in terms of $CO_2$-equivalent. In particular, the calculated $N_2O$ emissions $GWP_{100}$ are on the average one order of magnitude lower than $CH_4$ $GWP_{100}$ (with exception of lignite). CFCs are practically not emitted by the energy systems analyzed.

### 3.1. Fossil systems

Existing conventional technologies for fossil systems have been analyzed. Systems under development such as atmospheric/pressurized fluidized-bed combustion of coal, coal gasification combined cycle, magnetohydrodynamic systems, etc., have not been included in the study.

#### *3.1.1. Coal systems*

Raw lignite, pulverized lignite, and briquettes are the energy carriers described for the first group. On the level of final use, typical power plants burning lignite in Austria, Spain, ex-Yugoslavia, France, Greece, Italy and Western Germany are described. The average UCPTE mix of lignite power plants is then constructed on the basis of the contributions of each country to the total electricity generation by lignite. Heat produced in residential stove-heaters using lignite briquettes is also analyzed.

Within the hard coal group, results are presented for typical coals mined in Europe and coals imported to Switzerland and Europe from overseas. Production of coke is analyzed separately from production of briquette. On the level of final use, typical power plants firing hard coal in Austria, Belgium, Spain, ex-Yugoslavia, France, Italy, The Netherlands, Portugal andWest Germany are described and used to calculate the average UCPTE mix of hard coal power plants. Heat from residential boilers using briquettes, coke and hard coal is included. Results for industrial boilers in the range 1-10 MW are given.

For lignite and hard coal Tables II and III show the methane emissions associated with underground and open pit mining in the countries supplying coal to UCPTE. On the average, the methane emitted in the mining of hard coal is two orders of magnitude greater than in lignite mining.

TABLE II. METHANE EMISSIONS FROM UNDERGROUND AND SURFACE MINING OF LIGNITE FOR SUPPLY TO UCPTE

| Countries | Soft lignite | | Lignite | | Average $CH_4$ emission ($m^3$/tonne) |
|---|---|---|---|---|---|
| | Production (Mtonne/a) | $CH_4$ from mining ($m^3$/tonne) | Production (Mtonne/a) | $CH_4$ from mining ($m^3$/tonne) | |
| West Germany | 112 | 0.02 | - | - | 0.02 |
| Greece | 54 | 0.02 | - | - | 0.02 |
| former Yugoslavia | 43.7 | 0.2 | 9 | 2.28 | 0.55 |
| Spain | 14.5 | 0.2 | 5.1 | 2.28 | 0.74 |
| Austria | 2.1 | 0.2 | - | - | 0.2 |
| Total | 228.3 | - | 14.1 | - | - |
| Average UCPTE | - | 0.068 | - | 2.28 | 0.2 |

### *3.1.2. Oil systems*

All steps in the production and use of crude oil and oil products are described: exploration, production, transportation, refining, regional distribution, and final use. Resources and emissions to be ascribed to electricity from oil power plants, to heat from residential and industrial boilers (systems with capacities from 10 kW to greater than 5 MW), and to various oil products for energy and non-energy use have been analyzed, for both average Swiss and UCPTE conditions. The emissions associated to the production of petrol (leaded and unleaded) are substantially higher than those of diesel fuel, due to the higher energy needs for refining compared to other sub-processes of the oil chain. For most oil products, the long-distance transportation of crude oil and oil products contributes considerably to the total emissions.

### *3.1.3. Natural gas systems*

Typical natural gas systems for average Swiss and European end uses are analyzed. No gas fired power plant exists in Switzerland. Various energy chains are described depending on the origin of the natural gas, namely gas from Germany, from the Netherlands, from Norway, from the Russian Federation, and from Algeria. Because about 15% of the gas is produced in combination with oil, it was necessary to define allocation criteria. Onshore gas production has been treated separately from offshore production, and high-sulphur gas separately from low-sulphur gas. High-sulphur gas must be treated before combustion, leading to higher sulphur

TABLE III. METHANE EMISSIONS FROM UNDERGROUND AND SURFACE MINING OF HARD COAL FOR SUPPLY TO UCPTE

| Countries | Surface mining | | Underground mining | | Surface/ underground | Average $CH_4$ emission |
|---|---|---|---|---|---|---|
| | Share of total (%) | $CH_4$ emission ($m^3$/tonne) | Share of total (%) | $CH_4$ emission ($m^3$/tonne) | (%) | ($m^3$/tonne) |
| Australia | 17.6 | 2 | 2.6 | 10 | 71/29 | 4.3 |
| Belgium | - | - | 1.5 | 25 | 0/100 | 25.0 |
| Canada | 4.4 | 1.7 | - | - | 100/0 | 1.7 |
| China | 0.5 | 2 | 1.5 | 25 | 11/89 | 22.5 |
| Columbia | 10.8 | 3 | - | - | 100/0 | 3 |
| former Czechoslovakia | - | - | 2 | 26 | 0/100 | 26 |
| France | 3 | 2 | 6.1 | 25 | 15/85 | 21.5 |
| Germany | - | - | 48.4 | 25 | 0/100 | 25 |
| Poland | - | - | 4.5 | 5.7 | 0/100 | 5.7 |
| Russia | 5 | 1.7 | 2.7 | 21 | 40/60 | 13.2 |
| South Africa | 18.3 | 2 | 10 | 9 | 40/60 | 6.2 |
| Spain | 3.8 | 2 | 7.8 | 12.5 | 15/85 | 10.9 |
| U.K. | 0.4 | 0.5 | 0.7 | 19 | 17/83 | 15.8 |
| U.S.A. | 36.4 | 1.54 | 12.2 | 17 | 52/48 | 8.9 |
| Total | 100 | - | 100 | - | - | - |
| Average Europe | - | 2 | - | 23.5 | 2.3/97.7 | 23.0 |
| Average UCPTE | - | 1.9 | - | 20.1 | 27/73 | 15.2 |

dioxide emissions and higher energy consumption, with associated GHGs. Gas transportation via pipeline over long distances (typically more than 1000 km) has an important influence on some of the total cumulated emission factors (e.g. methane and nitrogen oxides). The available data for gas production and transportation in the Russian Federation should be considered highly uncertain. Gas leakage in the order of 2% of the delivered gas was assumed for gas of Russian origin. For local gas distribution grids in Switzerland, an average of 0.9% leakage was considered realistic. These assumptions lead to total gas leakage in the order of 1% for industrial consumers and of 1.9% for residential consumers. For the calculation of the emissions associated with the average UCPTE gas systems for electricity generation, the gas is assumed to be made of 84% natural gas, 8% coke gas, and 8% blast-furnace gas. The contribution from gases other than natural gas increases some of the emission factors, especially $CO_2$. Gas power plants are generally used to cover peak demands of electricity, leading to relatively low load factors. On the other hand, the energy-specific material use is lower than other fossil systems because of the limited extent of flue gas treatment, and the reduced need for cooling devices and chemicals. Of the fossil systems, the natural gas FENCH has the lowest total electricity consumption, i.e. approximately 1% versus 3% for the oil chain, 4% for the lignite chain and 4.5% for the hard coal chain. This fact also influences the total cumulated emissions, including GHGs.

### 3.2. Nuclear systems

The analysis is based primarily on the Swiss nuclear power plants and the associated energy chain. Boiling water reactors (BWR) have been treated separately from pressurized water reactors (PWR), using for reference respectively the Leibstadt (General Electric Mark III) and the Gösgen (Siemens) power plants, both of the 1000 MW(e) size. A once-through nuclear full energy chain (or open cycle) was assumed, including mining (underground and open pit), milling, conversion, enrichment (gaseous diffusion and centrifuge), fuel fabrication, power plant, reprocessing, intermediate storage of radioactive waste, final disposal of conditioned solid waste in deep repositories (high and low/medium radioactive level), and shallow land disposal of low level radioactive waste. All spent fuel is assumed to be reprocessed. The separated fissile material is not re-introduced in the described chain into mixed-oxide fuel. The potential energy that can be extracted from mixed oxide fuel has not been considered in the present assessment.

Operational data for the selected Swiss power plants were available. The assumed average burnup values were 35 000 and 39 000 MWd/tU for Swiss and UCPTE BWRs respectively; 42 000 and 40 000 MWd/tU for Swiss and UCPTE PWRs respectively. All steps of back-end processes are considered in spite of the fact that the repositories do not yet exist, in order to calculate a complete nuclear energy chain. In particular, data from the planning studies for the two Swiss final repositories are used. For the remaining steps of the nuclear chain, data were mostly extracted from literature published in the 80s, especially of US origin. For the enrichment step it is assumed that all nuclear power plants in UCPTE countries, including Switzerland, are supplied by the diffusion plant Eurodif in Tricastin, France (about 90% of the total), and by the three URENCO gas centrifuge plants in Germany, Great Britain and the Netherlands (about 10% of the total). For the highly energy-intensive gaseous diffusion process it is assumed that the electricity is delivered by PWRs, consistently with the real case in Tricastin. Data from the Swiss power plants are extrapolated to UCPTE plants using the average load factors, burnups and enrichments valid for major part of the European BWRs and PWRs. Data collected for the nuclear chain associated with the Swiss power plants are transferred to describe the average UCPTE situation by modifying the enrichment of the fuel and the shares of gaseous diffusion and centrifuge in the enrichment step.

### 3.3. Renewable energy systems

#### *3.3.1. Hydroelectric systems*

Hydropower plants typical for Switzerland and the Alpine region are described. The average hydropower systems in UCPTE countries were derived by extrapolation of the Swiss data. Hydro electric dams, run-of-river plants and pumped storage plants are treated separately. Hydro electric dams and run-of-river plants contribute about 50% each in the Swiss as well as in the UCPTE hydro mixes for electricity generation. For these systems the following are estimated: concrete, steel, consumption of explosives, energy needs for construction, land use, capacity of water reservoirs and useful water volumes for energy conversion. The total calculated environmental interventions largely derive from the consumption of cement and steel as well as diesel oil used in construction machinery (cranes, bulldozers, trucks, etc.).

#### *3.3.2. Photovoltaic energy systems*

Many photovoltaic systems are considered, covering monocrystalline and polycrystalline cell technologies. The systems include building-integrated 3 kW units for use in the residential and commercial sectors for distributed applications on roofs and facades, and larger power plants concentrated at a site, specifically a 100 kW plant installed on the guard-rails of a Swiss highway and the PHALK 500 kW pilot power plant in operation in the Swiss Jura mountains since 1992. The postulated operational lifetime of all systems is 30 years. For the calculation of the 3 kW systems a relatively good site in Switzerland with associated yield of 3.6 GJ(e)/a is assumed. However, the analysis of the larger facilities is plant and location specific and should not be used directly for different sites and conditions. Monocrystalline and polycrystalline cells and modules are analyzed separately, mostly based on German production data (Japanese and US production data are also used). The photovoltaic systems are calculated both for the use of monocrystalline and polycrystalline cells. A sensitivity calculation shows the effect of technological improvements and increased production efficiencies achievable in the near future (1995).

### 3.3.3. *Other renewables energy systems*

Other systems based on renewable sources have been analyzed in the study, but they do not include electricity conversion. These are here shortly described for completeness.

- Energy from biomass (wood). Heating systems with boilers in the range 30-300 kW(th) burning wood harvested from natural forests typical of the Swiss Alpine region (beech and pine) have been analyzed, considering separately briquettes from chips. The whole chain from the natural growth of the trees to the burning in the boiler is covered and includes cutting, transportation, disposal of ashes in communal incinerators, etc. Fixation of carbon during the growth of trees is included in the calculation of $CO_2$ emission factors. It is assumed that pine wood chips are produced as a by-product of saw-mills, thus energy production from this type of wood is not charged with the emissions from the steps related to the production of chips. The results show that forest operations and end use in boilers dominate the cumulated emissions.

- Small scale geothermal energy systems. A typical low-temperature system for small scale residential use (a single dwelling-house) was analyzed. It consists of an earth probe, a heat-pump and a heat distribution system.

- Solar thermal energy systems. Different types of solar collectors for the production of warm water in the residential sector (single dwelling and multiple dwelling houses) were analyzed in the study. All systems are equipped with an additional electric boiler to compensate for insufficient production during periods of reduced solar radiation. Two approaches are considered: in the first case the environmental burden for producing, operating and disposing the collector is related only to the heat produced by the collector; in the second case the total environmental burden of heat and electricity generation is related to the total heat output of the hybrid system.

## 4. RESULTS

### 4.1. FENCHs for electricity generation

The results obtained by linking all processes are described in this section. Origin of the various contributions to the total GHGs emissions is discussed. In particular, the shares of the steps within energy chains as well as shares from various sectors are given. As discussed, the cumulated environmental inventories have been calculated independently of geographical boundaries. Consequently, the exact shares of emissions in Switzerland and external to Switzerland are not provided here. Where feasible, an estimate of the shares is given; the same applies to the UCPTE case.

Figures 1-8 show the share of the various steps in the energy chains and of the different LCA-sectors to the total $CO_2$ and $CH_4$ emissions in the coal, oil and nuclear chains in UCPTE. The shares are normalized by the electricity at power plant busbar. The contribution of different LCA-sectors is calculated by considering the direct inputs into the main process steps in the energy chains. For example, all contributions related to the materials flowing into the step 'Refinery' in the oil cycle are attributed to the sector 'Materials' at the step 'Refinery'. On the x-axis the LCA-sectors are shown. On the y-axis the main process steps in the energy chains are listed. The far-right columns on the x-axis show the summation of all LCA-sectors for each step. The rear-most columns correspond to the total values for each LCA-sector. The cumulated emission per unit of electricity produced is the rear-most, far-right column.

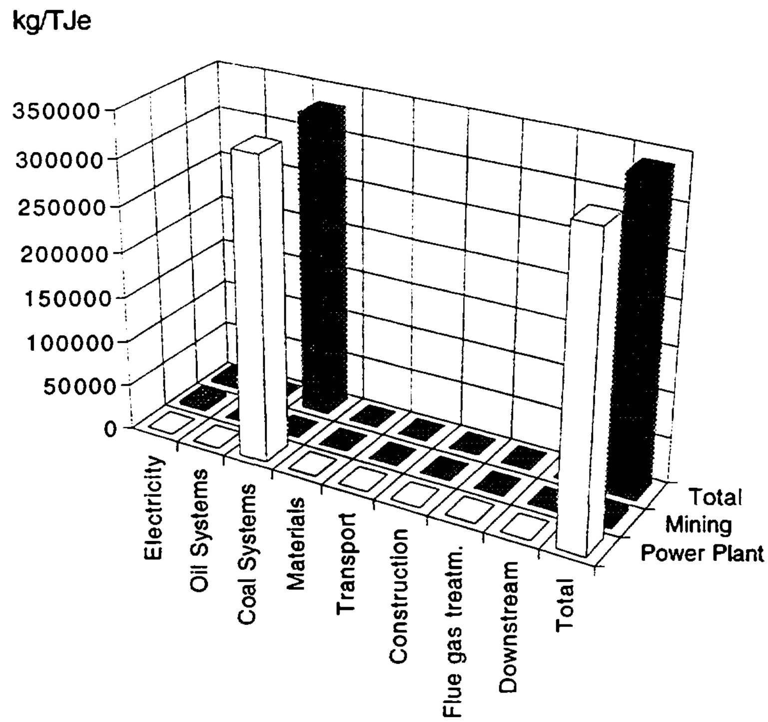



*Fig. 1. $CO_2$ emissions from lignite FENCH relevant to power plants in West-Germany.*

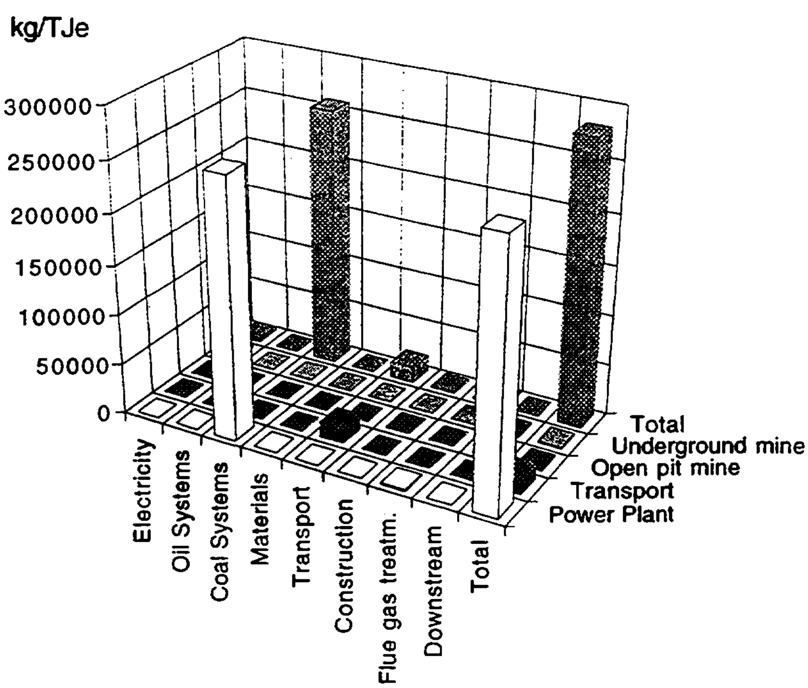



*Fig. 2. $CO_2$ emissions from hard coal FENCH relevant to power plants in West-Germany (imported coal).*

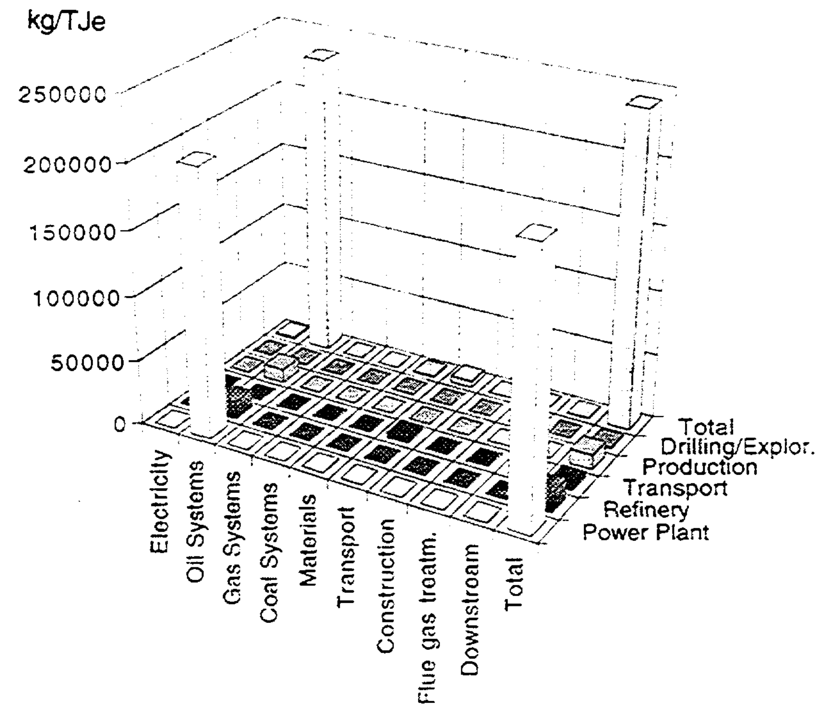



*Fig. 3. $CO_2$ emissions from oil FENCH in UCPTE.*

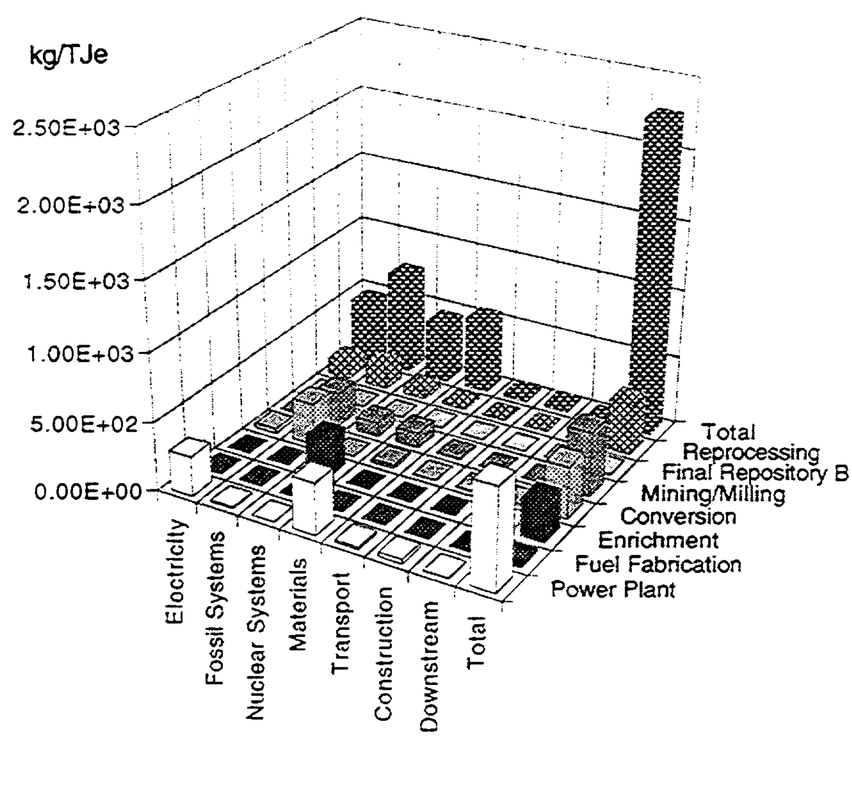



*Fig. 4. $CO_2$ emissions from nuclear FENCH in UCPTE.*

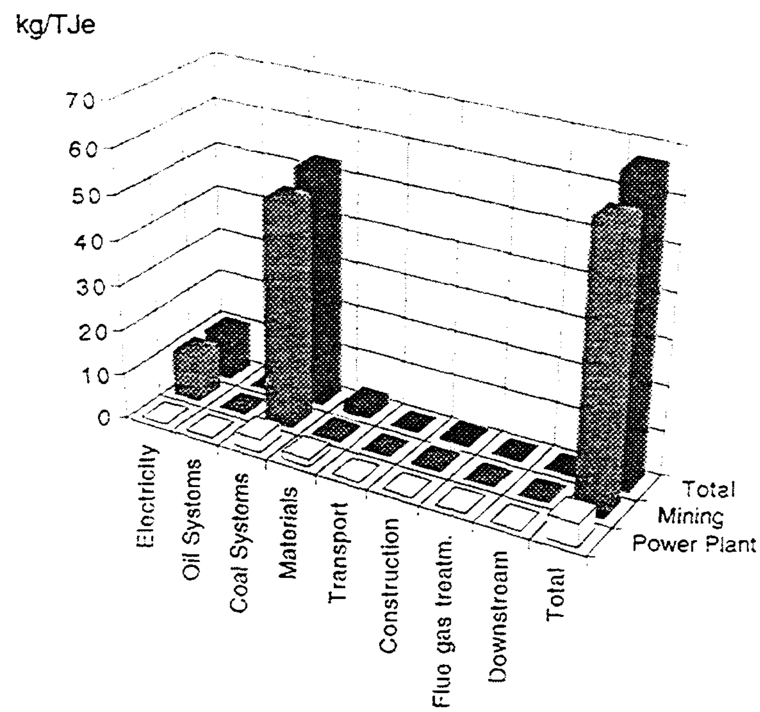



*Fig. 5. $CH_4$ emissions from lignite FENCH relevant to power plants in West-Germany.*

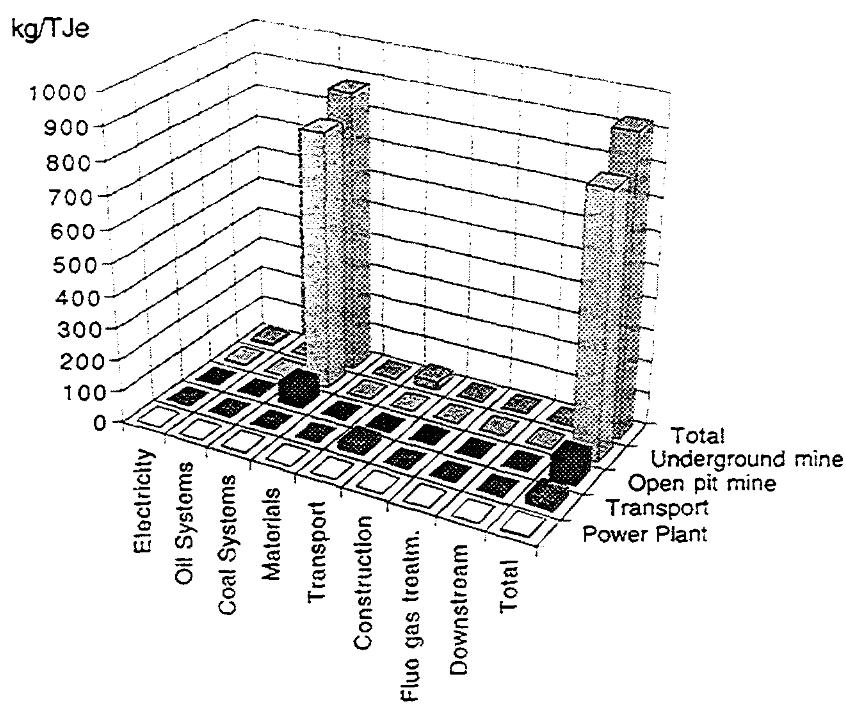



*Fig. 6. $CH_4$ emissions from hard coal FENCH relevant to power plants in West-Germany (imported coal).*

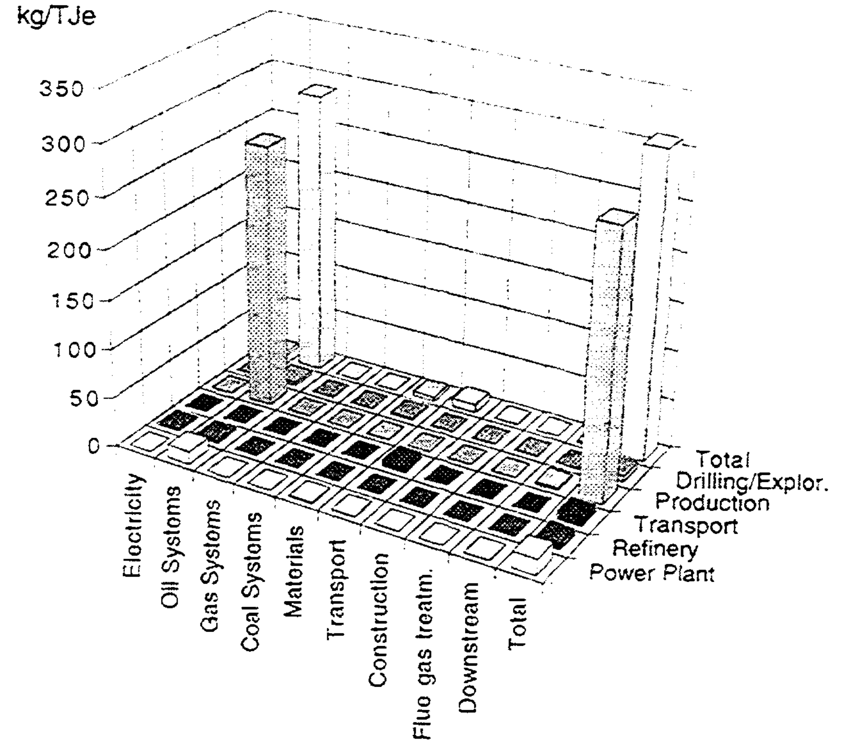



*Fig. 7. $CH_4$ emissions from oil FENCH in UCPTE.*

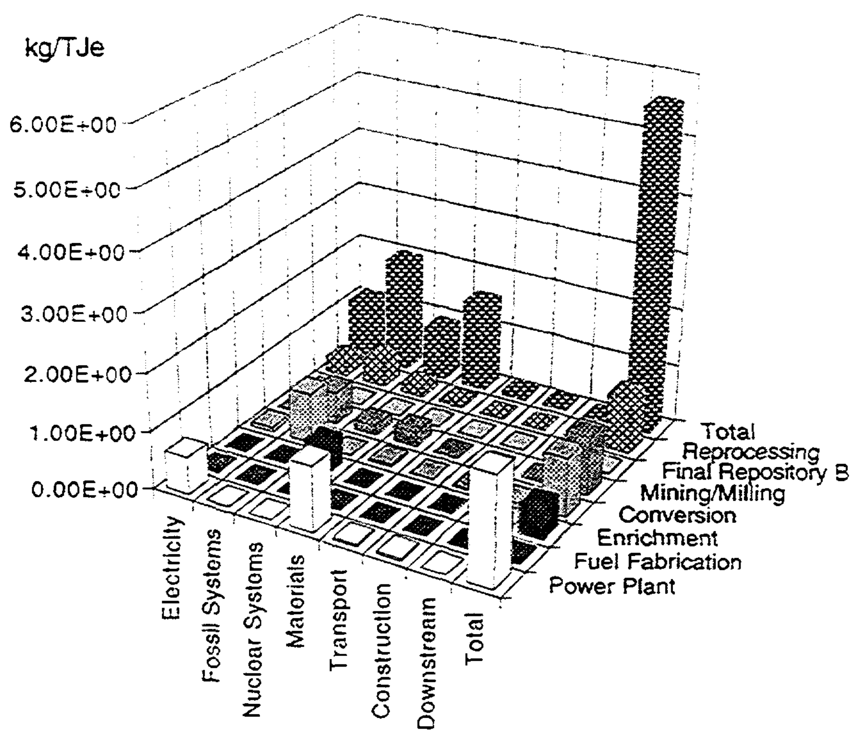



*Fig. 8. $CH_4$ emissions from nuclear FENCH in UCPTE.*

For fossil fuel FENCHs the greatest part of emitted $CO_2$ is from combustion in power plants, as expected, but contributions from the other steps of the chains, from material production and transport are not negligible. Most of the methane is released during mining of hard coal (especially underground), production of oil, and transportation and distribution of natural gas via pipelines. The contribution of fossil systems to specific GHGs emissions are mostly dependent on the efficiency of the technologies and on the fuel qualities.

Since no coal power plant exists in Switzerland, only results for UCPTE plants are given. The figures show the result obtained for West German coal power plants. An interesting result of the study is the estimation of the environmental burden of process steps in the coal energy chains other than final use; this burden was often underestimated in the past. In particular, the international long-distance transport of hard coal contributes considerably to the overall emissions. In the case of $CO_2$ transport is the second contributor, with a few percent of the total, because of the long-distance transportation from the USA, South Africa and Australia to Europe; for methane, the percentage of transport is lower.

Results obtained for coal products and coal use are generally somewhat higher than in previous studies. This can be explained by considering that i) a larger number of relevant sub-systems and material inputs was included, ii) iterative interactions between energy systems were thoroughly considered, and iii) plants equipped with outdated technologies and burning low-quality coal were included in the average European mix of coal power plants.

In the oil FENCH the power plant produces the greatest part of $CO_2$ (about 93% of the total). Instead, emissions of $CH_4$ occur most in the production phase (approximately 90% of the total) due to flaring and leakages, with small contributions from other steps of the chain. It is interesting to note that the refining step contributes the most to the total air emission of pollutants. The refining step contributes roughly 6% of cumulated $CO_2$ emission (a relatively low value compared to earlier studies), and the production step 5%.

The operation of a nuclear power plant does not generate carbon dioxide. The $CO_2$ emissions that may be attributed to the nuclear full energy chain are due to energy requirements in all steps of the chain. The total emissions depend on the share of the gaseous diffusion process in the enrichment step and on how the electricity supplied to this process is generated. In fact, the gaseous diffusion plant in Tricastin typically consumes about 2 400 kW.h/SWU (Separative Work Unit), whereas a modern gas centrifuge enrichment facility needs only about 75 kW.h/SWU, i.e. 32 times less. The cumulated electricity requirement for the full nuclear chain calculated in the study is approximately 3.7% of the generated electricity, of which about 80% is the requirement for the enrichment of uranium through gaseous diffusion (electricity from PWRs) and about 20% the remaining (electricity mix from the Swiss and/or UCPTE grid). The emissions associated with the electricity requirements are included in the cumulated emissions for the chain. As a result, on the one hand the cumulated $CO_2$ emission from the whole chain is relatively low compared to other studies, on the other hand the calculated total radioactive releases attributed to the enrichment step are substantially greater than the direct emissions from this step. About 6.5 g $CO_2$/kW.h (1 800 kg $CO_2$/TJ(e)) are calculated for the Swiss nuclear mix and about 8.3 g $CO_2$/kW.h (2 300 kg $CO_2$/TJ(e)) for UCPTE nuclear mix.

The $CO_2$ emissions associated with the nuclear systems considered in the study originate mostly from static sources, with very little coming from transport systems (3% of the total). The major contributions are from milling, conversion, enrichment, power plant and reprocessing; these were calculated to be each on the order of 15% of the total. The sources are the requirements of electricity, transport, fuel and other materials.

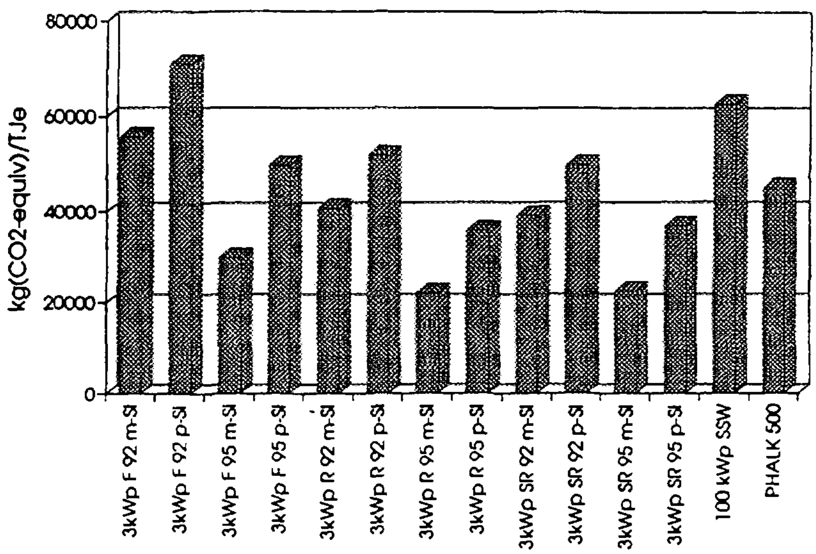
$CH_4$ is directly emitted only in the final repository step, being released during the digging of the pit and the tunnels of the deep repositories planned for Switzerland. The estimated value is very small, on the order of $3 \times 10^{-4}$ g $CH_4$/kW.h. Thus, the value that is attributed to the nuclear chains (approximately 2 x $10^{-2}$ g $CH_4$/kW.h) is derived from the indirect contributions from the UCPTE electricity mix, the fuel and the material requirements throughout the various steps, mainly milling, conversion, power plant, and reprocessing.

The calculated environmental factors for hydro systems are generally lower than those of other electricity systems when normalized to the generated electricity. The reason consists in the long lifetime of hydro systems, which more than compensates the high consumption of materials in the construction phase. In particular, the total $CO_2$ emission calculated for the Swiss hydroelectric dams' FENCH is 3.8 g $CO_2$/kW.h (1045 kg $CO_2$/TJ(e)), for the run-of-river plants is 3.5 g $CO_2$/kW.h (961 kg $CO_2$/TJ(e)).

In the case of pumped storage plants, the inventory is dominated by the contributions associated with the electricity needed for pumping that compensates the losses in the conversion of energy. It is estimated that the ratio of high voltage electricity supplied to the plant to the electricity delivered to the grid is approximately 1.45. Thus, the carbon dioxide emissions of the pumped storage plants are strongly influenced by the electricity mix supplied that is converted to potential energy of water. Therefore, the chain associated with the Swiss pumped storage plants, which are supplied through the Swiss grid, releases 28 g $CO_2$/kW.h, but the same chain associated with the UCPTE plants emits 25 times more, 698 g $CO_2$/kW.h, because the converted electricity is supplied by the UCPTE grid.

For all hydro systems, the associated emissions of methane are relatively small, approximately 1.6 x $10^{-2}$-2.1 x $10^{-2}$ g $CH_4$/kW.h (4.5-5.8 kg $CH_4$/TJ(e)), imported in the hydro FENCH through the energy and the material requirements.

Results for **photovoltaic systems** show that a large share of the total environmental burden of photovoltaic systems, in particular the GHGs, derives from the use of the UCPTE electricity mix for the production of the modules. The relatively high values for electricity requirements vary in the range 13-44% of the generated electricity, the lower values being calculated for the expected performances of the 1995 panel systems. Figure 9 shows the GHGs emissions for the systems analyzed (included are $CO_2$, $CH_4$, $N_2O$, CFCs and $CF_4$). The values are between 81-257 g $CO_2$/kW.h ($2.2\cdot10^4$-$7.1\cdot10^4$ kg $CO_2$/$TJ_e$) for panels, 164 g $CO_2$/kW.h ($4.5\cdot10^4$ kg




3kWp=3kW panel; F=façade; R=horizontal roof panel; SR=slanted roof panel; 100 kWp SSW= 100 kW plant along a Swiss highway; PHALK 500=500 kW demonstration plant at Mont Soleil, in the Jura Mountains, Switzerland.

m=monocrystalline; p=polycrystalline; 92=model available in 1992; 95=performances of model expected in 1995.

*Fig. 9. GHG emissions from solar photovoltaic systems.*

$CO_2/TJ_e$) for the PHALK plant, and 228 g $CO_2$/kW.h ($6.3 \cdot 10^4$ kg $CO_2/TJ_e$) for the 100 kW plant along a Swiss highway. The contribution of $CF_4$ is approximately 5% of the total. The expected reduction in electricity requirements for the future panels decreases the total GHG emissions, as shown in the figure. The contribution of electricity to total GHG emission is 80-90% for the 3 kW panels, approximately 80% for the pilot plant PHALK 500; the remaining is associated with material requirements.

### 4.2. Results for electricity mixes

Table IV presents the structure of the Swiss and UCPTE electricity mixes assumed in the study, where year 1990 was used as reference. Table V shows the results related to GHG emissions for the average Swiss and UCPTE electricity mixes.

TABLE IV. STRUCTURE OF THE SWISS AND UCPTE 1990 ELECTRICITY MIXES ASSUMED IN THE STUDY

| Countries | Share of electricity production at busbar by system | | | | | | |
|---|---|---|---|---|---|---|---|
| | Lignite (%) | Hard Coal (%) | Oil (%) | Gas (%) | Nuclear (%) | Hydro (%) | Other (%) |
| Switzerland | - | - | 1.2 | - | 41.2 | 56.7 | 0.9 |
| UCPTE | 10.5 | 18.3 | 9.6 | 9.5 | 36.2 | 15.2 | 0.7 |

As shown in Table V, the GHG emissions from the fossil chains are approximately of the same order of magnitude. The highest GHG producers in the fossil group are the coal chains. The GHG emission values for hydro and nuclear chains are each about two orders of magnitude lower than the fossil chain values.

TABLE V. GHG EMISSIONS ASSOCIATED WITH SWISS AND UCPTE -RELEVANT FENCH FOR ELECTRICITY GENERATION AND ELECTRICITY MIXES

| GHG | Countries | Emissions from FENCH [g/kW.h from the relevant chain] | | | | | | Mix (g/kW.h from mix). |
|---|---|---|---|---|---|---|---|---|
| | | Lignite | Hard Coal | Oil | Gas | Nuclear | Hydro[a] | |
| $CO_2$ | Switzerland | NA | NA | $8.59 \times 10^2$ | NA | 6.89 | 3.62 | 15.4 |
| | UCPTE | $1.33 \times 10^3$ | $9.73 \times 10^2$ | $8.71 \times 10^2$ | $7.51 \times 10^2$ | 8.14 | 3.99 | 482 |
| $CH_4$ | Switzerland | NA | NA | 1.02 | NA | $1.73 \times 10^{-2}$ | $7.97 \times 10^{-3}$ | 0.024 |
| | UCPTE | 0.269 | 4.21 | 1.11 | 1.79 | $2.03 \times 10^{-2}$ | $8.82 \times 10^{-3}$ | 1.09 |
| $CO_2$ equiv. | Switzerland | NA | NA | $8.75 \times 10^2$ | NA | 7.13 | 3.72 | 15.9 |
| | UCPTE | $1.34 \times 10^3$ | $1.02 \times 10^3$ | $8.89 \times 10^2$ | $7.72 \times 10^2$ | 8.42 | 4.10 | 495 |

[a] Pumped storage not included.
NA: Not applicable.

The fossil systems cover about 48% of the total electricity generated in UCPTE. Expressed in percentages, the $CO_2$ attributed to the FENCHs of the fossil systems is more than 99% of the total calculated for the UCPTE mix, and methane is more than 98%, as illustrated in Table VI. Hydro and nuclear systems together generate more than half the total electricity produced in UCPTE but their contribution to $CO_2$ and $CH_4$ emissions for the UCPTE electricity mix is less than 1%. Approximately three quarters of the total methane emissions associated with the UCPTE electricity mix is due to the coal chains, the rest mainly from the gas chain.

TABLE VI. PERCENTAGE CONTRIBUTION OF FENCH TO $CO_2$ AND $CH_4$ EMISSIONS CALCULATED FOR THE AVERAGE SWISS AND UCPTE ELECTRICITY MIXES

| GHG | Countries | Share FENCH to electricity mix (%) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Lignite | Hard Coal | Oil | Gas | Nuclear | Hydro[a] | Mix |
| $CO_2$ | Switzerland | NA | NA | 66.7 | NA | 18.4 | 13.1 | 100 |
| | UCPTE | 29.4 | 37.8 | 17.5 | 15.0 | 0.6 | 0.1 | 100 |
| $CH_4$ | Switzerland | NA | NA | 50.3 | NA | 29.3 | 18.4 | 100 |
| | UCPTE | 2.6 | 70.6 | 9.7 | 15.4 | 0.7 | 0.1 | 100 |

[a] Pumped storage not included.
NA: Not applicable.

An additional result of the study is that electricity distribution can substantially increase the environmental burdens of electricity required by consumers at different voltage levels. Especially the high losses and material intensive infrastructure of the low-voltage distribution grid increases some of the environmental interventions of electricity generation by more than 20%. The effect of inclusion of the GHG emissions associated with the materials/energy required for high, medium and low grids is shown in Table VII. The increase for UCPTE is approximately 14%.

TABLE VII. EFFECT OF INCLUDING ELECTRICITY TRANSPORTATION AND DISTRIBUTION TO TOTAL EMISSION OF GHGs

| Electricity mix | GHGs emission relative to power plant (busbar=100) | | | |
|---|---|---|---|---|
| | electricity supplied at busbar | electricity by high voltage grid | electricity by medium-voltage grid | electricity by low-voltage grid |
| Switzerland | 100 | 108.2 | 111.9 | 147.2 |
| UCPTE | 100 | 100.4 | 101.8 | 114.1 |

The modification is proportionally larger for the Swiss mix (up to about 50% for carbon dioxide and 140% for methane) because most of the material for the networks is produced with supply of UCPTE electricity, but still the total GHGs associated with the unit of low-voltage electricity for Switzerland remain substantially lower than UCPTE. The high increase of methane is mostly due to the methane associated with the production of copper used in the low voltage network.

Table VIII shows the fraction of $CH_4$ to total $CO_2$-equivalent with $GWP_{20}$ and $GWP_{100}$. It is of interest to comment the values calculated for the fossil systems in UCPTE. The hard coal FENCH has the largest ratio of methane to total GHG per unit of electricity.

TABLE VIII. PERCENTAGE $CH_4$ OF TOTAL $CO_2$-EQUIVALENT FOR FENCH FOR ELECTRICITY GENERATION

| | Countries | $CH_4$ in total $CO_2$-equivalent (%) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Lignite | Hard Coal | Oil | Gas | Nuclear | Hydro[a] | Mix |
| $GWP_{20}$ | Switzerland | NA | NA | 4.0 | NA | 8.0 | 7.1 | 5.2 |
| | UCPTE | 0.7 | 13.1 | 4.2 | 7.7 | 8.0 | 7.2 | 7.4 |
| $GWP_{100}$ | Switzerland | NA | NA | 1.3 | NA | 2.7 | 2.4 | 1.0 |
| | UCPTE | 0.2 | 4.5 | 1.4 | 2.5 | 2.6 | 2.4 | 2.4 |

[a] Pumped storage not included.
NA: Not applicable.

As shown in Table IX, $N_2O$ values are one order of magnitude lower than $CH_4$, except in the case of lignite.

TABLE IX. PERCENTAGES $N_2O$ AND $CH_4$ IN TOTAL $CO_2$-EQUIVALENT FOR UCPTE FENCH FOR ELECTRICITY GENERATION

| GHG | Percentage in total $CO_2$ -equivalent(%) | | | | | | |
|---|---|---|---|---|---|---|---|
| | Lignite | Hard Coal | Oil | Gas | Nuclear | Hydro[a] | Mix |
| $CH_4$ $GWP_{20}$ | 0.7 | 13.1 | 4.2 | 7.7 | 8.0 | 7.2 | 7.4 |
| $N_2O$ $GWP_{20}$ | 0.1 | 0.1 | 0.5 | 0.2 | 0.7 | 0.4 | 0.2 |
| $CH_4$ $GWP_{100}$ | 0.2 | 4.5 | 1.4 | 2.5 | 2.6 | 2.4 | 2.4 |
| $N_2O$ $GWP_{100}$ | 0.1 | 0.2 | 0.6 | 0.2 | 0.7 | 0.4 | 0.2 |

[a]Pumped storage not included.
NA: Not applicable.

## 5. SENSITIVITY ANALYSES

### 5.1. $CH_4$ Emissions in the Russian natural gas production and transportation system

In the base case a net leakage of 2% for natural gas in the Russian production and transportation system is assumed. According to a more pessimistic scenario, based on backward calculations starting from measured atmospheric methane concentrations, the leakage rate in Russia could be as high as 10% of the transported gas [5].

Figure 10 shows the $CH_4$ emission factors for different chains normalized by the unit of electricity. The increase in the emission factor for UCPTE electricity mix from the natural gas chain in the pessimistic 10% leakage scenario is shown. Even with this extreme assumption, the hard coal chain retains the highest methane emission. The impact of the increased methane leakage on the UCPTE mix is small, first because the Russian gas contributes only about 23% to the total in the assumed gas chain, second because gas has a share of only about 9.5% in the UCPTE electricity mix.

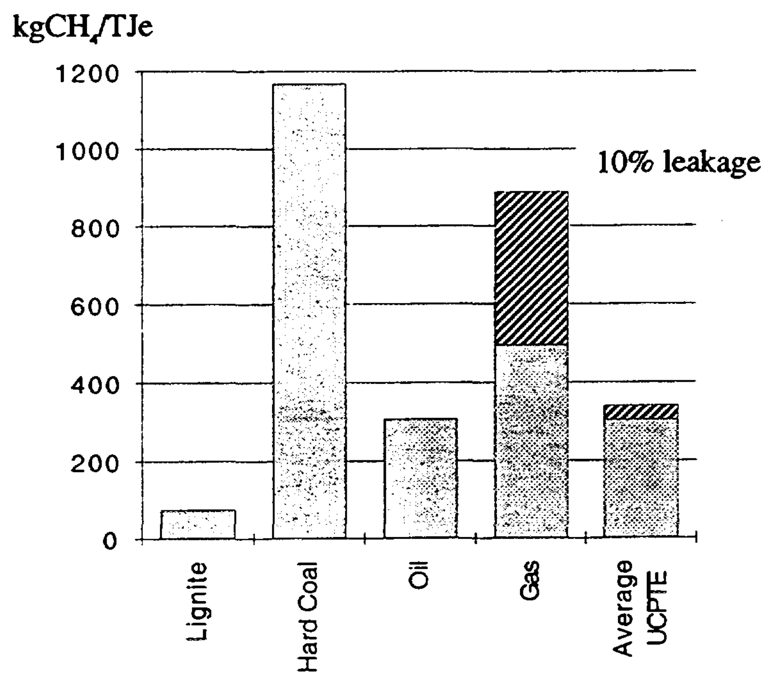



*Fig. 10. Sensitivity of $CH_4$ leakage during long-distance transport of natural gas from the Russian Federation.*

### 5.2. Electricity mix for enrichment step in nuclear FENCH

If it is assumed that the electricity for the gaseous diffusion enrichment plants is supplied by the UCPTE grid instead of PWRs, the calculated total $CO_2$ for the whole chain would be approximately three times greater than the value calculated in the study, i.e. 24 g $CO_2$/kW.h (6,700 kg $CO_2$/TJe). This result is based on unchanged shares of gaseous diffusion and gas centrifuge processes.

Separately, if the gas centrifuge process is hypothesized to be the only enrichment process used, the total electricity consumption in the whole cycle would decrease from 3.7% to approximately 0.8% of the generated electricity, which would give a total release of about 9.5 g $CO_2$/kW.h (2600 kg $CO_2$/TJ(e)), assuming the UCPTE mix.

## 6. APPLICABILITY AND TRANSFERABILITY

The study supplies the data necessary to consider energy contributions in the LCA for generic products. It allows to implement the LCA perspective in energy planning. The data can also be useful for comparison of energy supply-side and demand-side options. It provides results valid for the average electricity systems in the UCPTE network and in Switzerland. In the case of fossil systems (coal, oil and natural gas) data from specific utilities in UCPTE were available. It was thus possible to calculate emission inventories for different power plant classes in each country. This information is explicitly given in the study for coal power plants. Upstream steps in fossil FENCHs, on the other hand, were calculated on an average European basis. In using the average GHG emission factors reported in the study for other regions, care should be taken in considering the differences in technology and fuel mix, especially:

- power plant efficiency affecting $CO_2$ emission;
- the share of various fossil fuels from different origins affecting $CH_4$ emissions.

In contrast to fossil FENCHs, UCPTE hydro and nuclear electricity systems have been extrapolated from data relevant to the Swiss condition. Critical parameters for the calculated total emissions of GHGs for the nuclear chain are the electricity requirements (i.e., the electricity mix) in the enrichment step with gaseous diffusion process and the average burnup of nuclear fuel. In the study appropriate values for the UCPTE countries were applied. Results given for GHGs for the nuclear chain should be treated with care when considered for applications to different conditions.

The results for hydro systems reported in the study are valid for the Alpine region. UCPTE average values were extrapolated from data for Swiss hydroelectric dams, run-of-river and pumped storage plants. By no means should the results of the study be used to describe the situation of hydro systems in other regions.

In the comparative assessment of energy systems, the use of the data shown for greenhouse gases and for other environmental inventories covered by the study should be limited to the present situation or to small changes from it (assumption of linearity in LCA studies). No future technologies have been analyzed, with the exception of a two-year extrapolation for photovoltaic systems. Therefore, great care should be taken in using results for energy policy purposes, especially regarding the distant future. Another limitation arises from the fact that only existing West European power plants and related chains were considered in the study.

## 7. ECONOMIC AND TRANSBOUNDARY ASPECTS OF GHG EMISSIONS AND THEIR REDUCTIONS

Since the late eighties many studies have been published addressing costs of reducing greenhouse gas emissions (in practice focusing on $CO_2$). A recent survey [6] concludes that the estimated costs span a very wide range. 'Bottom-up' engineering models tend to underestimate costs by ignoring issues associated with implementation and other hidden costs. 'Top-down' economic models, on the other hand, tend to overestimate costs by neglecting the potential for enhancing structural changes and energy-efficiency improvements through regulatory policy. Within the GaBE project a Swiss-specific version of the large scale ('bottom-up') energy-economy model MARKAL is used. Since Switzerland uses almost exclusively hydro and nuclear for electricity generation any GHG reductions are bound to be expensive. This applies also to countries like Norway or Sweden while more moderate costs are expected in countries that to a higher extent employ fossil fuels for electricity production (such as Japan, The Netherlands, USA). These expectations have been confirmed by the results of IEA/ETSAP project [7] illustrating the interrelations between energy use, $CO_2$ emissions and the costs of emission control.

The above suggests that countries with strong differences in the structure of energy systems could have significant gains from international co-operation in trading $CO_2$ emissions. In Bahn et al [8] an example of an analysis decomposing and integrating several national models is provided. In this example Switzerland, the Netherlands and Belgium are co-operating in order to reduce their present $CO_2$ emissions by 20% in the year 2030. Marginal control costs are reduced for all countries under co-operation as compared to unilateral control strategies. The benefit distribution is estimated as: Switzerland 45%, the Netherlands 36% and Belgium 19%. Current MARKAL models usually include fuel-related emissions embodied in materials (e.g., emissions stemming from fossil fuel use in the steel industry). These emissions are, however, accounted for as steel industry emissions rather than being assigned to the products ultimately produced from the steel. This means that the available accounting framework is different from that needed by LCA [9]. It would also be desirable to track imports and exports of products that embody high $CO_2$ emissions. This complex task could be facilitated by linking MARKAL with an economic model.

Integrated energy and material flows within the MARKAL framework have been recently modelled by a Dutch group [10], showing a potential for decreasing $CO_2$ emission reduction costs. As pointed out, policies should primarily aim at the reduction of emissions in materials production and recycling. This is only possible in an international context since the whole material system is internationally embedded. There are indications that environmental product standards based on a 'cradle-to-grave' approach may not comply with free trade agreements (e.g., GATT). Furthermore, $CO_2$ emissions may vary within one material group. Consequently, $CO_2$ policies on materials based on the LCA analysis may be very difficult to implement internationally.

## 8. CONCLUSIONS

The study can be regarded as a very detailed environmental LCA of energy systems. A high level of completeness has been achieved by covering the whole energy chains and by considering material input, transportation and dismantling/disposal related to all process steps. The GHG emission values for hydro and nuclear chains are each about two orders of magnitude lower than values for the fossil chains; the contributions come mainly from energy and material requirements. On the other hand, the GHG emissions in the fossil chains are primarily from power plant operation, with mining and transportation contributing minor portions of the emissions in these chains. The contributions from electricity requirements dominate GHG emissions of photovoltaic systems; thus, the emission values are strongly dependent on the electricity mix used.

In energy planning, it is desirable in the global context to account for the emissions (of GHGs as well as of other species) outside of national boundaries. These emissions are straightforward to assess in some cases, e.g., direct emission of methane in mining or from gas pipelines. The assessments of other cases, such as emissions associated with material production (of less importance in the case of GHGs for mature electricity generation systems) or associated with imported electricity, may be equally important but are much more complicated tasks. The framework for such an approach is in principle available; however, its implementation, particularly on the international level, is subject to practical difficulties.

Research projects continuing the study described are in progress at the Swiss Federal Institute of Technology, with the aim of updating and expanding the environmental inventory database, further developing downstream (i.e. disposal) processes, regional and local impacts of energy transportation and distribution, as well as evaluating environmental interventions. Further GHG analyses, including extension of the LCA-based comparisons as well as economic analyses of GHG emission reduction scenarios, will be carried out within the GaBE project.

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