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T.S / S.T. 1.1 Environmental effects of energy.
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TOTAL POLLUTION INCLUDING "GREY" POLLUTION: LIFE CYCLE ANALYSIS FOR THE ASSESSMENT OF ENERGY OPTIONS

POLLUTION TOTALE Y COMPRISE POLLUTION "GRISE": ANALYSE INTÉGRALE POUR L' ÉVALUATION DE SYSTEMES ENERGÉTIQUES

CONTAMINACION TOTAL INCLUSO LA CONTAMINACION "GRISA": ANALISIS INTEGRAL PARA LA EVALUACION DE SISTEMAS ENERGÉTICOS

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1. Necessities of total environmental impact inventory
Nécessité d' inventaires écologiques totaux
Nececidades del inventario de contaminación

In the discussion of policies in the energy sector, especially concerning substitution processes or the promotion of renewable energies it has been recognized that the financial aspects, i.e. payback times, have to be complemented by consideration of the invested or "grey" energy, leading to an energetical payback time. If this time is to long, then the envisaged new energy system would require more energy resources than it delivers.

But in fact in many situations the problem of environmental pollution is far more important than the eventual scarcity of energy; serious ecological damage would be caused long before the depletion of the conventional primary energy resources, if they are used according to current technologies. Therefore it is necessary to investigate *total pollution*, comprising, in addition to the emissions during operation, also:

- emissions in the energetical chains upstream (precombustion),
- emissions due to the waste treatment and disposal,
- emissions during the fabrication of the installation, of its components and materials,
- emissions occuring in the decommissioning phase.

Compared to the analogous problem concerning energy, the task is far more complicated because there are a large number of substances to be investigated which are, furthermore, emitted in different sectors of the environment (atmosphere, hydrosphere, lithosphere). A careful, methodologically sound analysis of all relevant steps is therefore necessary, called "life cycle analysis".

This type of assessment is of course needed for all human activities. Studies already done show however that pollution due to energy involved in these activities generally accounts for a major part of the entire pollution; this was demonstrated for buildings <Hofstetter et al 1991> as well as for packaging material <BUWAL 1991>. Total pollution assessment for energy systems has therefore high priority.

2. Methodological aspects
Aspects méthodologiques
Aspectos metodológicos

2.1 Environmental impacts to consider
Impacts écologiques à considérer
Efectos contaminantes de ser tomados en consideración

A typical Life Cycle Inventory (LCI) of a product or a service considers the following environmental impacts (EI) <BUWAL 1990>, <Franklin 1989>, <Tillmann et al 1991>:

- air pollutants,
- water pollutants,
- energy as a resource,
- waste.

As it is a goal of the LCI of energy systems to build up an energy-database for future LCI's and because of the variety of environmental aspects related to energy systems, the environmental impacts should not be limited to the above mentioned list. To limit the investigation only to impacts covered by existing assessment methods or to focus on the "pollutants of the day", might result in ecologically suboptimal solutions. Other and more detailed impacts have to be considered like:

- non-energetic resources,
- land depreciation,
- waste heat (to air and water),
- radiation (ionizing and eventually non-ionizing),
- waste categories and chemical composition of waste.

With the impacts listed above, it is possible to cover most of the known environmental effects connected with energy systems <Guinée 1991>, <IUCN 1991>:

Effects changing the global conditions of system Earth:
- global warming,
- ozone depletion,

Effects causing depreciation inside system Earth:
- depletion and/ or depreciation of non-renewable resources,
- depletion of scarce renewable resources,

- depreciation of ecosystems (by landuse),
- ecotoxicity (water, soil),
- creation of photochemical ozone,
- acidification,
- nutrification,
- radiation.

2.2 Influence and importance of system boundaries
Influence et importance des frontières du système
Influencia y importancia de los limites del sistema

2.2.1 Definition of the system

The first step in doing a life cycle inventory of a product or a service is the definition of the system to be analysed. And here, different kinds of system boundaries play a significant role (see Figure 2.1):

- 1: upstream to the environment,
- 2: downstream to the environment,
- 3: up- and downstream to other anthropogenic systems,
- 4: sidestream.

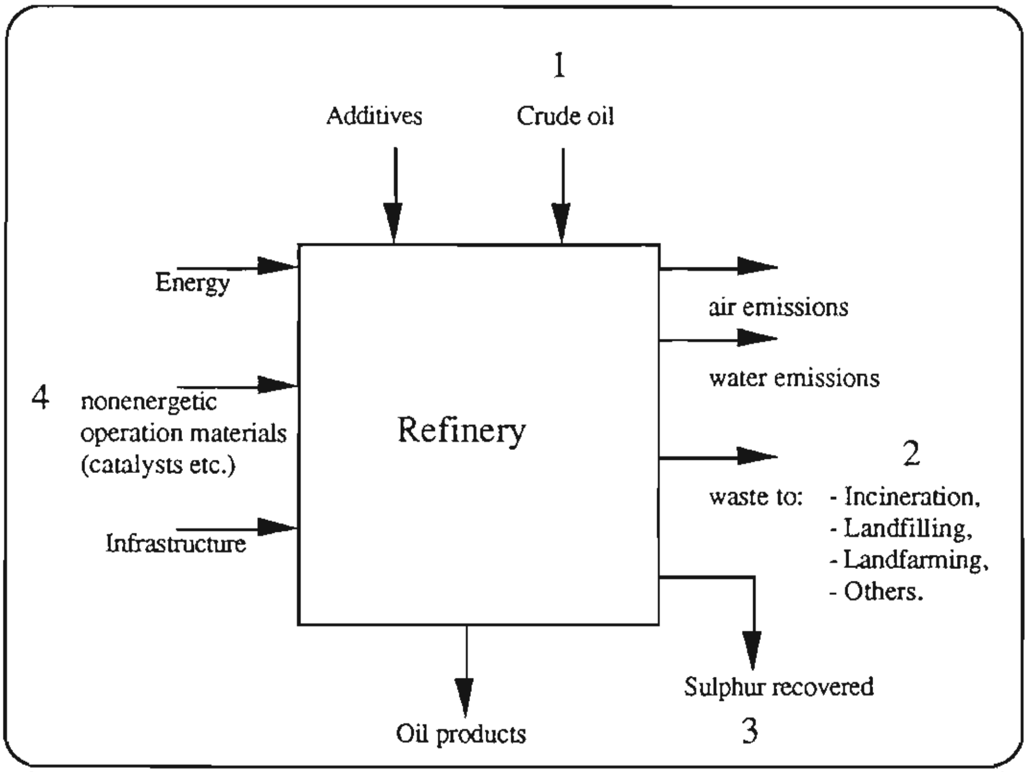

Fig. 2.1: System boundaries in a life cycle inventory. 1: upstream to the environment (e.g. exploration, extraction and transportation of crude oil, 2: downstream to the environment (e.g. sludge incineration), 3: up- and downstream to other anthropogenic systems (e.g. sulphuric acid production with recovered sulphur), 4: side-stream (e.g. production of catalysts).

2.2.2 Geographically motivated system boundaries

There might be a legitimate interest in evaluating energy options for a country. One might then argue that it is sufficient to consider only activities inside that specific region. This approach does not meet reality because:

- many impacts do not depend on (changing) national boundaries,
- improving measures in one region might result in a worsening somewhere else,
- an imported liter of gasoline is not cleaner than one produced within the national or regional frontiers.

Table 2.2 shows the consequences of omitting foreign processing steps for oil products consumed in Switzerland:

Processing step	CO_2 [g/t Crude]	NO_x [mg/t Crude]	SO_2 [mg/t Crude]	Source
Extraction	70	245	40	<Klitz 1980>
Sea transportation	60	135	510	<BUWAL 1991>
Rhine transportation	40	490	210	<BUWAL 1991>
Total foreign emissions	170	870	760	
Refinery	210	940	1400	<Shell 1990>

Table 2.2: Air emissions of crude oil processing steps.

If we choose e.g. the Swiss frontier as a system boundary, we neglect about the same magnitude of CO_2- and NO_X - emissions occuring in the refining step of crude oil within Switzerland. This shows the importance of following the energy system up to the point where the resources are extracted from the environment unless it can be shown that the environmental impacts of the omitted processing step are neglectable (see also 2.2.5 "Identifying environmentally relevant system components").

2.2.3 Anthroposphere - Environment, where to draw the line

In a life cycle inventory the amounts of flue gas and effluent released to the environment are important. For the sake of consistency, an analysis should include environmental impacts caused by waste water treatment facilities and filter techniques for flue gases as well as by waste incineration and landfilling sites.

Doing so, it is possible to follow chemical elements and potential pollutants down to their release into the environment and there will be no difference in methodology between for example factories with their own waste water treatment facility and factories using a public one.

To show the consequences of an incomplete analysis of the path of effluents and waste, we look at zinc in refinery effluents. Considering a typical sewage treatment facility it can be said that 20% of the zinc in the effluent will be released to the environment with the purified water stream whereas 80% remains in the biotreatment sludge. But it is very decisive how the sludge will be treated afterwards as it is shown in Figure 2.3.

Taking the statistics of european refinery sludge treatment technologies from <Concawe 1989> and transfer coefficients for incineration from <Baccini et al 1991>, for waste water treatment and landfilling from <Hofstetter et al 1990>, another 3% will be found in the water, about 75% remains in the landfilling or landfarming area and 2% will be emitted into the air. Because of its toxicity, the rather small amount of zinc air emissions should not be neglected.

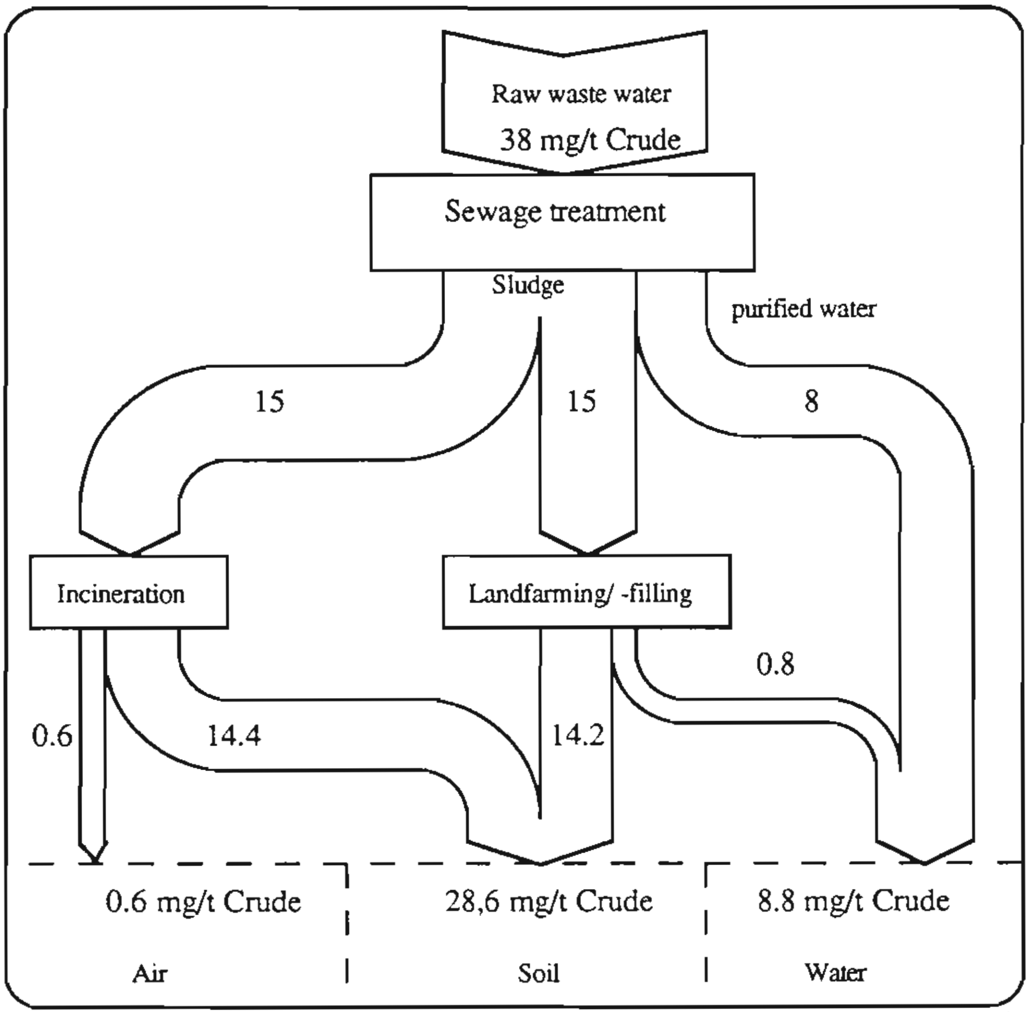

Fig. 2.3: The path of zinc from refinery waste water to the environment (all figures in [mg/t Crude]). Sources: <Snider et al 1982>, <Concawe 1989>, <Baccini et al 1991>, <Hofstetter et al 1990>.

2.2.4 How to deal with "useful waste"

When analysing a process it is important to define its function <Frischknecht et al 1991b>. In multioutput-processes for instance it helps to define co-products and by-products in a coherent manner. The function of a refinery for example is producing oil-related consumer goods from bitumen to fuel oil, gas oil to petrochemical products. Therefore these are all co-products, sharing a part of the environmental impacts of a refinery (see also 2.3 "allocation convention").

But what about the recovered sulphur? For the refinery it is a by-product which cannot be avoided and which initially must be considered waste (flue gas or liquid waste) whereas for the producer of sulphuric acid it is a raw material. Both the seller (refinery) and the buyer (producer of sulphuric acid) of the sulphur will claim that they help reduce

- the primary sulphur requirements and
- the amount of sulphur released to the environment.

Obviously the process of sulphur recovery and transport operations are not considered. Moreover the overall energy- and materials-balance is not met.

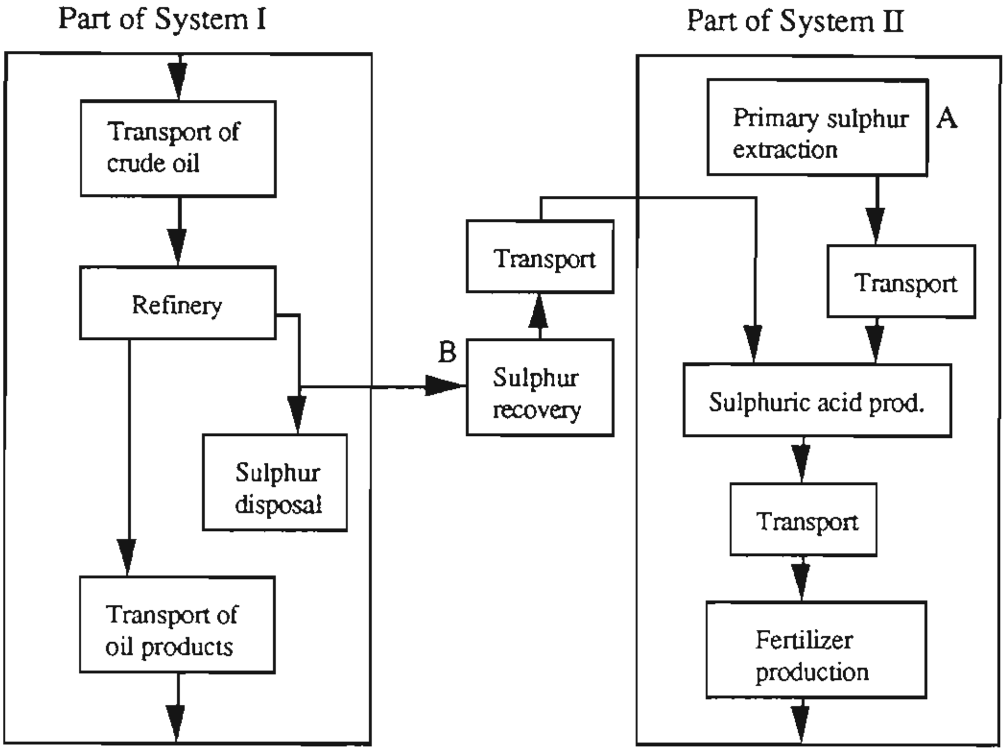

Fig. 2.4: Sulphur as a by-product in system I and as a secondary raw material in system II.

There are several ways to handle the problem of allocating the benefits to the systems involved.

a) Divide the total amount of increased and reduced environmental impacts between system I and system II (e.g. halving).
b) Giving the benefit of waste reduction to the refinery and the benefit of primary sulphur requirement reduction to the producer of sulphuric acid. The sulphur recovery process is seen as the secondary resource production process and therefore added to the acid production process.

In both cases no double counting of benefits occur. Whereas in case a) both systems have to be analysed, the two systems are considered separately in case b). In addition to the better applicability, the allocation method in case b) gives benefits only in the sphere of influence of the particular system (waste savings for system I, resource savings for system II).

As a general rule it can be said, that a process which serves to diminish environmental impacts of system I by gaining a secondary (material or energetic) resource for system II will be accounted to system II (e.g. Claus unit for sulphur recovery, heat recovery in a municipal waste incineration plant).

As a desulphuration of flue gases has to be done anyhow, the focus will be on the comparison between primary (process A in Figure 2.4) and secondary (process B in Figure 2.4) sulphur recovery.

Pollutant	Emissions for primary sulphur extraction [mg/kg S]	secondary sulphur recovery [mg/kg S]
CO_2	270'000	310'000
SO_2	300	2'100
NO_X	500	1'400
HC	125	2'800
particles	9	140
primary energy [MJ/kg S]	5.3	4.0
Source	<Häne et al 1991>	<Shell 1990>

Table 2.5: Air emissions and primary energy requirement of primary sulphur extraction and secondary sulphur recovery.

For the primary sulphur recovery, only energetically induced emissions (mostly by gas-fired heaters or electricity-related) are available <Häne et al 1991>. Concerning secondary sulphur recovery it is assumed that 0.15% of the total energy requirement of a refinery is used for the Claus unit. The emissions are derived from the average emissions of european refineries given in <Shell 1990>.

Looking at air pollutants only, the emissions of the secondary sulphur recovery process are higher than these caused by the primary sulphur extraction process. So the use of secon-dary sulphur seems to be a disadvantage for the sulphuric acid producer. But other factors should be considered as well, like:

- non-renewable resource savings,
- required transport operations and related environmental impacts,
- water emissions,
- waste generation and
- land depreciation.

2.2.5 Identifying environmentally relevant system components

In a first-order approach, the environmental analysis of energy systems takes into account only direct operational pollution, caused by energy and materials throughput of the system. In a second-order approach, the analysis must include also up- and downstream pollution caused by the preparation of operating resources, services, materials or by disposal of waste.

Because of limited time and means, an analysis will often have to focus on environ-mentally relevant system components, neglecting others. There is a need to define criteria that will help in choosing appropriate system boundaries.

Large amounts of energy-intensive operating resources or materials, for example, indicate a high level of indirect, energy-related pollution that needs special attention. In identifying critical *process*-related pollution in up- or downstream processes, the experience of the analyst is required. Often, certain substances contained in operating resources or in the infrastructure are "flags" alerting the analyst that highly toxic emissions probably occur up- or downstream.

In a first step, it is advisable to make a rough calculation of the most important direct and indirect contributions to total pollution. The comparison with reference values internal and/ or external to the system will indicate relevant contributions that need further investigation.

We take the example of a natural gas pipeline (table 2.6) to illustrate the abovementioned concept.

	Gas transportation (by gas-turbines)	Construction materials	Total
SO_2 [t/a]	1	30	31
NO_X [t/a]	860	20	880
Particles [t/a]	4	37	41
Primary Energy [TJ/a]	3430	90	3520

Table 2.6: Air emissions [t/a] primary energy requirement of pipeline gas transportation (total for Swiss gas supply in 1990). The list of pollutants is not complete.

An important question is if the production of pipeline construction materials is a relevant component of the system. If we consider only primary energy consumption, the module "construction materials" makes up for only 2.6% of total energy consumption. But if we look at emissions of pollutants into the environment the picture changes remarkably. It appears for example that emissions of SO_2 and particles caused by the production of pipeline steel make up for more than 90% of total corresponding emissions. On the other hand, NO_X emissions are caused almost entirely by energy consumption for transportation.

In deciding whether to include or to omit "construction materials" the environmental relevance of different pollutants should be considered. For this purpose we use criteria based on the capacity of the environment to absorb pollutant loads. One of these criteria is discussed in section 2.4 "Ecological payback time". They are e.g.:

- criteria based on critical immission concentrations in air/water/soil ,
- criteria based on the concept of ecological scarcity of the ecosystem.

Tables 2.7 & 2.8 show the application of the two abovementioned criteria to the pollutants listed in table 2.6.

Immission concentration criteria	Total emissions [t/a]	Relative toxicity scale of different pollutants [-]	Total SO_2 equivalent emissions [t/a]	SO_2 equivalent emissions from "construction materials" [t/a]
SO_2	31	1	31	30
NO_X	880	.44	387	9
Particulates	41	.34	14	13
Total			430	52 (12%)

Table 2.7: Application of the immission concentration criteria as defined in <Hofstetter 1991> to the data of table 2.6.

From tables 2.7 & 2.8 it follows that emissions from pipeline steel production make up for 4 to 12% of total SO_2 equivalent emissions depending on the relevance criteria used. In this case the contribution of construction materials should not be omitted. We remind, though, that relevance criteria used in tables 2.7 & 2.8 are still very rough and that they apply only to Switzerland. It is therefore advisable to use different relevance criteria in assessing the importance of a system component.

Criteria of ecological scarcity (as defined for Switzerland)	Total emissions [t/a]	Relative toxicity scale of different pollutants [-]	Total SO_2 equivalent emissions [t/a]	SO_2 equivalent emissions from "construction materials" [t/a]
SO_2	31	1	31	30
NO_x	880	1.8	1576	35
Particulates	41	0	0	0
Total			1600	65 (4%)

Table 2.8: Application of the criteria of ecological scarcity as defined in <BUWAL 1991> to the data of table 2.6.

2.3 Allocation convention
Conventions d' allocation
Convenciones para la allocación

While section 2.2.4 dealt with by-products this section will contain some remarks about the allocation of environmental impacts to co-products resulting from multioutput-processes like refineries or cogeneration plants. Other than by-products, co-products share a part of the environmental impacts of the related process.

The allocation procedure can be divided in two steps. First, the environmental impacts that can be clearly traced back to a specific co-product, will be directly allocated to the corresponding co-product. Second, the remaining environmental impacts will be allocated according to one of the following methods:

- according to mass-units,
- number of mols,
- price-weighted units of quantity (economic values),
- the energy-content or
- the exergy-content.

An allocation of environmental impacts corresponding to the masses of the outputs is very frequent. For purely chemical processes a mol-based distribution might be suitable because of the difference in molecular weight of the different co-products.

An allocation based on economic values is theoretically preferable because it reflects the relation between the "driving forces" of a multioutput-process. Nevertheless there are important disadvantages of this method:

- variation of prices,
- market imperfections (like monopoles, cross subventions),
- the prices do not include external (social) costs.

Dealing with energy systems, an allocation by energy- or exergy-content is useful. Taking for example a gasfired standard 200 kWe/ 360 kWthermal cogeneration unit installed in Zurich <Pauli et al 1989>, we get the following allocation parameters for precombustion and operational emissions, operation materials (catalysts, lubricating oils etc.), construction, maintenance and repair of the power unit.

	Electricity	Heat
Output [kW]	204	365 (at 90°C)
economic value [$/h]	18	9
allocation parameter for EI [%]	67	33
energy-content (capacity) [kW]	204	365
allocation parameter for EI [%]	36	64
exergy-content (capacity) [kW]	204	70
allocation parameter for EI [%]	74	26

Table 2.9: Allotment of environmental impacts (EI) to electricity and heat produced by a gasfired standard cogeneration unit <Pauli et al 1989>.

In this example, the exergetic approach leads to nearly the same allocation as the economical, whereas the energetic approach results in a completely different distribution of environmental impacts (Table 2.9).

Using these allocation modes, the heat part will be charged with the following operational emissions:

	cogeneration unit				gas furnace, < 1 MW
	total	Emissions allocated according to:			Emissions
	Emissions [mg/$\mathrm{kWh_{Out}}$]	economic value [mg/$\mathrm{kWh_{Out}}$]	energy [mg/$\mathrm{kWh_{Out}}$]	exergy [mg/$\mathrm{kWh_{Out}}$]	[mg/$\mathrm{kWh_{Out}}$]
CO_2	230'000	76'000	147'000	60'000	220'000
NO_X	83	27	53	22	120
NMVOC	33	11	21	9	8

Table 2.10: Operational air emissions for the heat part of a gasfired standard cogeneration unit using different allocation parameters compared with a gas furnace, <Pauli et al 1989>

In any case air emissions produced by a cogeneration unit are lower compared to conventional gas furnaces, but the benefit depends considerably on the allocation parameter.

Environmental impacts unequivocally classed with space heating (e.g. energy requirement, construction of boilers and the heat distribution net, electricity needed for the circulation pumps) will be entirely added to the space heating system.

2.4 Ecological payback time
Temps de remboursement écologique
"Payback time" écologico

In decision making for energy conservation or product evaluation methods are needed to identify the most environment-sound technology. A method to assess the efficiency of a technology with the aim of saving energy or environmental pollution is the ecological payback time. The concept of payback time is well known since many years and is further developed for our purposes <Suter et al 1989>.

The economic payback time is an often used method to evaluate how many years it takes till the invested money is paid back through savings or profits resulting from investments.

$$\text{Economic Payback Time} = \frac{\text{invested money [\$]}}{\text{saved or gained money [\$/a]}} \quad [a]$$

If the economic payback time is shorter than the life of the investment, a profit is expected.

The energy payback time determines how long it takes till the primary energy invested in a certain energy saving project is payed off.

$$\text{Energy Payback Time} = \frac{\text{invested energy for energy saving product or process[MJ]}}{\text{saved or substituted energy [MJ/a]}} \quad [a]$$

To obtain overall energy savings, the energy payback time has to be shorter than the life-time of the energy saving product or process.

Even if the economic and the energy payback time are both shorter than the life of the investment, this shouldn't lead to conclusions about the environmental effectiveness of the system.

Ecological Payback Time =

$$\frac{\text{invested pollution of the environment for product or process [Eco-Points]}}{\text{saved pollution during the operation of the product or process [Eco-Points/a]}} \quad [a]$$

If in addition the ecological payback time for the investment planned is shorter than the life of the investment, the product or process really saves money, energy and environmental pollution.

While the calculation of the money and the energy payback time is relatively easy (although the energy invested in goods isn't always known), the ecological payback time is very difficult to calculate.

In calculating the ecological payback time it is necessary to define a standard case and the proposed "better" case. After evaluating the specific differences between these two cases, a life cycle inventory has to be set up. On the one side the pollution of the environment by the construction, use, and disposal of the (e.g.) energy saving product is considered, and on the other side, the avoided pollution through lower energy consumption.

If the environmental pollution can be aggregated into one index, there is no problem to calculate the ecological payback time. In reality it is not easy to do this, because e.g. the radioactive radiation, the use of land, and the emission of NO_X have to be added. Methods exist to add different pollution factors, but the approaches are often arbitrary <BUWAL 1984>, <Suter et al 1989>, <BUWAL 1990>, <Hofstetter 1991>.

The method based on environmental standards is probably the most used one <BUWAL 1984>. By dividing the emission ratio [mass] of a certain pollutant through his maximal immission level [concentration] a volume of air or water, which is polluted up to the immission standard, is obtained.

$$\text{burden volume} = \Sigma \frac{\text{emission of pollutant i} \quad [g]}{\text{immission standard level of pollutant i} \quad [g/\text{volume}]} \quad [\text{volume}]$$

Some examples of life cycle assessments and ecological payback time calculations are listed in chapter 3 for better understanding.

3. Examples of Application
Examples d' application
Ejemplos de aplicación

3.1 Oil versus natural gas for heating purposes
Chauffage à gaz ou à mazout
Petróleo contra gas natural para la calefacción

A major national project for assessing total pollution of different energy systems is under way at the Swiss Federal Institute of Technology <Frischknecht et al 1991a>.

The environmental advantages or disadvantages of using oil or natural gas for heating purposes are discussed. A cradle to grave approach is being used with Switzerland as end-use country for comparing oil- versus gas fired residential furnaces. Not only operational pollution, but also "grey" pollution, emitted during precombustion processes, construction and decommissioning of all components will be considered. If reliable data is available water effluents and solid waste should be included.

First results will be presented during the WEC-Conference.

3.2 Low-energy buildings
Bâtiments à basse consommation d'énergie de chauffage
Edificios con consumo reducido de energia de calefacción

3.2.1 Problem Definition

In this example, the investment for energy savings in a low-energy house are analysed. A low-energy house is a building without or with a very little requirement for space heating. The electricity can be used from the grid or/and from photovoltaic cells etc. The question was here, if there is really an energy saving or if the embodied energy of the additional building materials counts more than the whole saving of space heating. Further it interests, if the production of the building materials causes less environmental impacts than the burning of fuel for space heating. A first tentative answer to some of these questions can be found in <Hofstetter et al 1991>. More detailed works on this topic started at the Swiss Federal Institute of Technology Lausanne together with the Hochschule für Architektur und Bauwesen, Weimar (Germany) <Kohler et al 1991>.

Starting from a standard house one glass pane and two silver coatings were added to the windows, a thicker insulation (0.15 W/m^2K) was chosen, an air heat recovery, sun collectors, a large heat reservoir and a water heat recovery was installed. All the additional materials, which were needed to built the low-energy house, were quantified for each conservation step. On the other hand the energy savings for each step were calculated.

The life cycle inventory for the production of the building materials and for the avoided environmental impact of the fuel burning was calculated. In this inventory energy resources and solid, liquid and gaseous wastes were considered. Data about solid and liquid wastes was difficult to record or just unknown. For this reason only energy requirements and air emissions will be discussed.

3.2.2 Results

In Figure 3.1 the saved and the invested energy for each energy saving measure are given with bar-codes. The energy payback time is given in digits. Every energy saving measure is paid back within the life-span of the house. Only the very large heat reservoir with 20m^3 water, built with concrete and polyurethane foam needs more than ten years for amortisation. The better windows and the air heat recovery are very effective ways to save energy. All steps together need additional 80'000 kWh for the production and transportation of the building materials (without construction on place) and save about 25'000 kWh/a oil for space heating.

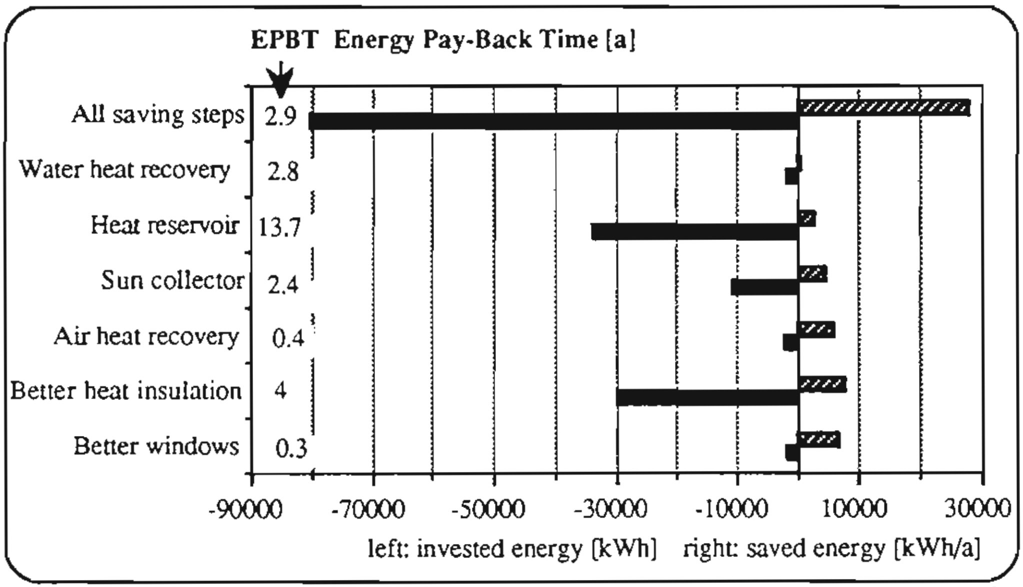

Fig. 3.1: Energy payback time of measures to attain a low-energy building in Switzerland <Hofstetter et al 1991>.

In a next step the air pollution from material production, transportation and disposal can be calculated. Nearly 40 different air pollutants are considered and weighted with the immission standards (see section 2.4). In Figure 3.2 the Air-Emission Payback Time is given in digits. The absolute volume of air which is polluted up to the immission level is calculated to 12.5 * 10^{9}m^3 air. This volume has no practical meaning, because in reality a m^3 air can be polluted by more than one pollutant and most of the pollutants have short degrading times.

As a result of this calculation we learn, that some energy saving measures can pollute the environment through production, transportation and disposal in the same order of magnitude as the avoided space heating. The heat reservoir needs a very large amount of materials and stores just little amounts of heat. The high payback time of the extruded polystyrene insulation is caused by only one effluent, chlorethane. The emission figure is very uncertain because the producers give or have no reliable data. All other conservation steps have a payback time which is significantly shorter than the expected life-span. Especially the better windows and the air heat recovery are very effective in protecting the environment. These results are still very uncertain because of unreliable data and problems of aggregation.

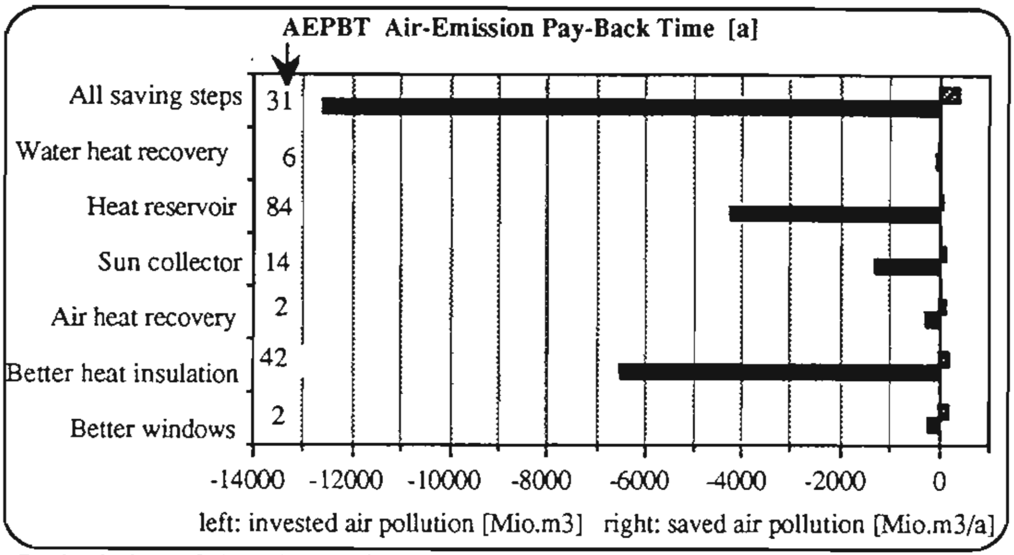

Fig. 3.2: Payback time of air pollution of measures to attain a low energy building in Switzerland <Hofstetter et al 1991>.

From the economical point of view, using 1990 prices for Switzerland, only the windows are competitive. The insulation should be thinner or constructed with cheaper materials to be economically competitive.

3.2.3 Conclusions

Low-energy buildings save large amounts of energy over their life-span. The energy for production and transportation of materials is payed back after three years or in other words energy is saved through a lower consumption of oil.

If our goal is to minimize the environmental impacts of buildings, though, we can't just consider the energy consumption. The production process, the transportation, the construction and the disposal have to be taken into consideration. From this point of view the materials for a low-energy building have to be selected carefully, otherwise the total environmental impact of the building can be higher than the impact of a standard house.

Nevertheless, it must be considered that the environmental pollution of products and processes derives to a large extent from energy conversion. This was one motivation for a major research project under way at the Swiss Federal Institute of Technology in Zürich <Frischknecht et al 1991a>.

Better consistent environmental data for building materials and energy carriers is urgently needed. The lack of data is not only a problem for Switzerland but worldwide. Only for packaging materials enough data is available <BUWAL 1984>, <BUWAL 1990>, <Franklin 1989>, <Tillmann et al 1991>.

Methods for the assessment of different products, processes, or energy systems are not sufficiently reliable to draw final conclusions. The aggregation methods should be further developed.

3.3 Photovoltaic plant
Installation photovoltaïque
Unidad fotovoltaica

Renewable energy systems like photovoltaic plants are nowadays very expensive, when they are compared with existing fossil fuel power plants. External costs aren't included in present prices and nobody can say how high they are. Photovoltaic plants are called environmental friendly and some experts think even, that photovoltaics will solve our energy and environmental problems.

Some experts and a large part of critics of photovoltaic plants say, that more energy is needed for the production of cells and infrastructure, than the plant can deliver during life-time. While this might be true for some applications in space technology, many studies in the last years have shown, that cells for conventional power plants need less energy than they produce (e.g.<Hagedorn et al 1989>).

In two studies a large 500kW plant installed in the Swiss Jura region was analysed <Häne et al 1991>, <Schmocker et al 1991>. In a first step the energy needs for the production of cells, carrier and electronics were calculated. Secondly the associated environmental impact was analysed. This is motivated by the fact that overall energy savings do not necessarily mean an overall reduction of environmental pollution as we have shown in the example about low-energy housing (Section 3.2)

The power plant consists of 10'560 monocristalline modules installed on 110 carriers with normal efficiency of 12.5%. The peak power DC is 560kW while the expected AC-power is 500kW. Over one year the net electricity production is calculated to be 676.8 MWh.

Figure 3.3 shows the production steps of a photovoltaic module and shows the energy balance in primary energy units. On the left side are shown electricity inputs and on the right side thermal energy inputs for transportation, production of commodities and plant operation. About 90% of the whole energy demand is covered by electrical energy. For one module with 36 monocristalline cells (without frame) 2.6 GJ primary energy are required. Wafer production is not the only energy intensive step (33% of energy input). Other steps are energy intensive too. The material use efficiency is not very high especially in relation to MG-silicium. This is true also for the energy contained in this material.

For the production of the whole power plant including all infrastructure about 40 TJ primary energy are needed (Figure 3.4). 65% are used to produce the photovoltaic modules. 27% to produce and construct the carriers (incl. all construction work). Electronic components and infrastructure need only about 10% of total energy. Electronic components are difficult to calculate, because of lack of data from manufacturers.

The resulting energy payback time is 6.6 years, if it is assumed that it needs 2.59 kWh primary energy to produce 1 kWh electricity. For a photovoltaic plant a life-time of twenty to thirty years can be assumed, which means, that a photovoltaic plant produces about three to four times its construction energy. In future, when the production of cells will increase (in 1990 the worldwide production was about 50 MW), the production energy will decrease. Other technologies like multicristalline or amorphe cells already in use need less production energy. The energy demand for carrier, electronic and construction work will be minimized in future. Parts of the components will be reused after the life-time of the plant. This means that the energy payback time will be reduced considerably within the next ten years.

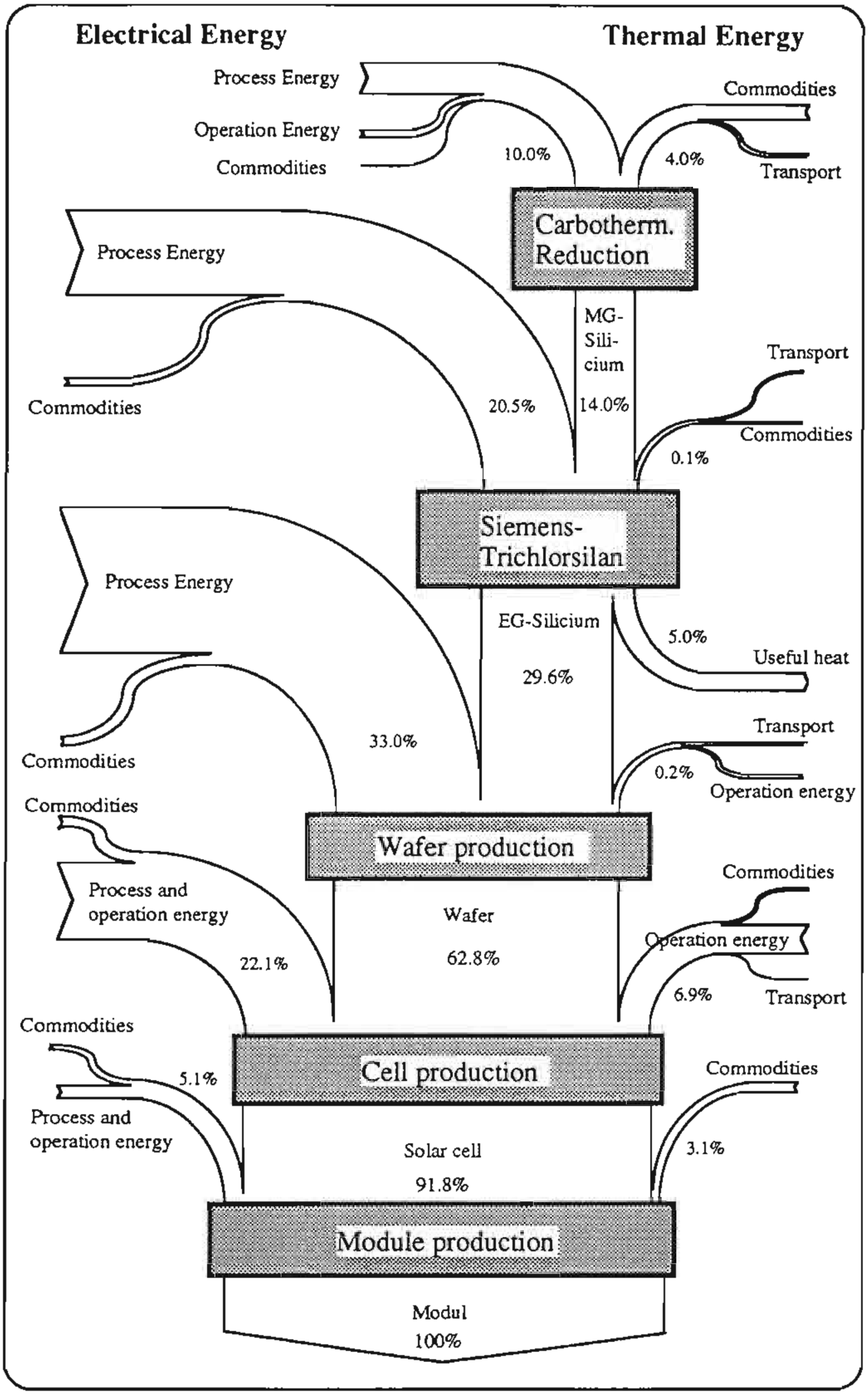

Fig. 3.3: Main production steps for a monocristalline photovoltaic module with indication of the energy flows. "Commodities" stands for energy requirements for the production of commodities. One module with 36 cells needs about 2.6 GJ primary energy <Häne et al 1991>.

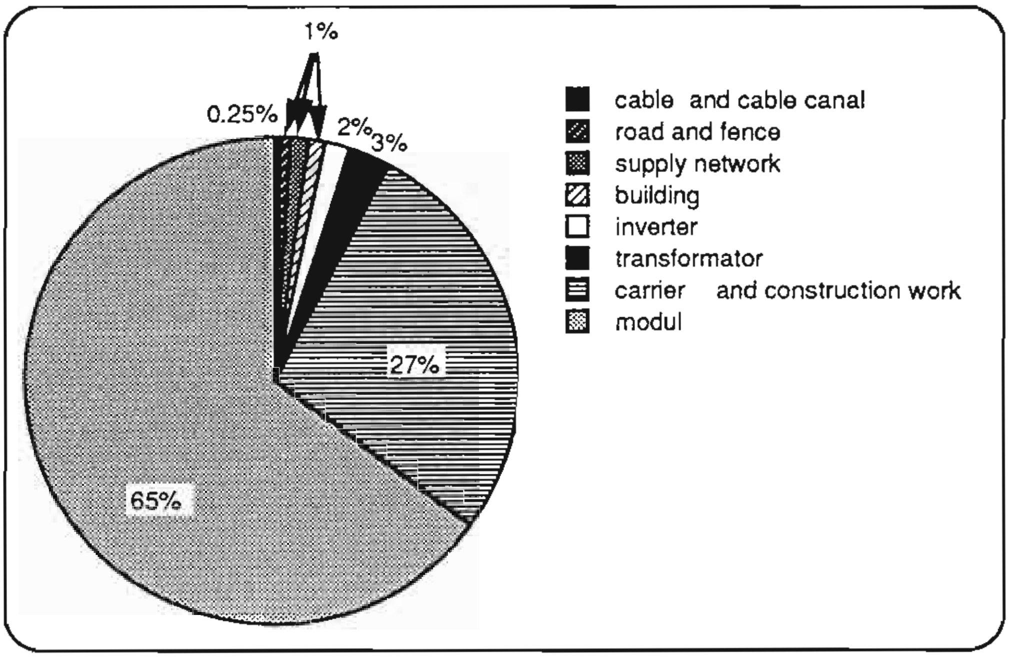

Fig. 3.4: Share of primary energy requirements to build a 500kW photovoltaic plant. Total primary energy demand is about 40 TJ or about 80 GJ per kWpeak <Schmocker et al 1991>.

We now consider the environmental impacts of photovoltaic plants. For this reason the whole production process of the modules and infrastructure, taking care of about 30 air pollutants, 30 water pollutants, waste volume and energy demand was analysed. Because of incomplete data for water pollution and waste production only the air pollution is discussed. For the decommissioning of photovoltaic modules no satisfying concepts exist, so that the environmental impact of module-waste treatment couldn't be studied. Producers should consider this at the stage of development.

Supposing, that the plant will produce 676.8 MWh each year for the estimated life-span (20 or 30 years) the emission factors per produced kWh of electricity can be calculated. In Table 3.5 the results are given for a few selected air pollutants. The uncertainty of this data is about 30% updated to the end of the 1980's. <Fritsche et al 1989> give much lower figures, because of an incomplete material list and special infrastructure. The emission factors of electricity produced by the solar plant lie just below those for conventional power plants. This data should not be used to oppose further development and installation of photovoltaic plants. <Strese et al 1988> showed the large cost and energy reduction potential of multicristalline cell production. The potential of development of photovoltaic modules is still very large.

Selected air pollutant	Life-span 20 years [g/kWhe]	Life-span 30 years [g/kWhe]
carbon dioxide (CO_2)	190	130
sulphur dioxide (SO_2)	0.8	0.56
nitrous oxide (NO_x)	0.6	0.4
NMVOC	0.7	0.44
particle	0.6	0.4

Table 3.5: Resulting emission factors of a few selected air pollutants for a life-span of the photovoltaic plant of 20 and 30 years.

If the air pollutants are aggregated with the concept of weighting by immission standards, traditional pollutants like NO_X, SO_2, NMVOC and particles have the biggest share in the pollution index. For the calculation of the air-emission payback time (AEPBT) the air pollution index for the production of the whole plant has to be divided through the air pollution index, which can be saved due to the electricity delivered to the grid. A medium European electricity mix was assumed.

$$\text{AEPBT} = \frac{863 \text{ Exp } 10^9 \text{m}^3 \text{ polluted air}}{50 \text{ Exp } 10^9 \text{m}^3/\text{a polluted air}} = 17 \text{ years}$$

The uncertanity of this result is large because of missing or old data and because of the aggregation method, which can't depict the environment. Using another method <BUWAL 1990> based on the concept of environmental scarcity the pay back time increases even more to 24 years. The payback times are in the same order of magnitude as the proposed life-span of the plant. Larger production capacities in the future and a high development potential mean that the emission factors of photovoltaic plants are expected to decrease in the next years.

More studies for other types of cells and other plants will be carried out at ETH to compare the results and to draw saver conclusions.

4. Conclusions
Conclusions
Conclusiones

Total pollution assessment of energy systems by life cycle analysis is a new and efficient tool, which allows qualitative and quantitative evaluations, at least if environmental effects in individual sectors (acidification or greenhouse effect etc.) are considered. Nevertheless it must be admitted that the available data has a considerable uncertainety and that several important methodological problems are not yet solved, e.g. the variation of standards in time or the equivalence of different pollutants. For other types of ecological impact, e.g. noise or land use, it is not yet clear, how they could be included. Therefore the whole context needs further research which is and should be done in international cooperation. It is also necessary to produce the data for more energy systems, processes and materials.

In spite of all these limitations total pollution assessment is indicated yet today:

- It favours, as an awareness tool, the integral consideration of energy systems,
- It allows to identify ecologically harmful components in energy systems, and to introduce improvements,
- It helps to avoid policies or strategies which present advantages in only one sector, but drawbacks in other aspects.

The essential point for the usefulness of the method is, however, consistency of the assumptions and boundary conditions and furthermore a perfect transparency of all indications, so that the results and findings can be adjusted to new and better data.

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Summary

Ecological arguments are a major driver for the substitution of existing energy options by new ones, for the promotion of renewable energies and for conservation measures. In order to assess correctly the different solutions and options it is important to take into account not only the pollutant emissions in operation of the concerned plant but also the emissions in the whole antecedent energy chain as well as the "grey" pollution, emitted during construction and decommissioning of all components. Results of such detailed investigations are presented, leading to total pollution emission lists of energy chains from primary to commercial and from commercial to end use energy. Special considerations are devoted to an adequate definition of system boundaries, and to the correct handling of material and equipment imported from countries with different emission standards. In the context of "grey" pollution invested in the components of an energy system the relative contributions of different antecedent fabrication steps normally decrease rapidly so that convergent procedure can be found.

An intrinsic problem in the use of these emission lists for the assessment and in the search for convergent procedures is the equivalence problem of different pollutants (e.g. "greenhouse"-gases versus "acidification"-gases etc.). In this respect different methods are discussed.

Three examples (oil- versus gasfired furnaces, low-energy buildings, photovoltaic plant) are given in order to illustrate the effect of "grey" pollution, leading to considerable changes in the assessment of ecological benefits. Yet another effect is the identification and modification of especially polluting fabrication steps.

The examples emphasize furthermore the importance of correct handling of technology variations in time: Emission standards can vary considerably during the whole life cycle of an energy system. In this context further methodological investigations are needed.

Résumé

Les considérations écologiques sont des arguments principaux pour l'introduction de nouveaux systèmes énergétiques, pour la production des énergies renouvelables ou pour la conservation d' énergie. Pour évaluer correctement differentes options il est indispensable de tenir compte non seulement de l' émission de polluants en service mais aussi de la pollution "grise" émise de la chaîne énergétique en amont et pendant la construction et même la mise hors service de tous les composants de l' installation considérée. Les résultats de telles investigations detaillées concernant la pollution totale émise indiquent que normalement l' importance relative des différentes phases de fabrication antécédantes dêcroit rapidement, facilitant ainsi la démarche. La définition des frontières du système considéré est cruciale et une attention particulière est nécessaire, si les composants proviennent de pays avec différentes normes en ce qui concerne les émissions.

Un problème intrinséque est l' équivalence de différents polluants (p.ex. gaz de l' effet de serre/ polluants atmosphériques etc.); à ce sujet différentes méthodes sont discutées.

Trois exemples (chauffage à gaz ou à mazout, bâtiments à basse consommation d' énergie de chauffage, installation photovoltaïque) illustrent l' importance de la pollution "grise" pour l' évaluation écologique. Cette considération permet d' ailleurs aussi l' identification de points faibles, en ce qui concerne l' environnement, dans la fabrication.

Dans son état actuel la méthode a besoin d' être développée et améliorée, notamment pour tenir compte correctement des changements techniques qui ont souvent lieu pendant la durée de vie de systèmes énergétiques.

Resumen

Argumentos de caracter ambiental son una fuerza motriz para la substitución de sistemas energéticos existentes con nuevos, para la promoción de las energías renovables y de las economias de energía. Para evaluar corectamente diferentes soluciones y opciones es importante tomar en consideración no solamente las emisiones de contaminantes operacio-nales del sistema, sino tambien la contaminación "grisa", incluso las emisiones en la cadenas energéticas antecedentes y la contaminación causada durante la construcción y el desmontaje de todas las componentes. Resultados de investigaciones tan detalladas estan presentados en forma de inventarios de contaminación total a partir de las energías primarias y comerciales, hasta l'utilización final de energía. Una atención particular esta dedicada a la definición adecuada de los limites del sistema y a la consideración correcta de materiales y equipos importados de estados con diferente estandardización ambiental. En el contexto de la contami-nación "grisa", las contribuciones de diferentes procesos de fabricación previos en general disminuien rapidamente asi que existen procedimientos de convergencia.

Un problema intrinsico de la aplicación de los inventarios de emisiones es la equivalencia de los diferentes contaminantes (p.e. gases responsables del "global warming" encontra-posición con gases que causan las lluvias acidas). En ese contexto diferentes metodos estan discutidos.

Tres ejemplos (petróleo contra gas natural para calderas, edificios con consumo reducido de energia de calefacción, unidad fotovoltaica) ilustran la importancia de la contaminación "grisa" que lleva considerables modificaciones en la valutación écologica de los sistemas. Un otro efecto es la identificación y la modificación de procedimientos particularmente contaminantes.

Los ejemplos muestran adémas la importancia de una consideración adecuada de la evolución temporal de los sistemas tecnologicos: la estandardización ambiental puede variar considerablemente durante el ciclo de vida de un sistema energético. En este campo hacen falta investigaciones de caracter metodologico mas aprofundidas.