GREENHOUSE GAS EMISSIONS FROM ENERGY SYSTEMS: COMPARISON AND OVERVIEW

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The paper provides an overview and comparison of Greenhouse Gas Emissions associated with fossil, nuclear and renewable energy systems. In this context both the direct technology-specific emissions and the contributions from full energy chains within the Life Cycle Assessment framework are considered. Examples illustrating the differences between countries and regional electricity mixes are also provided. Core results presented here are based on the work performed at PSI, and by partners within the Swiss Centre for Life-Cycle Inventories.

1 INTRODUCTION

According to the Inter-Governmental Panel on Climate Change (IPCC), the Earth's climate system is continuously evolving, both globally and regionally, with some of the changes being attributable to human activities, and resulting in emissions of Greenhouse Gases. Energy supply systems, and fossil-fuel systems in particular, are the dominant contributors to the emissions of these gases. This article provides comparisons of Greenhouse Gas (GHG) emissions primarily derived using the most recent results from a comprehensive Swiss study addressing Life-Cycle Assessment (LCA) issues based on environmental inventories of European-wide energy systems [1]. The work has been undertaken by PSI and its partners in the framework of the *ecoinvent 2000* Project [2]. Results are compared with other selected studies carried out in other countries. Information on the methodological aspects of LCA, as applied in the Swiss study, will be provided in Chapter 2.

The main aim of *ecoinvent 2000* was to achieve consistency between the different LCA databases maintained by the participating organisations, and to update and integrate them within the *ecoinvent* database. Those included are: energy systems (PSI); materials and metals (EMPA); transport systems (ETHZ); waste treatment and disposal (EMPA); chemicals (ETHZ); and agricultural products (FAL). Approximately 2500 individual processes have been modelled, and 1000 elementary environmental flows placed in the inventory, including emissions, solid wastes, resources and land usage. The modules are integrated based on an algorithm reflecting the interaction of industrial activities within the economy.

The energy systems which have been assessed, making up about half of the processes available in the database, include electricity and heating systems. Fossil, nuclear and renewable systems, associated with Swiss and European power plants, boilers and cogeneration plants, have all been assessed; these reflect prevailing conditions around the reference year 2000.

The centralised, web-based, LCA data system *ecoinvent 2000* has been developed and implemented by the Swiss Centre for Life Cycle Inventories, and supported by Swiss Federal Offices. Since September 2003, its first user-friendly version has been available via the Internet.

1.1 Global Greenhouse Gas Emissions from Energy Systems and Other Sources

According to the IPCC, the anthropogenic greenhouse gas (GHG) emissions contributing most evidently to Global Warming in terms of relative radiative forcing are CO_2, CH_4, halocarbons and N_2O [3]. Radiative forcing is the change in the net vertical irradiance (in Wm^{-2}) at the boundary between the troposphere and the stratosphere. Compared to the pre-industrial era (250 years ago) additional radiative forcing due to increases of GHGs is estimated to be 2.43 Wm^{-2}, of which CO_2 contributes most (1.46 Wm^{-2}), followed by CH_4 (0.48 Wm^{-2}), halocarbons (0.34 Wm^{-2}), and N_2O (0.15 Wm^{-2}).

Other possible factors influencing the global climate are less well-understood, and so quantitatively more uncertain. Among them are: stratospheric ozone (cooling); tropospheric ozone (warming); sulphate (cooling); black carbon and organic carbon (warming or cooling); biomass burning (cooling); mineral dust (warming or cooling); aerosol indirect effects (cooling); land-usage (change of albedo, i.e. share of reflected sun light); and solar variation (minimal).

Table 1 gives the global emissions of the major GHGs and the contribution of anthropogenic sources in the late 1990s. CO_2 emissions originate mainly from combustion of fossil fuels, and are quite well-known. However, total emission rates of CH_4 and N_2O are much more uncertain. Halocarbons are molecules containing carbon, and either chlorine, fluorine, bromine or iodine. Among the halocarbons are several refrigerants, used as working fluids for cooling or heating. Many refrigerants of use in the industry sector (in refrigerators, heat pumps, air conditioners, etc.) have very high Global Warming Potential (GWP) on a per-kg-emitted basis. Energy scenarios for the reduction of CO_2 emissions often include increased use of heat pumps, which substitute for fossil-fuel heating systems, and for which refrigerant emissions caused by leakages counteract (to a certain extent) the total GHG balance. In contrast, halocarbon emissions are almost completely man-made. Table 1 does not include refrigerants such as CFC-11 or CFC-12, which have been banned because of their high ozone-depleting potential; they currently have low emission rates, but are still abundant in the atmosphere because of past emissions.

Table 1: Annual emissions of important greenhouse gases in the late 1990s [3].

	Annual Emissions [Mt/year]	Life time [years]	GWP 100-yr	CO_2-equiv. 100-yr [Mt/year]
CO_2:	29000		1	29000
- Fossil fuels	*22400*			*22400*
- Cement production	*700*			*700*
- Land use, etc.	*6000 (3000-9000)*			*6000*
CH_4:	600	8.4-12	23	13800
- Energy	*100 (89-110)*			*2300*
- Biomass burning	*40 (23-55)*			*900*
- Other anthropogenic sources	*230*			*5300*
- Natural sources	*230*			*5300*
N_2O:	26	120	296	7700
- Automobiles	*0.3 (0.2-0.4)*			*90*
- Industry, incl. Energy	*2.0 (1.1-2.8)*			*600*
- Other anthropogenic sources	*8.5 (7.6-9.6)*			*2500*
- Natural sources	*15*			*4500*
HFC refrigerants:				
HFC-23	0.007	260	12000	84
HFC-134a	0.025	13.8	1300	33
HFC-152a	0.004	1.4	120	0.5
Other halocarbons:				
Perfluoromethane (CF_4)	0.015	>50000	5700	86
Perfluoroethane (C_2F_6)	0.002	10000	11900	24
Sulphur hexafluoride (SF6)	0.006	3200	22200	133

Emissions are given in real mass per year and CO_2-equivalent mass per year.GWP=Global Warming Potential; HFC=Hydrofluorocarbon. All figures have been rounded.

1.2 Methodological Basis and Scope of Comparisons

The most straightforward accounting of GHG emissions is based on emission factors associated with combustion of the various fossil fuels. This approach can also be used for estimating the overall national emission inventories, but is not practical when trying to fully account for emissions associated with the use of specific technologies. While uses of nuclear and renewable energy sources exhibit practically negligible emission levels for GHGs at the stage of power generation, the same is not necessarily true for other stages of the corresponding energy chains. In addition, emissions may arise when manufacturing the components for the plants, transporting fuels and other materials, or at the decommissioning stage.

LCA, an approach utilising process-chain analysis specific to the types of fuels used in each process, allows for the full accounting of all such emissions, even when they take place outside the national boundaries. Thus, LCA considers not only emissions from power plant construction, operation and decommissioning, but also the environmental burdens associated with the entire lifetime of all the relevant upstream and downstream processes within the energy chain. These processes include exploration, extraction, processing and transport of the energy carrier, as well as waste treatment and disposal. The direct emissions include releases from the operation of power plants, mines, processing factories and transport systems. In addition, indirect emissions are also covered, originating from manufacturing and transport of materials from energy inputs to all steps in the chain, as well as those from the infrastructure.
An alternative, non-process-oriented approach is the Input/Output (I/O) method, which divides the economy into distinct sectors, and is based on the input and output between the sectors to generate the energy flows and associated emissions. A hybrid approach is also frequently employed, combining LCA and I/O methods; the I/O method is then used exclusively for assessing the processes of secondary importance.

2 ENERGY CHAIN SPECIFIC GREENHOUSE GAS EMISSIONS

Some basic features of the LCA methodology, as applied to the Swiss applications, are summarised below; most of these principles also apply to other state-of-the-art studies which, however, may differ in terms of scope, level of detail, specific assumptions, and methodology applied (some results are based on hybrid approaches). The most important features are listed here.

- Energy systems, transport systems, material manufacturing, production of chemicals, waste treatment and disposal, as well as agricultural products, have all been assessed using detailed process analysis developed under common and consistently defined rules.
- Electricity inputs have been modelled using production technology or supply mix as close as possible to the actual situation. In the case of lack of specification, the UCTE (Union for the Co-ordination of Transmission of Electricity, mainly continental Western Europe) mix was used as an approximation.
- Allocation criteria were developed for multi-purpose processes.

The results provided in this section focus on electricity supply, but selected results are also given for heat generation and cogeneration systems. All GHG emissions are given using GWP for the 100 years time horizon [3].

2.1 Fossil Energy Chains

2.1.1 Coal

Hard Coal

In the Swiss study [1], European, country-specific, average power plants were analysed, operating around year 2000. For the estimation of the infrastructure of the plants, two rated power levels of 100 MW and 500 MW were considered; a mix with a share of 10% and 90%, respectively, was defined for the reference plant. The reference unit was assumed to be used under mid-load, with 4000 hours of operation per year at full capacity, and 150 000 hours over its entire lifetime. Emission of CO_2 was estimated on the basis of coal characteristics (i.e. at Lower Heating Values, in the range 22.1 MJ/kg to 26.6 MJ/kg), and at the average net efficiencies of single units operating in Europe (29% to 40%); the emissions of CH_4, N_2O and CO are averages taken from the literature.

Average coal from eight supply regions was considered: West and East Europe, North and South America, Australia, Russia, South Africa and the Far East. Specific average data were used for the coal characteristics (i.e. at Upper Heating Values, in the range 20 MJ/kg to 28 MJ/kg), the share of open pit to underground mines, methane emissions, land usage and energy use for each of the regions. Import mixes have been defined for the year 2000 for all European countries with coal plants.

The average methane emissions from coal mining in the eight regions modelled range from 0.16 g CH_4/kg (typical emission from open-pit coal mines in the USA) to 13.6 g CH_4/kg (coal produced in Western Europe).

The results for GHG GWP 100a from the chains associated with the average hard coal power plants in European countries is from 949 g CO_2-equiv./kWh for the NORDEL (Scandinavian) countries to 1280 g CO_2-equiv./kWh for the Czech Republic (including several co-generating plants in which the emission is entirely allocated to electricity generation). The average for UCTE countries (excluding the CENTREL countries, i.e. the Czech Republic, Hungary, Poland and Slovakia) in year 2000 is 1070 g CO_2-equiv./kWh. Methane contributes nearly 7% to the total GHG emissions for the UCTE average hard-coal chain, N_2O about 0.8%, while CO_2 emissions essentially make up the rest.

The upstream chain contributes between 8% (Portugal) to 12.5% (Germany) to the total GHG emission. The total GHG associated with production regions varies between 0.04 kg CO_2-equiv./kg coal (in South America) to 0.288 kg CO_2-equiv./kg coal (in Russia).

Figure 1 gives a comparison between the range of averages estimates of normalised GHG emissions for the UCTE countries [1], the averages for Japan [4] and the USA [5], the range obtained for the coal chain in the Shandong Province in China [6], and the range according to a world-wide survey carried out in 1997 [7]. As can be seen, the Japanese and the US results are on the lower side of the ranges for the UCTE countries, and for the world-wide 1997 survey; the same applies to the lower range estimates from the study for China. The higher range from the Chinese study reflects the low efficiency characteristics of their plants, in particular for the smaller units, as well as the large contribution from mining. The potentially very substantial (but difficult to estimate) additional GHG emissions from uncontrolled coal fires have not been included in the statistics.

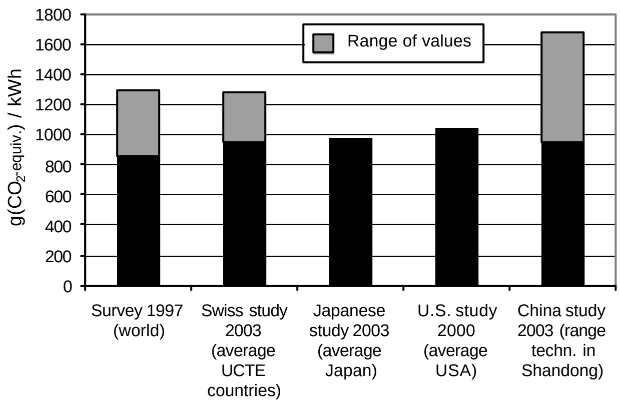

Fig. 1: GHG emissions from coal-power plants and associated fuel cycles according to different studies.

Lignite

The reference plant used for lignite in the Swiss LCA study [1] has similar characteristics to those for hard coal, but a larger share of plants of low-rated power has been used. The reference unit is assumed to be used for a base load of 6000 hours of operation per year, at full capacity, and for a total of 200 000 hours during its lifetime. Emissions of CO_2 are estimated on the basis of the characteristics of average lignite boring (i.e. Lower Heating Values, in the range 5.2 MJ/kg to 16.6 MJ/kg), and the average efficiencies of single units operating in Europe (between 23% and 40%, averaged over all countries), while emissions of CH_4, N_2O and CO are UCTE-averages taken from the literature.

Considering that lignite plants are mine-mouth, only an average European open-pit mine has been modelled, and this on the basis of information limited to a few mines. Only 0.23 g CH_4/kg lignite is assumed to have been emitted during the mining operations.

The results from the chains associated with the average lignite power plants in the European countries is from 1060 g CO_2-equiv./kWh (for Austria) to 1690 g CO_2-equiv./kWh (for Slovakia). The average for the UCTE countries (excluding CENTREL) in the year 2000 is calculated as 1230 g CO_2-equiv./kWh. Methane contributes about 0.6% to total GHG emission for the UCTE-averaged lignite chain, N_2O

about 0.5%, while the CO_2 emissions essentially make up the rest. Mining contributes marginally between 0.9% (France) to 2.6% (Greece) to the total GHG level.

2.1.2 Oil

Since the role of oil in electricity generation is decreasing, only a few key factors are provided in the Swiss study [1].

The average GHG emissions of oil chains from the European countries range from 519 g CO_2-equiv./kWh to 1200 g CO_2-equiv./kWh, depending on the respective use of power plants for base or peak load. The UCTE average for the year 2000 was about 880 g CO_2-equiv./kWh, of which about 88%, or 775 g/kWh, may be attributed to direct emission during power plant operation.

For the fuel-oil supply, emissions occur during crude oil exploration, long-distance transport (e.g. in trans-oceanic tankers), processing in refineries, and local distribution. For an average oil-based power plant in Europe, the highest contributions to the upstream GHG emissions occur at the oil exploration phase, and in the processing of heavy oil in refineries.

2.1.3 Gas

Natural Gas Chain

For natural gas, as for the other fossil-fuel electricity or heating systems, the dominant contributor to GHG emissions is CO_2 from the power plant or boiler. Natural gas is transported in pipelines over long distances. Since natural gas consists mainly of methane (i.e. natural gas itself is a greenhouse gas!), leakages in the pipelines can contribute significantly to the total GHG emissions. For European countries, the CO_4 emissions can make up to about 10% of the total GHG emissions in the full chain, depending on the location of the natural gas power plant or boiler. Together with CO_2 and other GHG emissions in the upstream chain, the emissions other than directly from the power plant can constitute more than 10% of the total GHG emissions for European natural gas power plants (about 17% for the UCTE-average plant in the year 2000).

The country-by-country averages of the full chain GHG emissions of natural gas power plants in Europe range from 485 to 991 g CO_2-equiv./kWh. The UCTE average for the year 2000 was about 640 g/kWh CO_2-equiv, which includes about 530 g/kWh of direct CO_2 emissions generated during operation of the power plants.

For the modelling of the best-technology, combined-cycle, gas power plant, data from the new 400 MW plant in Mainz-Wiesbaden (Germany) were used. According to the operators, this is currently the natural gas power plant with the highest net electrical efficiency (58.4%) worldwide (for the year 2001). Because the efficiency depends also on local conditions (the Mainz-Wiesbaden plant is located directly on the Rhine, which provides good cooling conditions), it was assumed that a comparable plant at an average location in Europe would have a net efficiency of about 57.5%. The full-chain GHG emissions of the best combined-cycle power plant (about 420 g/kWh) are much lower than those of an average gas-powered plant.

Figure 2 compares the average estimates of normalised GHG emissions from the gas chain for the UCTE countries against the average for the LNGs in Japan [4], the combined-cycle plants in Europe [1], Japan [4] and the US [8], and those obtained from a world-wide survey carried out in 1997 [7]. The upper range in the survey probably represents a plant using a gas mix rather than pure natural gas.

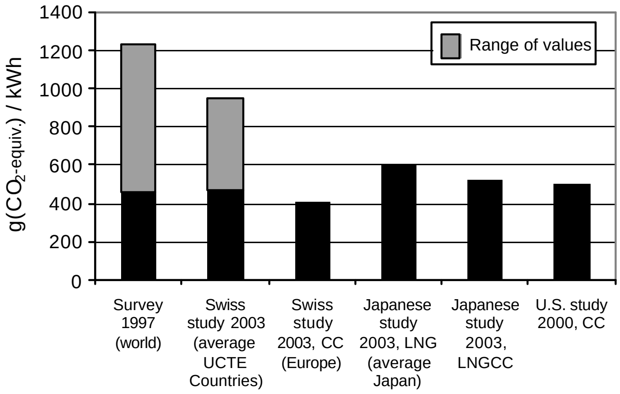

Fig. 2: GHG emissions from gas power plants.

Industrial Gas

Industrial gas covers blast furnace gas from pig iron production and coke-oven gas. The results cited here are based on the mix used for electricity production in the UCTE countries for the year 2000. Due to its high CO_2 content, blast furnace gas has high CO_2 emission factors of 90 g/MJ to 260 g/MJ of burned gas, while emission factors of coke-oven gas range from 40 g/MJ to 90 g/MJ of the gas burned. These lead to an exceptionally high total GHG emission: exceeding 1700 g CO_2-equiv./kWh for the European-average industrial gas mix. The methane contribution comes mainly from the coke-oven, gas-production chain.

2.1.4 Heating and Cogeneration

Heating

Two hard-coal heating systems were modelled in the Swiss LCA study [1]: an industrial furnace with thermal capacity in the range 1 MW to 10 MW, and a stove of about 5 kW to 15 kW. The thermal efficiency of the furnace is 80%, while that of the stove is 70%. The industrial furnace is assumed to be fuelled with the average Western European hard-coal supply mix, the stove either with coke or briquettes.

Assuming that all the CO is oxidised to CO_2, it contributes about 10% to the total GHG emissions associated with the stove. Direct CH_4 emissions from burning briquettes are 20 times higher than from burning coke, and direct methane emissions are about

50% of the total methane emissions calculated for the chain. Due to a lower carbon content per unit energy, burning briquettes results in lower direct CO_2 emissions than those produced by burning coke.

Condensing-gas and oil boilers use the heat of combustion, as well as that from condensation of the water in the flue gas. Modern condensing, natural gas boilers can achieve annual net efficiencies of about 102%, and modern oil boilers about 98%. (The ratio refers to the LHV (Low Heating Value) of the fuel. Therefore, efficiencies of more than 100% are possible for condensing boilers.) High efficiency reduces the CO_2 emissions. Direct CO_2 emissions of a modern condensing natural gas boiler of less than 100 kW capacity are about 56 g/MJ. (The GHG emissions of the full chain for similar boilers in Central Europe for the year 2000 add up to about 71 g/MJ CO_2-equiv. For a 10 kW condensing, non-modulating oil boiler, with direct CO_2 emissions of about 74 g/MJ, the full-chain GHG emissions for plants located in Central Europe are about 89 g/MJ CO_2-equiv.)

Figure 3 gives a comparison of GHG emissions for the energy chains based on various heating technologies of different capacity: hard coal, natural gas and oil. The lowest emissions are for the natural gas systems, followed by the oil systems.

Cogeneration

Figure 4 gives a comparison of CO_2 emissions per kWh_e for modern small cogeneration plants of different capacity and technology located in Switzerland [1]. Allocation of emissions to the products is in this case based on *exergy*. The higher the capacity, the higher the electrical efficiency, and the lower the CO_2 emissions for electricity. The total efficiency is approximately constant for the different plants shown. The CO_2 emissions per MJ fuel burned are the same for all natural gas plants, but higher for diesel plants, because of the higher emission factor of diesel oil.

2.2 Nuclear Energy Chain

The amount of GHG emissions from the nuclear chain associated with Light Water Reactors (LWRs) is controlled by several parameters: the nuclear cycle considered, the average enrichment and burn-up at discharge of the fuel, the lifetime of the plant, especially of the power plant, and, most important, the enrichment process used, together with the electricity supply to the enrichment diffusion plant (if its services are required).

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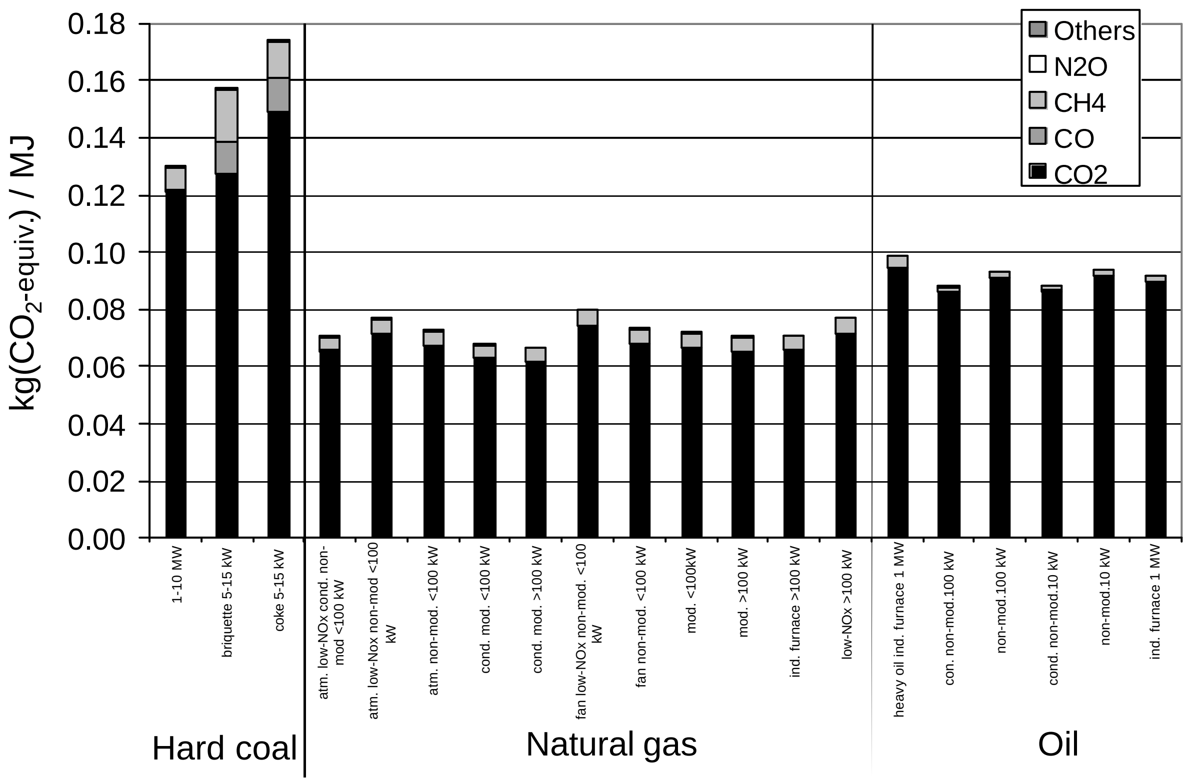

Fig. 3: GHG emissions from fossil-fuel heating systems operating in the year 2000 in Central Europe. Atm. = Atmospheric boiler; Fan = Fan burner; Mod. = Modulating boiler; Cond. = Condensing boiler; Ind. furnace = Industrial furnace; Low-NOx refers to boilers built in the early 1990s; Modulating boilers refer to the most modern technology on the market [1].

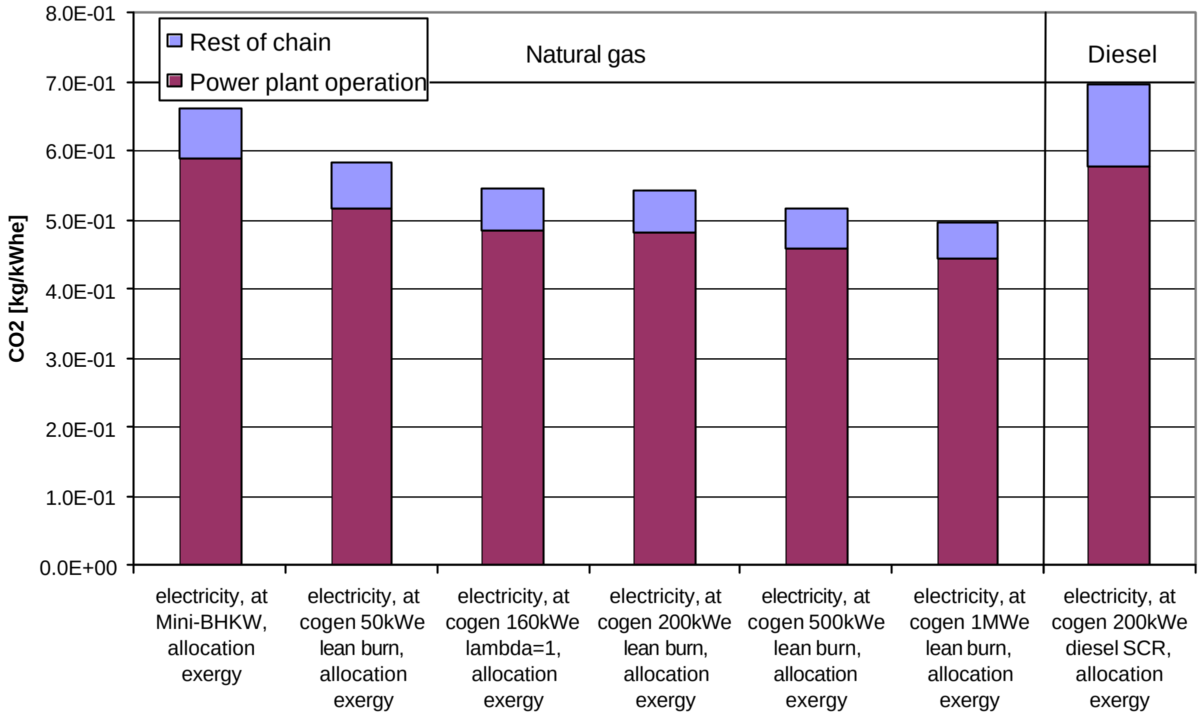

Fig. 4: CO_2 emissions per kWh_e from modern small cogeneration plants of different capacity and technology. Lambda=1: Cogeneration unit with three-way catalyst. Mini-BHKW: 2kWe small device designed for a small house. SCR = Selective Catalytic Reduction. The allocation to electricity is based on the exergy of electricity and heat, assuming an upper temperature of about 80°C for heat [1].

The Swiss LCA study on current energy systems [1] addresses the Swiss, French, German and average UCTE nuclear chains, separately modelling Boiling Water Reactor (BWR) and Pressurised Water Reactor (PWR) power plant technologies, with reference to the two 1000 MW class units installed in Switzerland.

The nuclear cycle was sub-divided into several steps: uranium mining (open pit and underground), milling, conversion, enrichment (diffusion and centrifuge), fuel fabrication, power plant (Light Water Reactors), reprocessing, conditioning (encapsulating spent fuel), interim storage of radioactive waste, and final repositories (geological, for high- and intermediate-level waste).

The study [1] assumes partial or total reprocessing of the fuel, according to the current conditions in West European countries. In particular, 40% of the total spent fuel produced at Swiss and German plants during their lifetime was assumed to be reprocessed. For France, this is most likely to be 100%, whereas for the UCTE countries, a weighted average of 80% was assumed. Mixed Oxide Fuel (MOX), in which recycled plutonium is mixed with depleted uranium from enrichment plants, was also considered in the study, because MOX is widely used in Western Europe.

A lifetime of 40 years was assumed for the power plants. Average U-235 enrichment ranges between 3.8% for French PWRs and Swiss BWRs, to 4.2% for Swiss PWRs. The corresponding average burn-up of spent fuel ranges between nearly 43 MW_{th}day/kgU for the French plants to 52 MW_{th}day/kgU for the Swiss PWRs. The study includes a description of enrichment supplies and relevant electricity input based on a literature search, together with assumptions on the current worldwide enrichment market and country-specific enrichment services.

The total emission of GHGs for the nuclear chains modelled is calculated to be between approximately 6 g CO_2-equiv./kWh and 12 g CO_2-equiv./kWh. The minimum is estimated for the French nuclear chain, assuming 10% MOX fuel usage and 100% enrichment at the diffusion Eurodif plant in Tricastin (supplied by nuclear plants, and using no CFCs as refrigerants, only water). The maximum was calculated for Germany, under the assumption of about 13% MOX, and a mix of enrichment services, including 10% of the USEC diffusion plant, which is assumed to be supplied by coal power plants. Nearly 70% of the enrichment services are assumed to be supplied by URENCO facilities (one is located in Northern Germany), and are based on centrifugal technology, which is about 65 times less energy intensive than the USEC plant.

Calculated, total GHG is predominantly from CO_2 emissions: between 90% and 93%. Methane contributes between 3% and 6%, and N_2O about 1% to 3%, while the hydrofluoro- and hydrochloro-carbon emissions from the enrichment stage are below 5%.

The GHG associated with the power plant ranges from (approximately) 1.0 to 1.3 g CO_2-equiv./kWh, while that from waste management (back-end or downstream) is between (approximately) 0.6 and 1.0 g CO_2-equiv./kWh. The upstream chain makes up the rest, though this may change substantially according to the main assumptions made for the cycle.

In comparison, the total GHG emissions for the Chinese reference (once-through) nuclear cycle were estimated at 9 g CO_2-equiv./kWh, assuming centrifuge technology for all enrichment services [6]. Conversely, taking the extreme assumption of only diffusion enrichment, powered by coal plants, the highest GHG emission was calculated at nearly 80 g CO_2-equiv./kWh. If electricity mixes and mixed fuels (also including gas and nuclear) would be used together, this amount could be almost halved, i.e. to about 45 g CO_2-equiv./kWh.

2.3 Renewable Energy Chains

2.3.1 Biomass

For biomass-burning boilers and cogeneration systems modelled in the Swiss LCA study [1], only untreated wood was considered; i.e. no account was taken of waste-wood combustion. The emission of direct, biogenic CO_2 due to combustion was calculated assuming a carbon content of dry wood of 0.494% for all types of wood fuels. All carbon absorbed by the trees, and contained in the wood eventually burned, was assumed to be emitted during combustion, either as CO_2 or as CO. Furthermore, all CO was assumed to be fully oxidised to CO_2 in the atmosphere, and as such contributed to the total GHG level.

It should be noted that infrastructure and emission data refer to average operation of modern wood boilers available on the central European market at or around the year 2000, and that the wood fuel supply chain also represents average central European conditions.

Several classes of heating technologies have been modelled, namely 6 kW, 30 kW and 100 kW for log furnaces, and 50 kW, 300 kW and 1000 kW for wood-chip furnaces, either using wood obtained directly from forests, or from residual wood from industrial processes. Boiler operation was modelled for hardwood (mainly beech), softwood (mainly spruce), and the Swiss commercial residual wood mix (72% softwood and 28% hardwood). Wood-pellet furnaces of 15 kW and 50 kW were also modelled.

For the industrial wood chips, practically all environmental burdens of the processes have been allocated to commercial wood products on the basis of an economic evaluation, rather than to the residues eventually burned in the furnaces. This "zero-allocation" assumption might not be applicable if wood chips become more important for heat production.

Figure 5 gives a comparison of the results obtained from the Swiss [1] and Austrian [9] LCA studies, the latter having analysed wood-heating systems throughout Central Europe. Only the systems of high efficiency have been included in the Austrian study, since these have comparable efficiencies as those assumed for the Swiss study.

The capacities of the log-fired and chip-fired boilers included in this comparison are between 6 kW and 1000 kW for the Swiss study, and 10 kW to 50 kW for the Austrian study, respectively. The pellet boilers have similar capacities for both studies. The electrical power rating of the CHP plants are between 335 kW_e and 400 kW_e for the Swiss study, and 210 kW_e to 36 MW_e for the Austrian study, respectively.

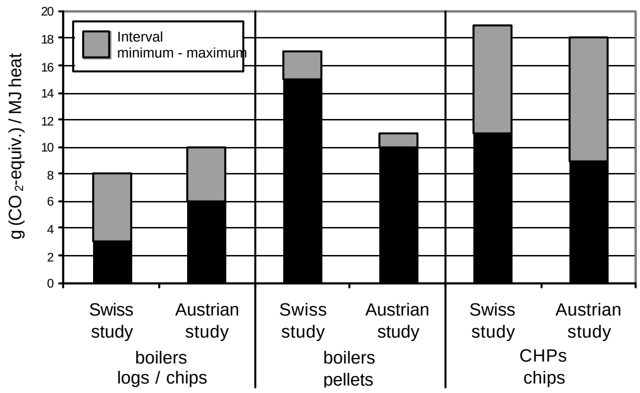

Fig. 5: GHG emissions for wood heating systems in Central Europe.

The total efficiency of the log/chip pellet boilers are between 68% and 85%. The electrical efficiencies of the cogeneration (CHP) plants in the Swiss study are between 0.9% and 2.3%, and thermal efficiencies are between 76% and 78%. The Austrian study reports electrical efficiencies of the CHP plants (used in this comparison)of between 8% and 39%, and thermal efficiencies between 51% and 80%.

All values for net GHG emissions of the systems considered in this study are within a relatively small range: 3–19 g CO_2-equiv./MJ. In addition, there is no obvious correlation between system capacity and net GHG emission: direct CH_4 and N_2O emissions are usually lower at higher capacity, but the indirect GHG emissions may be higher.

In general, the net GHG emissions from wood-chips and wood-log heating systems are not significantly different. Because of incomplete combustion, burning logs in automatically controlled furnaces produces more CO and CH_4 than burning wood chips. Compared to other heating systems, even modern 6 kW fireplaces still emit relatively high amounts of CO and CH_4.

Compared to other wood boilers, pellet furnaces have higher net GHG emissions of between 15 and 17 g CO_2-equiv./MJ. More than 90% of CO_2 emissions are of fossil origin. About 65% of these are due to material and energy consumption in the fuel supply chain, and 22% are due to material and energy usage resulting from fuel transport. The main reason is that energy requirements for pellet production are higher than for chips and logs, and that the transport distances of pellet fuel to the boilers are also higher.

Two wood-cogeneration systems in Switzerland, of 6400 kW_{th} and 1400 kW_{th} installed capacity, and burning industrial chips, have been assessed in the Swiss LCA study: one with a Multi-Cyclone-Filter, and the other with enhanced Emission Control (i.e. electrical filter plus Selective Non-Catalytic Reduction (SNCR), assumed to operate with urea). Both systems are designed primarily for heat production (thermal efficiency of nearly 77%); electricity production (efficiency between 1% and 3%) is mostly used internally in the plant.

Allocating all emissions to heat production, 11 g CO_2-equiv./MJ are estimated for the Multi-Cyclone-Filter system and 19 g CO_2-equiv./MJ for the Emission Control technology. The reason for the higher GHG emissions in the latter case is that the urea in the SNCR has been partially transformed to N_2O. However, the N_2O emission factor is rather uncertain, and only sparse information is available in the literature. The range of N_2O emissions is between 4 and 41 mg/MJ of wood input.

2.3.2 Hydro

Swiss and European Hydro Power Plants

In order to reflect the situation in Switzerland and the rest of Europe, two types of hydro-power plant (storage and run-of-river), and one type of pumped-storage plant, were analysed in the Swiss LCA study [1].

A representative sample was used, comprising four run-of-river power plants in Switzerland and one in Austria. Lifetime was assumed to be 80 years for the fixed structures, and 40 years for other parts. Net average efficiency is estimated at 82% (peak efficiency can be as high as 88%).

A representative sample of 52 Swiss concrete dams of height more than 30 m was considered for calculating the average. Lifetimes were assumed to be 150 years for the dam, 40 years for the turbines and pipes, and 80 years for all other components. Net average efficiency, including pipe losses, is 78% (though the efficiency can be as high as 84%). Furthermore, the data refer to a mix of dam types built between 1945 and 1970, so might not be fully representative of more modern constructions, or for a specific dam type or individual unit. The data have been extrapolated to provide preliminary information on dam mixes in other Alpine countries (Austria, Italy and France), and in non-Alpine (European) countries.

No data appear to exist for CH_4 and N_2O emissions from hydroelectric storage plants in the Alpine region. Consequently, the methane emission data have been roughly extrapolated from data for natural Swiss lakes, estimated as $4{\cdot}10^{-3}$ kg m^{-2} per annum. Applying this value as a first guess to Swiss reservoirs, the emission factor would be 0.014 g CH_4/kWh, or equivalently 0.32 g CO_2-equiv./kWh. Measurements for N_2O releases from a natural lake in Switzerland have been used to give a rough estimation of the emissions from reservoirs; namely $7.7{\cdot}10^{-5}$ g N_2O/kWh or 0.023 g CO_2-equiv./kWh. No account has been taken of CO_2 emissions in these studies due to the lack of information on the net balance (see below) for Alpine regions.

The Swiss LCA study has used currently available figures for direct GHG emissions from Norwegian and Swedish reservoirs, which average around 6 g CO_2-equiv./kWh, as well as from all non-Alpine regions (except for Finish reservoirs, for which 30 g CO_2-equiv./kWh were assumed).

The results show that, for Alpine regions, the construction of the dams contributes most to the total emission of 4–5 g CO_2-equiv./kWh; the material (mostly concrete) contributes about 70% to the total. With the above assumptions on direct CH_4 emissions, other European reservoirs would have average emissions of 10 g CO_2-equiv./kWh, and the Finnish reservoirs around 34 g CO_2-equiv./kWh. By increasing GHG fluxes, the emissions associated with the construction of the dam decrease in importance. In the case of run-of-river plants, emissions are of the order of 3 g CO_2-equiv./kWh.

A survey of several LCA studies performed in 1997 [10] concluded that indirect contributions range from about 1–10 g CO_2-equiv./kWh for both reservoir and run-of-river plants, the difference depending on the specific plant and site characteristics (i.e. type of dam, height/width ratio, capacity of reservoir, location, installed electrical capacity, load factor, and dedicated transmission lines). However, small hydro plants may have somewhat higher GHG emission factors.

Pumped-storage environmental burdens are functions of both the input electricity source and total efficiency, the latter assumed to be 70%. Hence, results for GHGs are strongly dependent on the assumption made for the input electricity mix. Results from the Swiss LCA study range from the lowest value for Norway of 0.027 kg CO_2-equiv./kWh (mix based predominantly on hydro) to 1.62 kg CO_2-equiv./kWh for Poland (mix based mostly on coal). However, these results should be compared only with other systems providing the same service as pumped storage: i.e. peak load.

Issues Related to Direct GHG Emissions from Hydro-Electric Reservoirs

In order to compare hydropower with other electricity systems, direct GHGs emitted during the operation of a reservoir, due to the decomposition of organic matter, should be accounted for in addition to indirect emissions related to the construction, maintenance and decommissioning of the plant.

Since the late 1980s, much research has been invested in the assessment of direct GHG emissions from the surfaces of reservoirs. Key parameters contributing to total GHG emission factors are: climate (in tropical reservoirs, bio-degradation is faster); amount of flooded bio-mass; the nature of the flooded soil; the depth of the reservoir (a factor which controls methane oxidisation); and the ratio of energy production to surface area.

The state-of-the-art situation in 2003 concerning the estimation of GHG emissions from reservoirs involves considerations of the emissions from flooded land area only, together with contributions from CO_2 diffusive emissions for the initial 10-year period after first filling, CH_4 bubbling and diffusive emissions, N_2O diffusive emissions, and degassing emissions for all the above species [11]. Ongoing research is directed towards modelling the net emissions, including the entire catchment area, and the various phases in the lives of the reservoirs in the boreal, temperate and tropical regions, including pre-impoundment and natural GHG emissions (which may be substantial [12]).

Diffusive flow generally leads to greater GHG emissions than bubbling flow. Indeed, t has been reported [13] that about 99% of CO_2 is released through diffusion, whereas for CH_4 the same mechanism releases only 14% to 90% of the total flow. Canadian researchers report [11] that diffusive CO_2 accounts for 80% of the total emissions in boreal and temperate sites, whereas methane bubbling makes up 60% of total emissions in shallow tropical sites, but less than 10% in deep reservoirs. In general, N_2O contributes only a few percent.

Canadian researchers have also estimated total GHG emissions (using IPCC 1996 GWP) of 265 (±150) g CO_2-equiv. m^{-2} per annum from boreal and temperate reservoirs, on the basis of measurements of diffusive emission fluxes at the water surfaces of 15 different hydroelectric developments [11]. Data for 6 tropical reservoirs was summarised, giving 4300 (±2300) g CO_2-equiv. m^{-2} per annum for reservoirs with large shallow-water areas (average depth less than 10 m), and 1700 (±400) g CO_2-equiv. m^{-2} per annum for deeper reservoirs (average depth >25m). It was concluded that reservoirs in tropical regions emit between 5 and 20 times more GHGs than those in boreal and temperate regions [11].

Brazilian researchers have reported results of two surveys of measurements for several reservoirs located in different parts of the country [12]. By extrapolating these surveys to one-year estimates, they obtain approximate ranges of 1050 to 3930 g CO_2-equiv. m^{-2} per annum (using IPCC 1996 GWP) for total CO_2 and CH_4 emissions. Methane contributed 7% to 86% of the total GHG emissions. Using an average capacity factor for Brazilian hydroelectric plants of 50%, direct emissions of 12 to 2077 g CO_2-equiv./kWh can be derived for the different reservoirs. The average GHG emission factor for direct CO_2 and CH_4 emissions from seven plants, weighted according to energy generation, would be around 340 g CO_2-equiv./kWh. However, it would be inappropriate to use such estimates for the lifetimes of the plants, because variations of the fluxes may occur.

On the basis of measurements of direct emissions taken by several teams in boreal and tropical reservoirs, and the expected electricity production (assuming a load factor of 0.6 and a lifetime of 100 years), Canadian researchers [11] have estimated ranges of GHG emission factors between 0.01 - 0.06 kg CO_2-equiv./kWh, whereas emissions from tropical reservoirs would range between 0.2 - 3 kg CO_2-equiv./kWh. The highest specific emissions were found in shallow (average depth between 4m and 10 m), tropical hydroelectric developments, where the ratio of energy production to flooded area is low. A 1997 survey [10] reported for the La Grande Complex in Canada a direct GHG emission of 34 g CO_2-equiv./kWh, based on measurements. (This would reduce to 15 g CO_2-equiv./kWh from all sources, assuming a gradual return to zero of net emissions after 50 years of operation.)

In addition to the decomposition of organic matter, there is evidence in Finnish reservoirs of a strong influence of flooded peat soil on methane emissions, especially if the areas are shallow. Finnish sources, based on direct measurements, have reported an average range of 65 to 72 g CO_2-equiv./kWh for such reservoirs [14,15].

Considering the potential developments of hydropower, the issue of net GHG emissions in various regions of the world deserves further attention

2.3.3 Wind

The production of electricity from wind turbines generates no direct GHG emissions, though indirect emissions may be attributed to the construction and assembling of the wind power plant itself, the production and assembling of the materials from which it is composed, the transport of these materials to the site, and the waste disposal processes.

The Swiss LCA study [1] analysed several such wind turbines, under both Swiss-specific and European-averaged conditions. Plants of 30 kW, 150 kW, 600 kW and 800 kW were modelled for on-shore conditions, and one unit (based on data from the wind park Middelgrunden, near Copenhagen) of 2 MW capacity for off-shore conditions. Actual capacity factors in Switzerland range from 8% to 14%. The average for Europe was assumed to be 20% for on-shore, and 30% for off-shore, units. The wind mix in Switzerland is mostly composed of 600 kW and 800 kW capacity turbines, making up 57% and 40% of wind electricity in 2002, respectively.

The GHG emissions decrease with increasing installed capacity of the turbine. Under Swiss conditions, a 800 kW unit emits 20 g CO_2-equiv./kWh, while, under average European conditions, this decreases to 14 g CO_2-equiv./kWh for both on-shore and off-shore units. Other studies [1] have estimated a typical release of GHGs associated with wind turbines in areas with optimal wind speed of the order of 10 g CO_2-equiv./kWh.

For an 800 kW plant, about 72% of GHG emissions stem from the production of materials, about 15% are caused by material processing, 8% by waste disposal, and the rest from transport, final assembling and installation. The fixed parts (foundation and tower) are responsible for 23% of the CO_2 emissions, and the moving parts for the rest. For the 2 MW off-shore plant, about 81% of the emissions originate from the production of materials used to construct the device; the fixed parts make up 44% of the total.

2.3.4 Solar

Mono (mc-Si) and poly-crystalline (pc-Si) silicon cell technologies, utilised in current photovoltaic (PV) panels, have been analysed [1] in a Swiss LCA study, and specifically for Swiss conditions (i.e. yield of 885 kWh kW_{peak}^{-1} per annum for slanted-roof units). The plants considered were grid-connected 3kW_{peak} units, installed on buildings in two (integrated and non-integrated slanted-roof) configurations; both façade and flat-roof options were considered. For this study, the production chain has been decomposed into detailed steps, and the efficiency of the PV cells is assumed to be 16.5% for mc-Si, and 14.8% for pc-Si, respectively.

Use of electronic-grade silicon from the European electronic industry was assumed as input to the PV industry. The production of metallurgical grade silicon is assumed to occur in Norway (hydro-based electricity mix), and the purification to occur in Germany, with use of a mix of hydropower and a highly efficient combined heat and power plant. To reflect current market conditions, besides the use of electronic grade materials, a 50% share of off-grade silicon has been considered for the production of the wafers. Energy usage for purification was allocated on the basis of the economic value of the two co-products, plus silicon tetrachloride. (Note that changing the above assumptions may lead to substantial differences in the calculated emissions.) In the future, solar-grade silicon will probably be used, with associated reduced energy inputs for purification. This production was also modelled in the Swiss study, assuming an increase of cell efficiencies to 17.5% for the mc-Si, and to 15.7% for the pc-Si systems; thirty years lifetime was considered under all conditions.

The above assumptions lead to a decrease of total GHG emissions compared to previous analyses. Non-integrated, slanted-roof mc-Si panels yield about 73 g CO_2-equiv./kWh, whereas, for the pc-Si technology, this reduces to 59 g CO_2-equiv./kWh; integrated types have slightly lower LCA emissions. For future conditions, the emissions may decrease to 46 g CO_2-equiv./kWh and 39 g CO_2-equiv./kWh for the mc-Si and pc-Si technologies, respectively [1].

2.3.5 Heat Pumps

An attractive alternative to fossil fuel boilers is the use of heat pumps. Heat pumps can gain heat from ambient air, from the ground, or from groundwater. The seasonal performance factor (SPF) of an electrical heat pump is the ratio of the annual heat energy output to the annual electrical energy input. The SPF depends on the efficiency of the heat pump (COP, Coefficient of Performance), but also on the local climatic conditions and the actual integration of the heat pump into the building (e.g. low-temperature or high-temperature hydronic heat distribution system). Field measurements have shown that the average SPF in Switzerland during 1998 was about 3.2. Air/water heat pumps using ambient air had an average SPF of 2.8, while brine/water heat pumps (using ground heat) had an average SPF of 3.9.

The total GHG balance of an electric heat pump depends strongly on both the SPF of the heat pump and the electricity mix used for operation. A heat pump is almost CO_2-free, provided an almost CO_2-free source of electricity (renewable or nuclear) can be utilised. But, heat pumps can also improve the GHG balance of heating if electricity from fossil fuels is used. A combination of a heat pump, with a seasonal performance factor of 3.5, and a cogeneration plant, with an electric efficiency of 35%, a total efficiency of about 90%, and electric transmission losses of 2.5%, yields about 174% heat relative to the fossil fuel input. The most modern natural-gas, combined-cycle (CC) power plants in Europe can attain a net electrical efficiency of 57-58%. A combination of a 57.5% CC power plant with an SPF 3.5 heat pump yields a heat efficiency of about 200%!

On the negative side, however, are the emissions of refrigerants from heat pumps (besides the indirect emissions from material production and maintenance, though this is valid also for other systems). The HFC refrigerant emissions from heat pumps over their lifetimes are roughly 2 to 5 mg/MJ. For a heat pump with refrigerant R134a (HFC-134a), which has a 100-years Global Warming Potential of 1300, this corresponds to GHG emissions of about 3 to 6 g CO_2-equiv./MJ [1]. Compared with the CO_2 emissions of a natural gas boiler, of the order of 60 g/MJ, heat pumps can still provide a GHG reduction potential, provided the electricity supply is favourable from the GHG point of view.

Assuming a market penetration of 30% in the building sector (using presently available technology), the IEA Heat Pump Centre has estimated the CO_2 reduction potential of heat pumps in 1997 to be about 6% of the total global CO_2 emissions from fossil fuels. Note, however, that this survey does not include a full LCA analysis, and consequently can only be regarded as a rough estimate.

3 SYNTHESIS AND CONCLUSIONS

The energy sector plays a dominant role in regard to world-wide emissions of GHGs, in particular CO_2. About 77% of annual CO_2 emissions world-wide originate from fossil-fuel combustion [3]. The contribution of the energy sector to the emission of the other most important GHGs, namely CH_4 and N_2O, is much smaller in relative terms, but still important. Based on the total GWP of all GHGs emitted annually world-wide, the overall share of the energy sector in emissions relevant for global warming is of the order of 50%.

3.1 Current Technologies

The detailed results presented in Section 2 are summarised here, and focus on the results of the Swiss LCA study for Switzerland and Europe, which was intended to cover a broad spectrum of options. For a number of detailed comparisons of results for specific chains with other studies, and for special issues, we refer the reader to Section 2 of this report. Figure 6 shows the overall contributions of the various GHGs to power production. In Fig. 7, the same results are given, but with the differences between contributions from power plants and the rest of the chain specifically emphasised. The Figures are complemented by the data provided in Table 2, which show the ranges of GHG emissions from the European, country-specific energy systems.

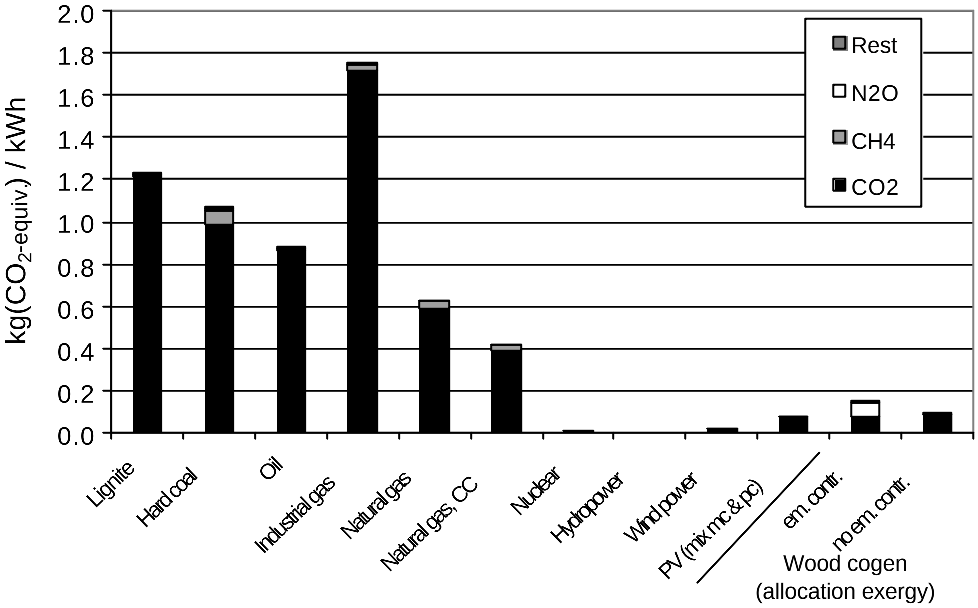

Fig. 6: Overview of full chain GHG emissions for different electricity generation systems [1]. Lignite, hard coal, oil, industrial gas, natural gas, and nuclear refer to energy systems associated with average UCTE power plants for the year 2000. Natural gas CC refers to combined-cycle power plants utilising the current best technology, and with gas supplied by the European high-pressure grid. The renewables — hydropower, wind power, photovoltaic, wood — refer to data pertinent to Switzerland.

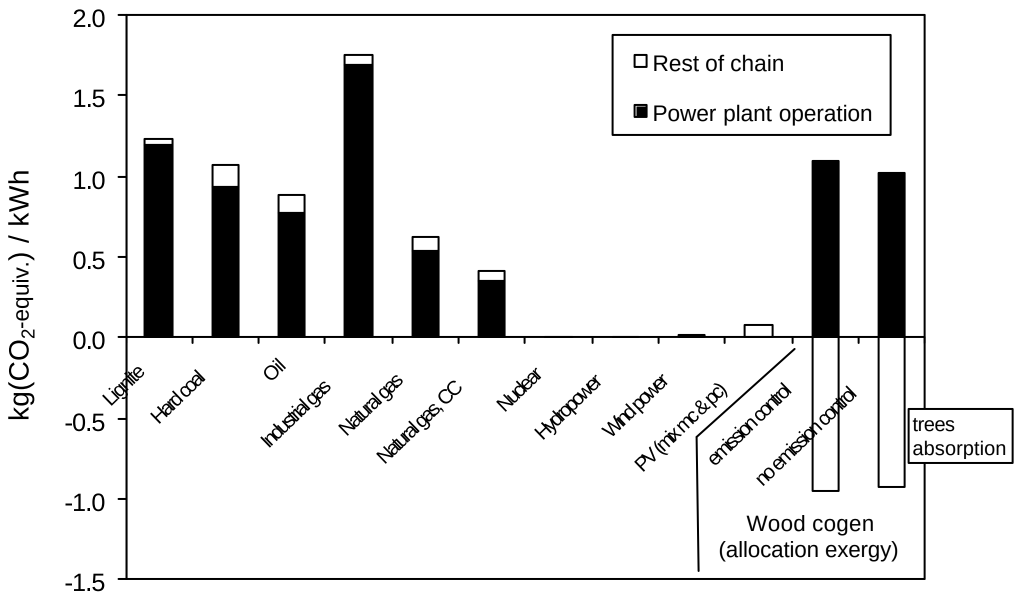

Fig. 7: GHG emissions from power plant operation, and from the rest of the chain, for different electricity generation systems [1]. For explanations see Fig. 6 and text.

Table 2: Ranges of GHG Emissions per kWh Electricity Production from European and Country-Specific Energy Sources, using a GWP of 100 years [1].

	Minimum (kg CO_2-equiv./kWh)	Maximum (kg CO_2-equiv./kWh)
Lignite	1.060	1.690
Hard coal	0.949	1.280
Oil	0.519	1.190
Industrial gas	0.865	2.410
Natural gas	0.485	0.991
Nuclear power	0.008	0.011
Hydropower[1]	0.003	0.027
Wind power[2]	0.014	0.021
PV (mix mc & pc)[3]	0.079	-
Wood cogeneration[4]	0.092	0.156

[1]Mix of reservoir and run-of-river plants.
[2]Calculated for average conditions in Switzerland (maximum) and Western Europe (minimum).
[3]Calculated for average Swiss conditions.
[4]Calculated for 6400 kWth (400 kWe) plant; allocation exergy; no emission control (minimum); emission control SNCR (maximum).

3.1.1 Electricity Systems Ranking Based on GHG Emissions

GHG emissions per unit of generated electricity are, typically, highest for industrial gas, followed by lignite, hard coal, oil and natural gas. Hydro exhibits very low GHG emissions in boreal and temperate regions: in most cases, two orders of magnitude lower than for coal. However, hydro-electric developments in tropical regions may emit during operation between 5 and 20 times more GHGs, which at the higher range is comparable to emissions from fossil sources. Taking into account full energy chain contributions (including also the “grey” ones), GHG emissions from nuclear and wind energy (under favourable wind conditions) are in the same low range as for hydro. The corresponding net emissions for biomass are in the middle range: i.e. one order of magnitude lower than coal, and one order of magnitude higher than for nuclear or wind power. The same applies to older-type solar photovoltaic systems in countries with climate conditions similar to those in central Europe, while current photovoltaic technologies exhibit smaller differences compared to nuclear and wind. However, better performance can be achieved in southern countries.

3.1.2 Differences between Industrialised and Developing Countries

Based on quite limited comparative material for fossil systems, a pattern can still be distinguished: namely, that the GHG emissions are significantly higher in developing countries. This is due to the use of technologies of lower efficiency, as well as distinct features of the particular fuel cycles: e.g. relatively large methane emissions from mines and gas pipelines, and from coalfield fires in China.

3.1.3 Dominant GHGs

CO_2 dominates GHG emissions from all energy systems. In the case of hard coal and natural gas, the methane contribution in terms of CO_2-equivalents may reach 10% as a consequence of high leakage rates from coal mines and gas pipelines. N_2O may be of high relative importance for wood cogeneration if pollutant emission controls are applied that employ catalysts to generate N_2O..

3.1.4 Role of GHG Emissions other than from Power Plant

For fossil systems, power-plant GHG emissions are clearly dominant. It can be noted, however, that in the case of major pollutants, the situation may be quite different, i.e. that emissions from power plants are higher than the other contributions, but that the latter may still be very substantial. For European conditions, the upstream part of the chain typically contributes about 10% of the total GHG emissions for the hard-coal chain, slightly more than 10% for the oil chain, and can approach 20% for conventional natural gas systems. For nuclear, wind and solar photovoltaic, the GHG emissions from other sources than from power plants are totally dominant in relative terms. The same applies to typical hydro plants, with the exception of dams operating under special conditions, and resulting in very large direct emissions from reservoirs [1].

For comparisons of current heating and cogeneration systems, we refer to Figs. 3,4,5. Gas boilers are, as expected, better performers than oil boilers. Biomass exhibits the best GHG performance, along with heat pumps, provided that electricity input to the latter comes from zero- or low-carbon sources. Cogeneration based on biomass is clearly favourable in terms of GHG emissions, if compared against the corresponding gas and oil systems. Evaluation of cogeneration is subject to variability, depending on which allocation scheme is employed.

3.2 Electricity Mixes

Calculating and presenting GHG emission data for single technologies is important for comparisons and decision-making. However, it is also essential to estimate the total overheads associated with the electricity mixes. These can then be used in LCA studies of their products.

Two approaches are currently used to generate the relevant mixes: namely, the marginal and average mix approaches. For the marginal approach, it is proposed to use the latest available technology, or mix of technologies (e.g. the cheapest available for base load, or the technologies which will most probably cover an increase in demand, or the specific energy technology which will be chosen for a particular process or industry), whereas with the average approach, only average mixes supplying the grid are considered.

The Swiss LCA study [1] addressed national production mixes for all European countries and the three major associations of electricity transmission operators, UCTE, CENTREL and NORDEL, for the year 2000. GHG results for these electricity mixes are summarised in Table 3.

Table 3: LCA-based GHG emissions for European Electricity Associations and Countries [1].

Electricity Mix	($kgCO_2$-equiv./kWh)
Production mix (at busbar)	
UCTE	0.470
CENTREL	0.932
NORDEL	0.132
Country-specific production mix [1]	0.007 - 1.13
Country-specific supply mix [1, 2]	0.010 - 1.11

[1]Minimum: Norway. Maximum: Poland.
[2]The model used adds all electricity imports to the domestic production, recalculates the shares of technologies on this basis, and applies this portfolio to domestic supply and exports.

Depending on the distribution of the technologies, the total GHG emissions can vary by several orders of magnitude, from the hydro-based Norwegian mix to the coal-based Polish mix. Additionally, the study addressed the issue of the supply mix. This was modelled by merging all imports to the domestic production mix, and then recalculating the share of technologies to be used, both for the domestic supply mix as well as for the export mix. This model may somewhat overestimate the effective import shares, and may not strictly follow seasonal exchanges. The results for Switzerland, a country with significant exchanges of electricity with neighbouring countries, due to its central position in Europe, are given in Table 4.

Table 4: LCA-based GHG emissions for Swiss Electricity Mixes [1].

Electricity Mix	($kgCO_2$-equiv./kWh)
Production mix (at busbar)	0.018
Supply mix (with import/export)[1]	0.120
High Voltage	0.123
Medium Voltage	0.126
Low Voltage	0.142

[1]See note 2 in Table 3.

The GHG-free production mix based on hydro and nuclear (58% and 38%, respectively, for the year 2000) changes to a supply mix with quite significant fossil components as a consequence of imports from Germany. Another issue concerns the influence of the grids (losses and material usage) on the GHGs associated with the electricity services. The analysis performed under Swiss conditions leads to increases of GHGs by 2.5%, 5%, and 18% with respect to the supply mix at the busbar of plants in the case of high, medium, and low voltage levels, respectively. With equal network losses, the increases may be lower in percentage terms for the case of country-specific supply mixes with higher fossil share.

A Japanese study [16] covered the electricity production mixes for ten electricity companies. Besides direct emissions from fossil plants, the authors included the emissions from the upstream chains, but excluded construction and decommissioning of the various facilities, as well as the transport systems. Only CO_2 and CH_4 were considered. Using GWP from IPCC 2001, results lie in the range 296-795 CO_2-equiv./kWh for nine of the companies (average 468 g CO_2-equiv./kWh), and 1079 g CO_2-equiv./kWh for Okinawa. Remarkably, the UCTE (2000) and the Japanese production mixes have practically the same GHG intensity.

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