LIFE CYCLE ANALYSIS OF ELECTRICITY SYSTEMS: METHODS AND RESULTS

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Abstract

The two methods for full energy chain analysis, process analysis and input/output analysis, are discussed. A combination of these two methods provides the most accurate results. Such a hybrid analysis of the full energy chains of six different power plants is presented and discussed. The results of such analyses depend on time, site and technique of each process step and , therefore have no general validity. For renewable energy systems the emissions from the operation of a back-up system should be added.

1. INTRODUCTION

Besides "conventional" issues, such as the provision of energy services with low costs, today's energy supply planning has to take into account environmental preservation and other aims. Aims of the energy policy - as formulated in German energy programs - are:

- security of supply
- low costs
- avoidance of risks for human health
- protection of limited natural resources
- protection of the environment
- consideration of the interests of developing countries
- inclusion of the interests of future generations.

One aspect at the centre of public and expert's discussion is global warming. This is considered to be a problem caused by the emission of greenhouse gases (GHGs) like CO_2, CH_4, N_2O etc.

The assessment of energy technologies has to take into account all these aims. Typical questions to be answered in assessing energy technologies are

- Assessment of weak points: What are the major problems or weak points of a technique? Are improvements possible?

- Choice of techniques: What technology or energy system should be chosen from different alternatives to meet a future energy demand?

- Assessment of a Technology: Is it useful to apply a technology? What should be the role of an energy technology in a future energy system?

- Strategies for reducing negative effects: What is the most efficient strategy (bundle of measures) to reduce negative effects caused by energy supply-systems (e.g. reduction of greenhouse gas emissions)?

- Future energy systems: How should a future optimal energy system look like?

A necessary tool to answer these questions is the Life Cycle Analysis (LCA) which allows to assess the entire economic, environmental and social impacts related to a product, service or technical system. 'Entire' means, that the impacts of upstream and downstream processes have to be included in the analysis. LCA can be subdivided into the four steps "system definition", "inventory analysis", "impact assessment" and "evaluation".

In the "system definition" the topic of the LCA has to be defined precisely. This includes the definition of the object under study (product, service, system or technique), but also the description of the boundaries of the assessment, aims and criteria of the analysis, time horizon and methodical assumptions. In the case of a comparative assessment the compared objects should have the same function, e.g. for electricity the same security of supply. The goal of the second step, the "inventory analysis", is the quantification of input and output flows of substances, heat, oscillation, etc.

The third step is the "impact assessment" which includes the quantification of effects or damages that are caused by the input and output flows of the system to be analyzed.
In the last step, the impacts have to be evaluated and to be summarized into one single characteristic. There are still no general rules. One approach is the monetization of impacts. It deduces monetary weight factors from individual preferences and from economic damages caused by the impacts. However, it should be noted, that for most technology assessments, other methods have to be combined with LCA. In principle, LCA is able to answer the above first and second question, i. e. the comparison of techniques, that could meet a certain additional demand and the assessment of weak points of a technology or system.

For assessments involving the whole national energy system, e.g. for the estimation of the role and potential of a technology within a future energy system or the identification of efficient emission reduction strategies, it is more appropriate to use energy optimization models, that reflect the processes and links of the whole energy system. Nevertheless, LCA is then useful to determine the input and output flows of the different processes.

In the following the methods to carry out a LCA are described. These methods then are used to calculate greenhouse gas emissions for several energy technologies that produce electricity in Germany.

2. METHODS OF INVENTORY ANALYSIS

In principle, there are three methods for carrying out a LCA: process analysis, input/output analysis and a combination of these two methods.

Traditionally, the process analysis is used to perform the inventory analysis. Process analysis is a micro analysis in which a complex system is divided into well defined process steps. Fig. 1 shows as an example a power plant as a process, that needs various inputs and, apart from its main output (electricity), produces various impacts on the environment. Since the input of a process stems from other processes, and, moreover, usually the output of a process again is input to another process, a process chain can be assembled by linking these input and output processes. Although a process chain usually has a defined end (e.g. one kWh of electricity produced or delivered), it doesn't have a clear beginning, because each process in the chain needs inputs delivered by other processes, etc. (Fig. 2). This means, that it is necessary to stop somewhere within the upstream part of the process chain and to leave the remaining links untreated. E.g. one could cut the chain after a certain number of steps have been regarded. However, then the error caused by the cutting of the chain remains uncertain.

A possible way to avoid this difficulty and to analyze all intermediate products is the use of input/output (I/O) analysis, since the I/O tables of a national economy describe the entire production of the branches and their interdependencies. Making the assumptions that no change

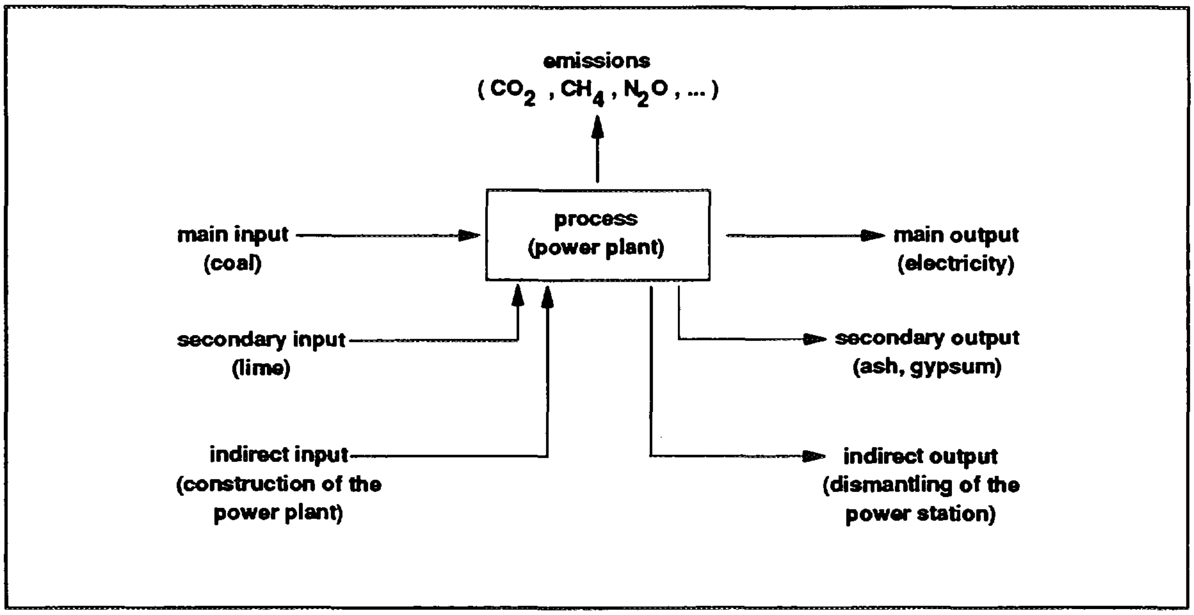


Fig. 1. The process as the basic element of process analysis.

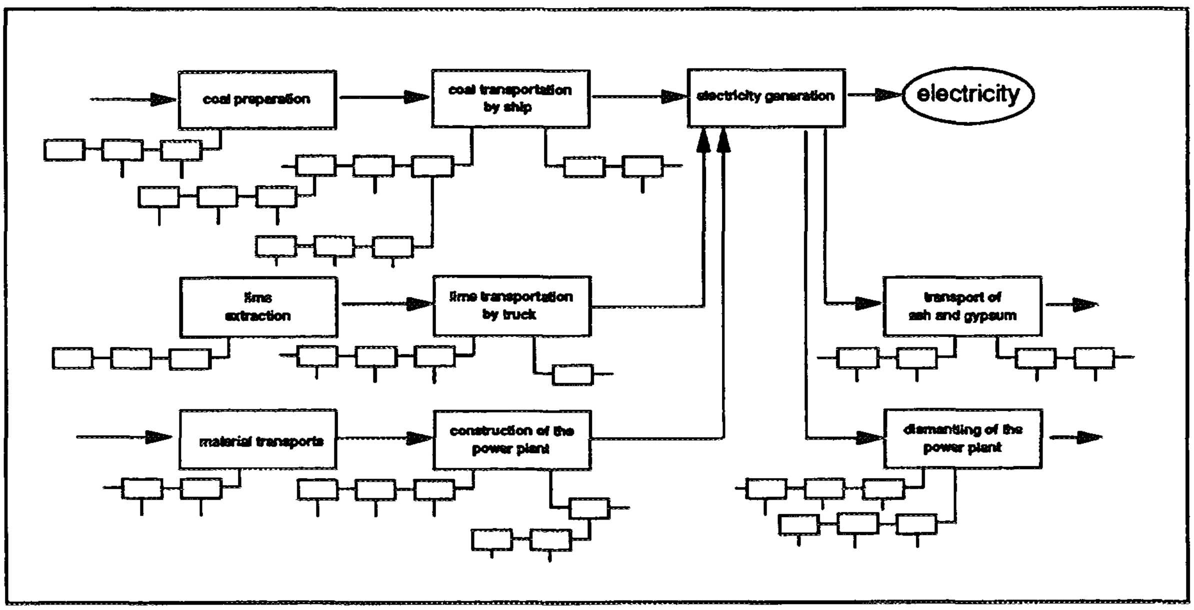


Fig. 2. Process analysis of a coal fired energy supply system.

of stock and no substitution take place, the total production required for providing a final demand can be calculated (Fig. 3). Branch specific emission coefficients can be deduced from production statistics, emission statistics and the energy balance of a country, so that a specific coefficient matrix can be created. Multiplying the production required in the different sectors of the economy with the corresponding emission coefficients gives the emissions for the whole life cycle (Fig. 4).

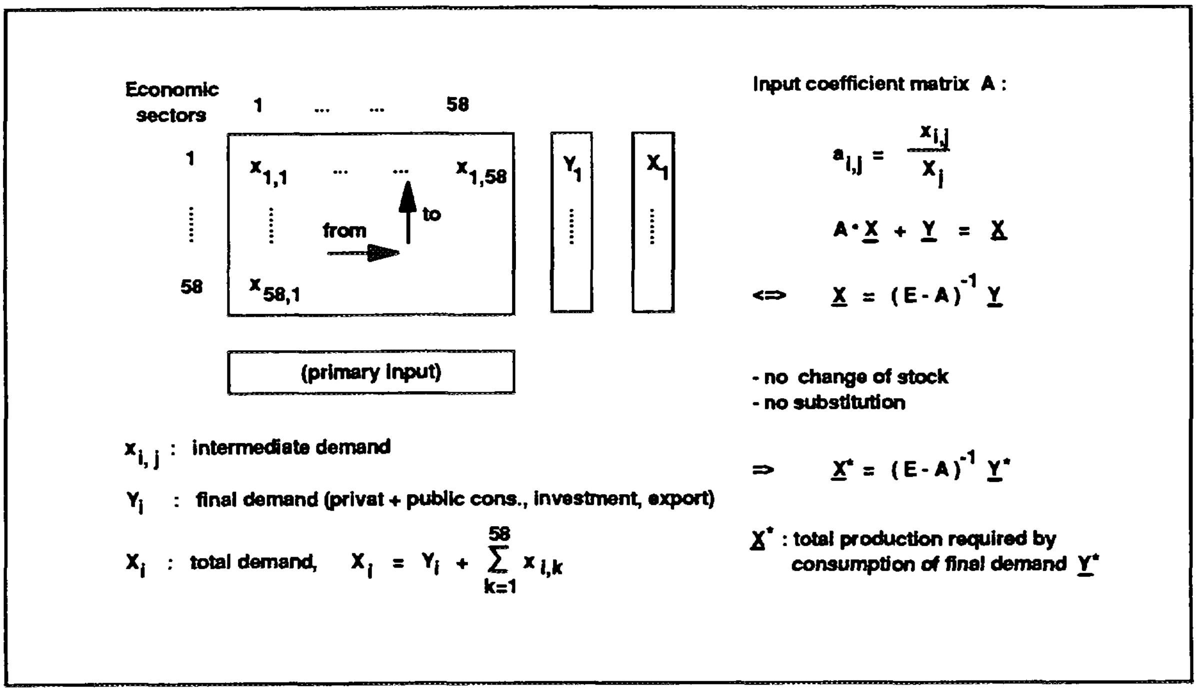


Fig. 3. The static Leontief model.

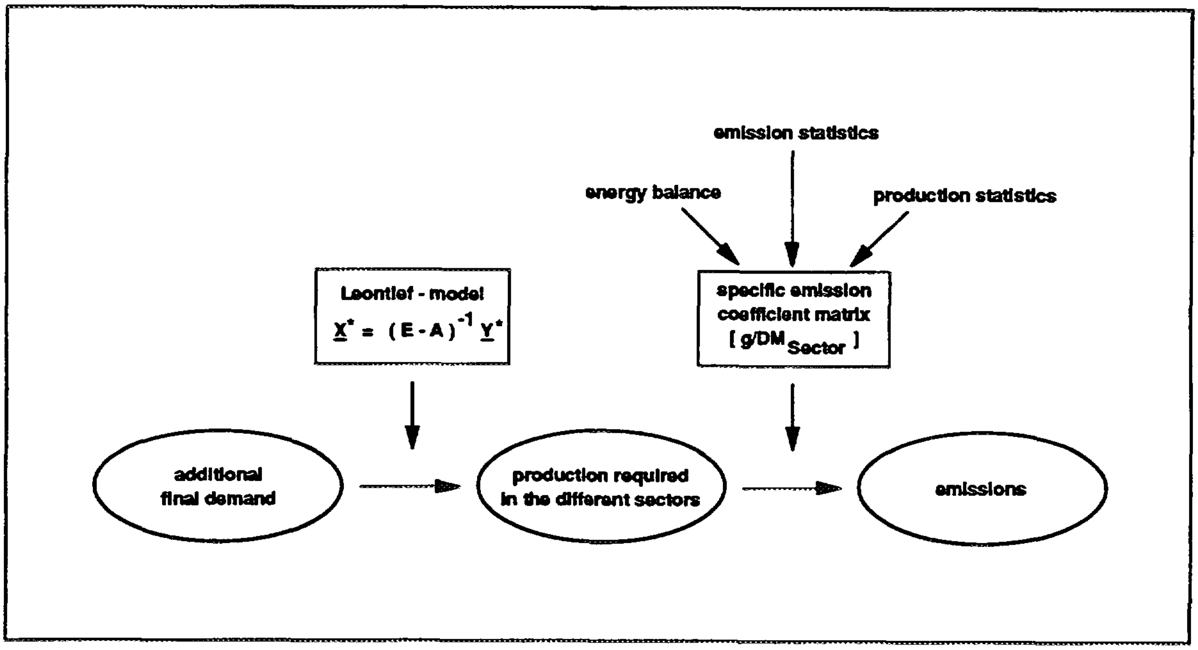


Fig. 4. Estimation of emissions caused by an additional demand using I/O analysis.

The advantage of I/O analysis is, that results for the whole chain are achieved with a relatively small effort, provided suitable I/O tables are available. Of course, only emissions from within a country are obtained. Imports, which have caused emissions outside the country, have to be assessed separately. The main disadvantage of I/O analysis is, that each sector generally includes economic activities with many technical processes which are very different. Therefore, I/O analysis averages over technical processes instead of looking precisely at the process that should be evaluated. Of course, the more sectors are included in the I/O table, the more accurate are the results. However, in most West-european countries I/O tables have less than 100 sectors. Generally, it is more accurate to look directly at the process instead of analyzing the economic sector in which the process is incorporated. For this reason a combination of process analysis and I/O analysis, with the advantages of both methods, might achieve an acceptable degree of accuracy on the one hand and an entire balance of emissions with an acceptable data requirement on the other hand.

To include the full branch production connected with a product or service, the balance has to start from I/O analysis. Then the processes and process chains that are to be balanced by process analysis have to be decoupled from the I/O analysis. It is general experience that a relatively small number of processes is sufficient to cover a substantial part of the LCA, so that an acceptable degree of certainty is achieved.

In order to avoid double counting of process emissions, the monetary value of the output of the process can be subtraced from the monetary value of the process sector (part 1 in Fig. 5). If not only one process, but several processes of a chain are calculated with process analysis, then the monetary values of this process chain have to be subtracted from the corresponding values of the I/O analysis. The equation for that is provided in part 2 of Fig. 5. As an example of a combined analysis the total GHG emissions caused by truck transportation are calculated using the German I/O table of 1988.

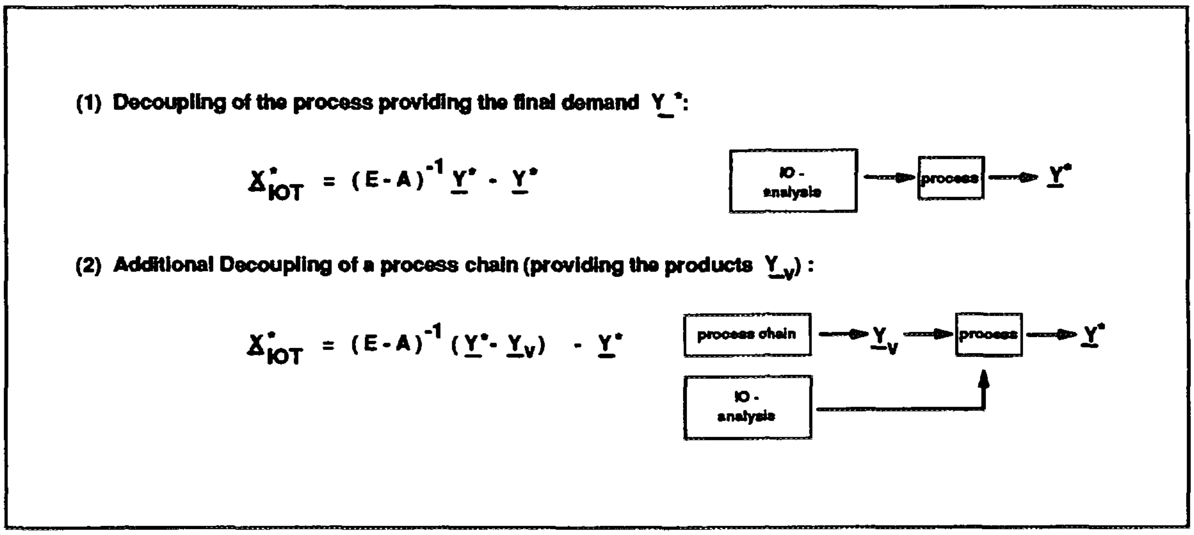


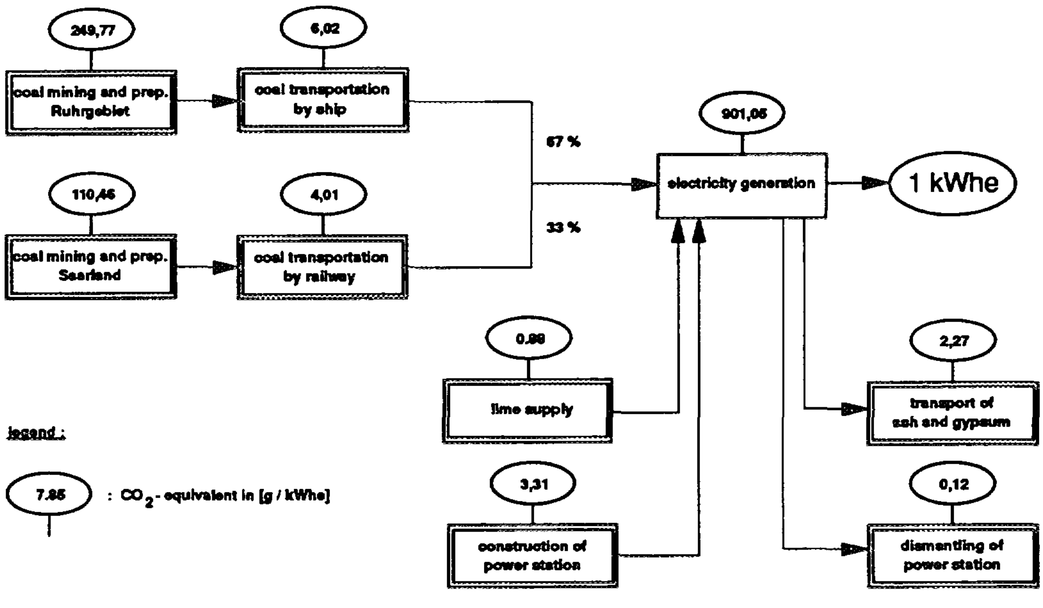
Fig. 5. Combined use of process analysis and I/O analysis.

In 1988 the average costs of transportation by truck amount to 0.235 DM per tkm (ton-kilometers). This service is provided by sector 48: "achievement of other traffic". Sector 48 receives supplies from sector 10, "petroleum products", at the rate of 0.0736 DM per DM output. Using these data, I/O analysis yields an estimate of the emissions of 83.3 g CO_2 eq. (equivalent) per tkm. If the process of truck operation is "subtracted" and the "process" emissions of truck operation are added, one obtains 205.7 g CO_2 eq./tkm. However, applying process analysis also to fuel supply, the outcome is 218.2 g CO_2 eq./tkm. From that amount, only 28 g CO_2 eq./tkm stems from I/O analysis. This shows, that the use of hybrid I/O-process analysis improves the result considerably.

The following hypothetical electricity supply systems, assumed to be in operation in Germany, were analyzed:

- a coal-fired power plant: 689 MW gross, net efficiency 37.6 %, 4010 full load hours/year, lifetime 35 years;
- a lignite-fired power plant: 624 MW gross, net efficiency 36.2 %, 7500 full load hours/year, lifetime 20 years;
- a nuclear power plant 1300 MW gross, LWR, 6000 full load hours/year, lifetime 30 years;
- a solar power station: 25 kW, polycrystalline cells, production 23 MWh/year, lifetime 25 years;
- a wind power station: 0.5 MW, production 1200 MWh/year, lifetime 20 years.

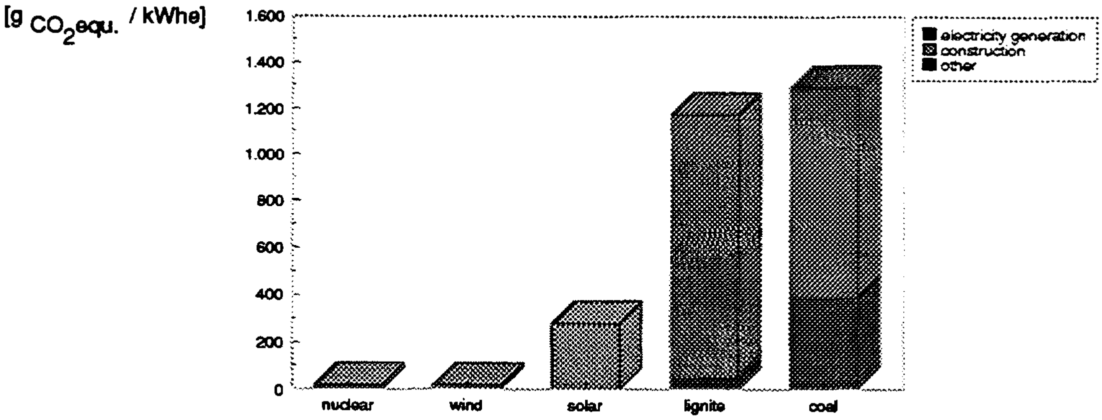
Emissions were calculated with a combination of process analysis and I/O analysis as described above. Fig. 6 shows the results for the coal fired power plant subdivided into process step and I/O method used. Obviously, the emissions not covered by the process analysis amount to only 1,4 % of the total emissions. The main contributors are the operation of the power plant and the methane emissions from the coal mine. The emissions of greenhouse gases were expressed in g CO_2-equivalents using the IPCC greenhouse warming potential (GWP) for a time horizon of 20 years. For such a time horizon the GWP of CH_4 is 35.



coal fired power plant	CO2 - equivalent in [g / kWh(el)]								
	Process Chain Analysis				Input/Output Analysis				
	CO2	CH4	N2O	total	CO2	CH4	N2O	total	total
electricity generation	900,00	1,05	0,00	901,05	-	-	-	-	901,05
coal transport	7,33	7,33	0,00	7,49	2,54	0,00	0,00	2,54	10,03
coal mining and preparation	14,63	345,56	0,04	360,23	12,56	0,00	0,00	12,56	372,79
lime supply	0,78	0,03	0,00	0,81	0,07	0,00	0,00	0,07	0,88
transport of gypsum, ash	2,01	0,07	0,00	2,08	0,19	0,00	0,00	0,19	2,27
construction of power plant	-	-	-	-	3,31	0,00	0,00	3,31	3,31
dismantling of power plant	0,11	0,00	0,00	0,11	0,01	0,00	0,00	0,01	0,12
				1271,77				18,68	1290,45

Fig. 6. Combined analysis of the coal fired energy supply system.

Fig. 7 shows the aggregated results from our analyses of electricity generation systems. Nuclear power generation and power generation by wind turbines have the lowest GHG emissions, both in the range of about 18 g CO_2 equ./kW(el).h. The electricity supply by solar-power station causes GHG emissions of 279 g CO_2 equ./kW(el).h, whereas the highest GHG emissions are from power plants fired with fossil fuels, such as lignite, 1175 CO_2 equ./kW(el).h, and coal, 1290 CO_2 equ./kW(el).h. One should keep in mind that the effect of global warming is only one aspect to be considered in technology assessment of energy supply systems.



coal	**1290,45**
- electricity generation	901,05
- coal transport	10,03
- coal mining and preparation	372,79
- lime supply, transport of gypsum, ash	3,15
- construction of power plant	3,31
- dismantling of power plant	0,12
lignite	**1174,94**
- electricity generation	1127,42
- coal mining, preparation, transportation	41,02
- transport of lime, ash, gypsum	1,76
- construction of power plant	4,52
- dismantling of power plant	0,06
- construction of bucket wheel excavator, spreader, conveying belt	0,16
solar	**278,79**
- construction of solar power station (including materials etc.)	258,14
- providing of factory buildings	20,65
wind	**18,21**
- construction of wind power station	16,26
- providing of factory buildings	1,95
nuclear	**18,63**
- construction of nuclear power plant	6,58
- uranium mining	5,18
- conversion	2,24
- enrichment	0,78
- production of fuel element	0,11
- providing of factory buildings	3,74

Fig. 7. Greenhouse gas emissions from various energy systems.

Table I presents other environmental and health impacts caused by electricity generation. The error bars in Table I do not represent the uncertainty of the calculated values. They result from the assessment of different options, e.g. underground or open pit mining, assumption of different average wind speed, etc.

TABLE I. ENVIRONMENTAL AND HEALTH IMPACTS OF POWER GENERATING SYSTEMS

	Wind	Solar	Coal	Nuclear
Emissions (kg/GW.h)				
- SO_2	10.9-23.5	300-380	704-709	33-50
- NO_x	16.0-34.2	300-380	717-721	64-96
- dust	2.0-4.3	60-80	150	6-8
Land use (m^2/GW.h/a)				
- totally built over	1300-2300	0-47 200	30-60	54
- restricted usage	10 600-71 000	0	1400	620
- mining	0	0	250-20 700	1350
Occupational risks				
- death/TW.h	0.02-0.05	0.10-0.19	0.22	0.04-0.11
- illness & injury/TW.h	80-200	600-1100	2300	209-218
Public risks				
- death/TW.h	0.0005	0.009-0.011	0.21-0.74	0.002-0.1
- illness & injury/TW.h	0.23-0.25	0.44-0.54	0.80-12.0	0.06-0.31

3. EVALUATION OF THE RESULTS

For assessing different technologies, the advantages and disadvantages of the various technology options have to be compared. This means, that e. g. differences in greenhouse gas emissions have to be weighed against differences in costs or number of injuries. One possibility to do this in a consistent way is to express all impacts into the some unit, e.g. monetary values. This can best be achieved by monetization of the damages caused by each of the technologies. In the case of greenhouse gas emissions, there are some studies available that estimate the costs of global warming. Some US authors estimate the costs of ca 0.1-0.7 US cents per kW.h for greenhouse impacts from a coal-fired power plant. However, these estimations are still very uncertain, not allowing political decisions to be based on these figures.

One possibility to overcome this difficulty is to estimate abatement costs for achieving a set goal of GHG emission reduction. For example the German government aims at reducing the German CO_2-emissions by 25 - 30 % from 1987 to 2005. After examination of the possible emission reduction measures and their costs, the marginal reduction costs for meeting this aim can be deduced. For the above mentioned German aim marginal costs amount to 80-100 DM/tonne of CO_2 (ca. 6-8 Pf/kW.h for a coal-fired plant), if due to lacking acceptance no new nuclear power plants can be built. If the construction of nuclear power plants is allowed, marginal costs decrease to ca. 40 DM/t CO_2. Another possibility to express GHG emissions into monetary units is to use existing or planned CO_2 taxes as a reference. For example, the European Union plans to introduce a combined CO_2/energy tax. The taxation would increase year by year from 2.8 to 9.4 ECU per tonne of CO_2 (1 ECU = 2 DM) in combination with an energy taxation that increases from 0.2 - 0.7 ECU per GJ.

LCA results can be compared only of electricity generating systems that fulfill the same supply task. For example, it would be incorrect to compare the GHG emitted from production of 1 kW.h of coal-fired electricity with that from 1 kWh of wind power. For a wind turbine is an intermittent power source, and cannot produce this kWh with the some security of supply as the coal-fired plant. Therefore, instead of comparing techniques, systems that are able to provide electricity according to demand with some security of supply, should be compared. This means that a combination of a wind power plant e.g. with a coal-fired power plant as back-up-system has to be compared with a coal-fired plant.

4. SUMMARY

For assessing the contributions of different electricity generating systems to the greenhouse gas emissions, the full energy chain including the fuel cycle and the construction and demolition of the plant should be analyzed.

A full-energy-chain assessment should be performed by using the process analysis method, if necessary complemented by an input/output analysis.

The results of a full-energy-chain assessment depend on time, site and technique of each process step. No universally valid numbers can be given.

For renewable energy systems the emissions from the operation of a back-up system should be added.