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Comparing Greenhouse-Gas Emissions and Abatement Costs of Nuclear and Alternative Energy Options from a Life-Cycle Perspective

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Introduction

The debate on nuclear energy has a long history - starting in the early 70ies with concerns on low-level radiation, accidents, and disposal of spent fuel, the late 70ies focused on the issue of limited energy resources for which nuclear promised relieve in applying breeder cycles. In the 80ies, the debate focused on the economics of nuclear power, and of its alternatives. In the 90ies, global concerns regarding the greenhouse effect peaked in the Rio Convention on Climate Chance, and the Kioto Protocol to limit greenhouse-gas emissions from industrialized countries.

Today. the two main arguments favouring nuclear electricity are:

- nuclear power is allegedly free of CO_2, and
- nuclear electricity can be produced at low cost.

In this paper, we present the results of a full life-cycle analysis of energy systems with respect to greenhouse-gas emissions, and cost.

We also discuss some other findings in this area, and indicate conclusions for the cost-effectiveness of greenhouse-gas abatement policies in the electricity sector.

Nuclear Energy - Free of CO_2?

The apparent advantage of nuclear power plants is based on the fact that they do **not** emit CO_2 **directly**. However, the production of nuclear electricity includes ore mining, enrichment of uranium, etc. Furthermore, steel, concrete, etc. are necessary for the construction of nuclear power plants, as well as for the facilities in the upstream fuel-cycle. The energy used for these purposes is partly produced by fossil energy.

Thus, nuclear power plants **indirectly** emit CO_2, as well as other greenhouse gases.

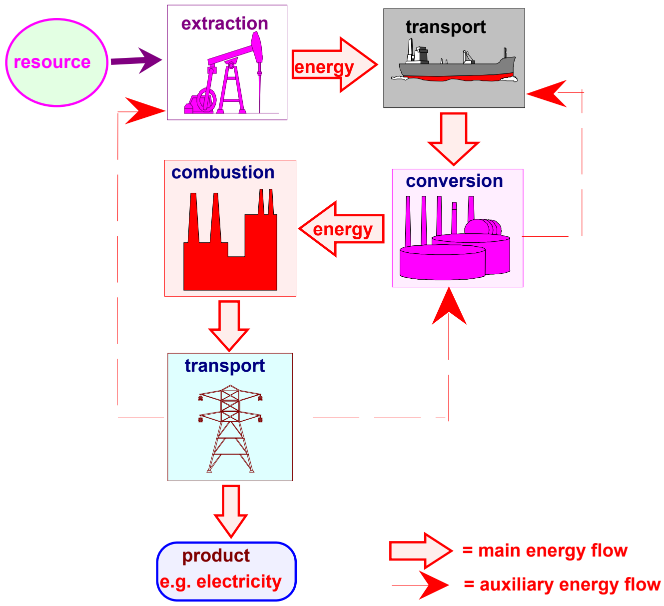
Life-Cycle Analysis: A Comprehensive Scope

Since the greenhouse effect works globally, and CO_2 emissions contribute to the greenhouse effect independently from their origin, the whole life-cycle of production from primary energy extraction to energy output has to be taken into account.

To do so, one has to follow all relevant steps along a life-cycle of energy technologies, tracking all activities which directly or indirectly emit greenhouse gases.

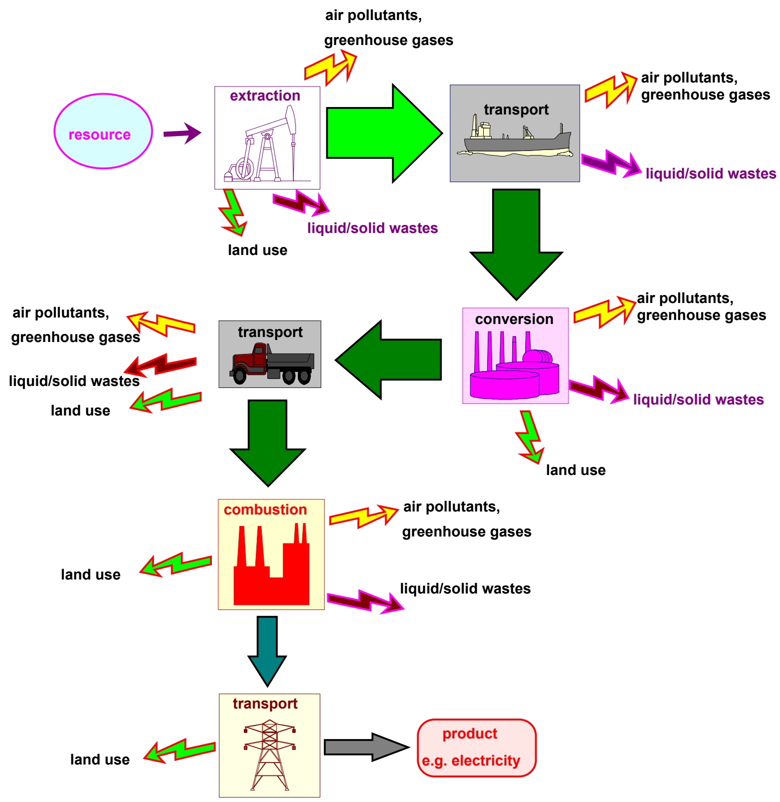
The following figure shows the principle structure of energy fuel-cycles (i.e. life-cycles without including construction of facilities):

Figure 1: Processes and Links in Energy Fuel-Cycles



Along the energy flow, emissions and other environmental impacts can occur on every stage of the cycle (called „process"), depending on the process technology and fuel characteristics on each stage (see following figure).

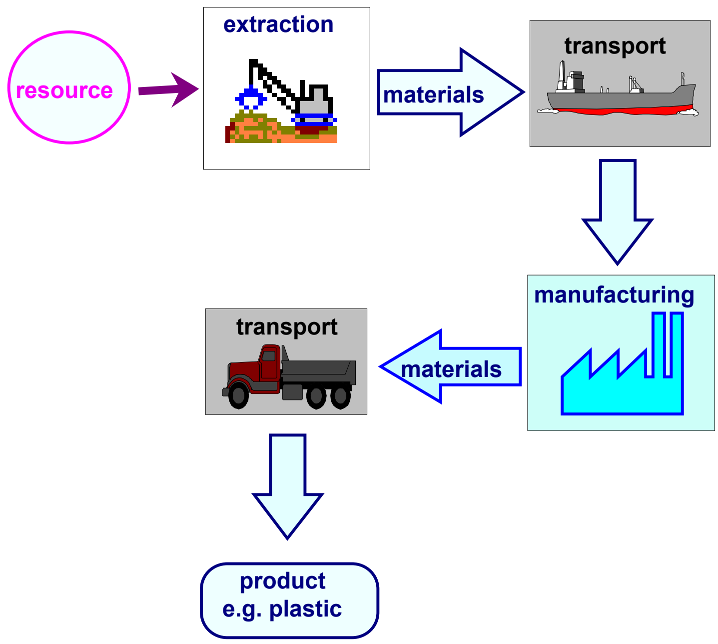
Figure 2: Environmental Effects from Energy Fuel-Cycles



In addition to the direct flow of energy, one has to consider that it takes materials to build the energy facilities (e.g. powerplants, pipelines, transmission lines).

For these material inputs, similar upstream cycles must be considered:

Figure 3: Processes and Links in Material Cycles

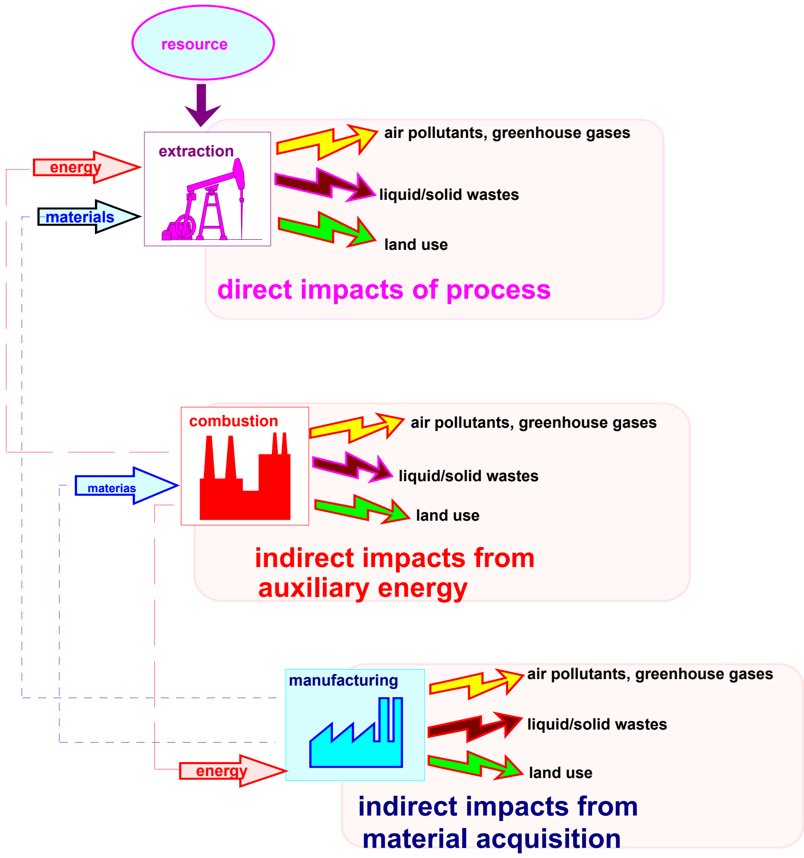


The **combination of both the energy and the material cycles** gives the so-called **life-cycle**, in which three levels of impacts can occur:

- direct impacts from the operation of processes
- indirect impacts from auxiliary inputs to these processes (energy materials)
- indirect impacts from the manufacturing of materials used during the construction of all processes.

In reality, these levels are linked to each other (e.g., electricity for steel making comes from a powerplant made of steel), so that a full life-cycle analysis will have to deal with the complete network of interactions between all processes.

Figure 4: The Levels of Impacts in Life-Cycles



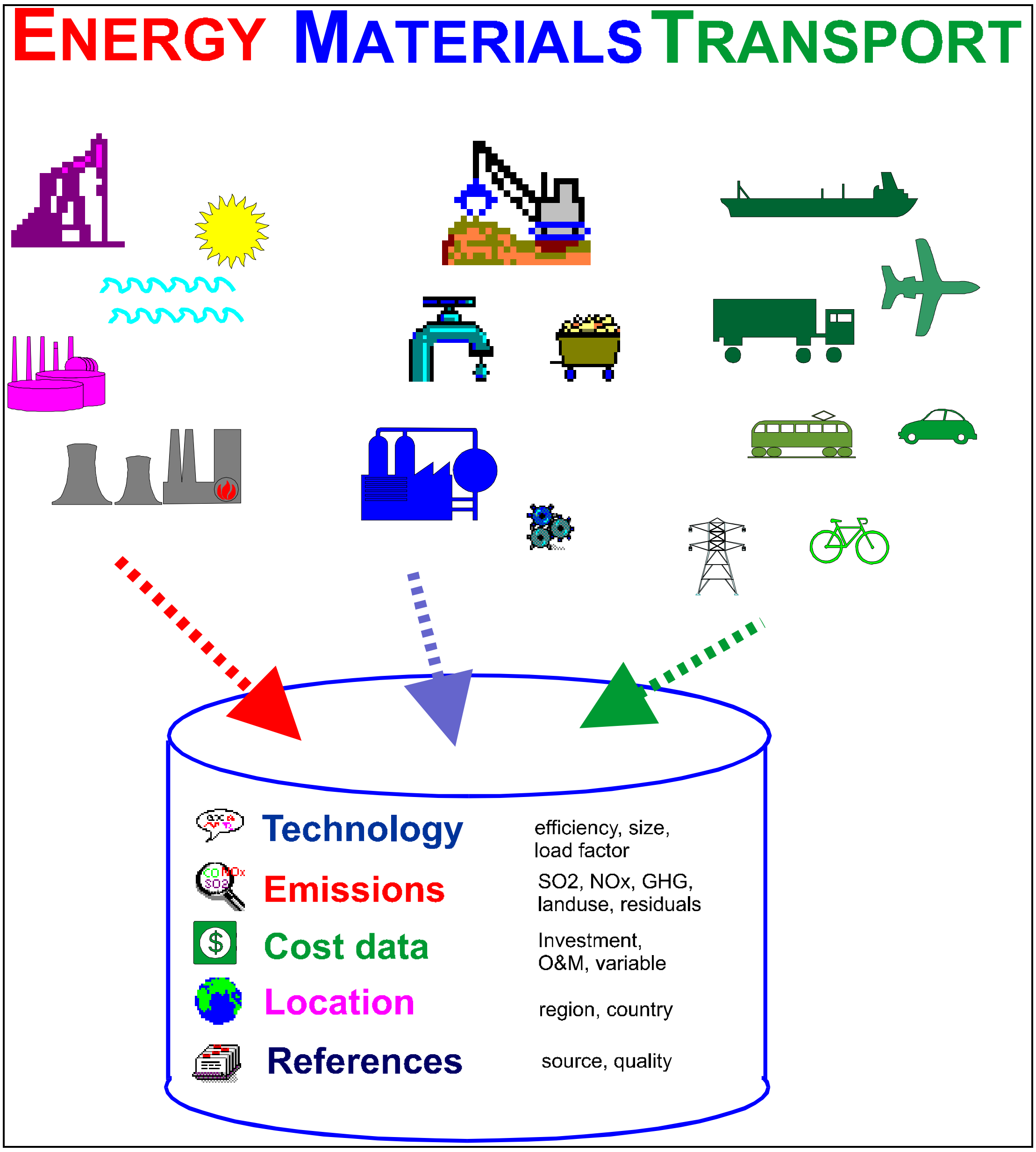
To make life-cycle analysis practical, one has to collect, store and process a huge variety of data (including the geographical variation of energy processes, fuel quality, transport distances, etc.).

Öko-Institut maintains for more than 10 year a research activity called GEMIS (Global Emission Model for Integrated Systems)[1], in which these data are compiled, and a computer-based model was developed.

The GEMIS database is shown in the following figure:

1 Since Version 3.x, both the German and the English versions of the model are called GEMIS (Global Emission Model for Integrated Systems). For developing countries, a simplified version concentrating on energy technologies is available - the so-called Environmental Manual for Power Development (EM). With GEMIS 4.0, the data from the EM are included in one model for all languages and countries. GEMIS, as well as its country databases, is available at no cost through the Öko-Institut's website.

Figure 5: Principal Structure of the GEMIS Database



Life-Cycle Analysis: Results for Nuclear Electricity

As nuclear energy is part of energy life-cycles, GEMIS also offers data on nuclear plants, their upstream fuel-cycle, and the materials needed to build nuclear plants.

According to these data, GEMIS calculates 34 grams of CO_2 for nuclear power plants in Germany per kilowatt-hour of electricity generated. These calculations are based upon data for the whole life-cycle (complete production process including ore extraction, transformation, enrichment, and construction of all facilities).

The results of other studies show higher figures: 30 to 60 grams of CO_2 per kilowatt hour are attributed to nuclear power (IEA 1994; CRIEPI 1995). In total, a nuclear power station of standard size (1250 MW, 6500h/a) indirectly emits between 276,250 (for Germany, Öko-Institut calculation with GEMIS 3.0) and 1,3 million tons (other countries) of CO_2/per year.

In comparison with the specific CO_2 emissions (per kWh) of alternative systems like electricity saving, cogeneration or renewable energy systems, nuclear power stations come off badly (see figure 6).

The „negative" cogeneration emissions result from the following calculation:

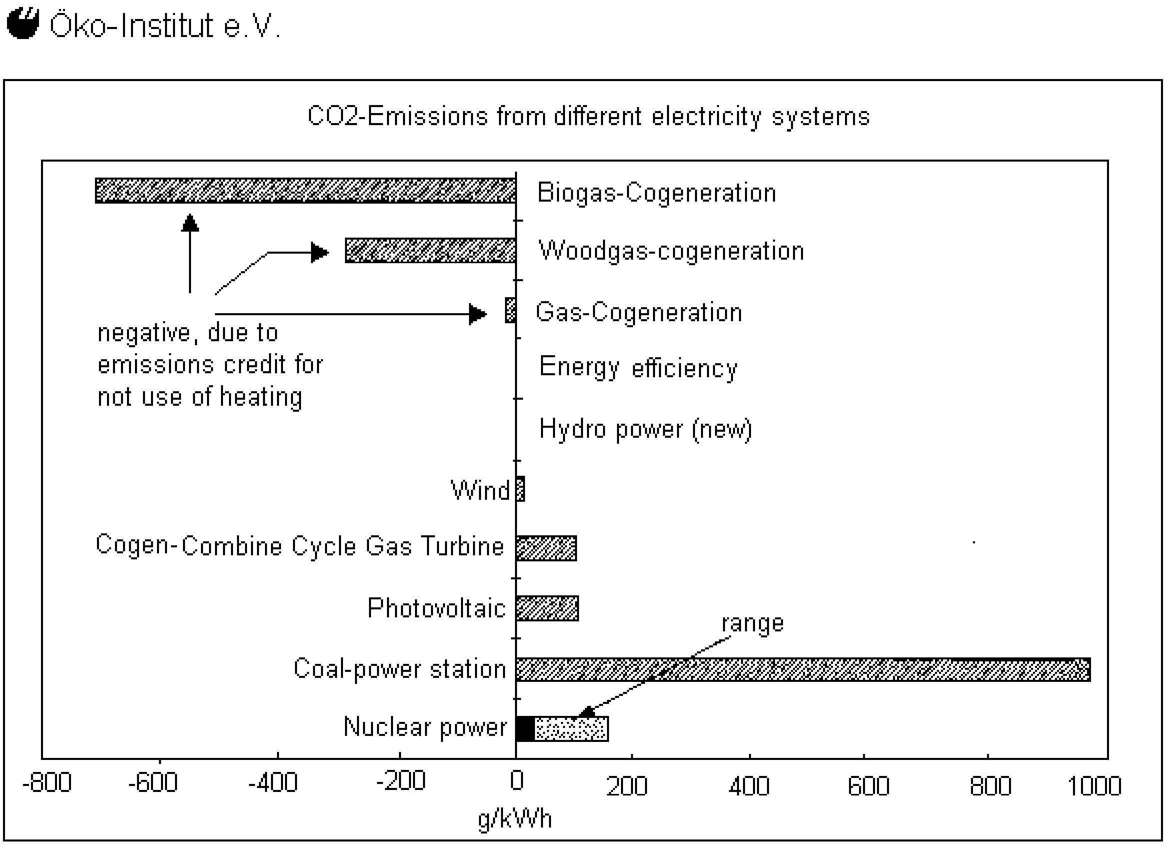
total CO_2 emissions of the cogeneration system minus emissions from an oil heating system, because the utilized waste heat of the cogeneration plant replaces the heat generation from the oil heating system.

For example, the production of one 1 kWh of electricity in a small-scale gas cogeneration plant also generates 2 kWh of heat which can be used onsite directly, or delivered to a district heating system. This cogenerated heat then substitutes heat from a heating system, i.e. the 2 kWh do not have to be produced any more by a separate heating system. The CO_2 emissions thus saved are credited to the cogeneration system.

The **net** CO_2 emissions of electricity from small-scale gas-fired cogeneration plants are lower than CO_2 emissions of electricity produced in nuclear power plants.

Electricity saving and electricity from renewable energy sources also clearly show fewer emissions.

Figure 6: Life-Cycle CO_2 Emissions from Electricity Generation



3 Generation Costs

An important issue in the discussion on nuclear energy is the amount of costs associated with the generation of a kWh of electricity. A broad range of data on investment, operating and decommissioning costs exists for nuclear plans, as indicated in the table below.

Table 1: Generation costs of nuclear power (1250 MW_{el}, PWR)

Parameter	Units	IKE*	IPSEP**	GEMIS
Investment	DM/kW el	3800	5260-7000	5000
	$/kW el	2235	3094-4117	2941
Operation costs	DM/kW*a	82	168-230	117
	$/kW *a	48	98-135	69
Fuel & disposal	DM/MWh el	2,5	2,1-2,9	3
	$/MWh el	1,5	1,2-1,17	1,8
Operating time	h/a	6000	6000	6000
Lifetime	a	35	20-25	25
Spec. Electr. cost ***	Pf/kWh	9,0	8,6-11,5	11,1
	$/kWh	0,05	0,05-0,07	0,07

* Institut für Kernenergetik und Energiesysteme

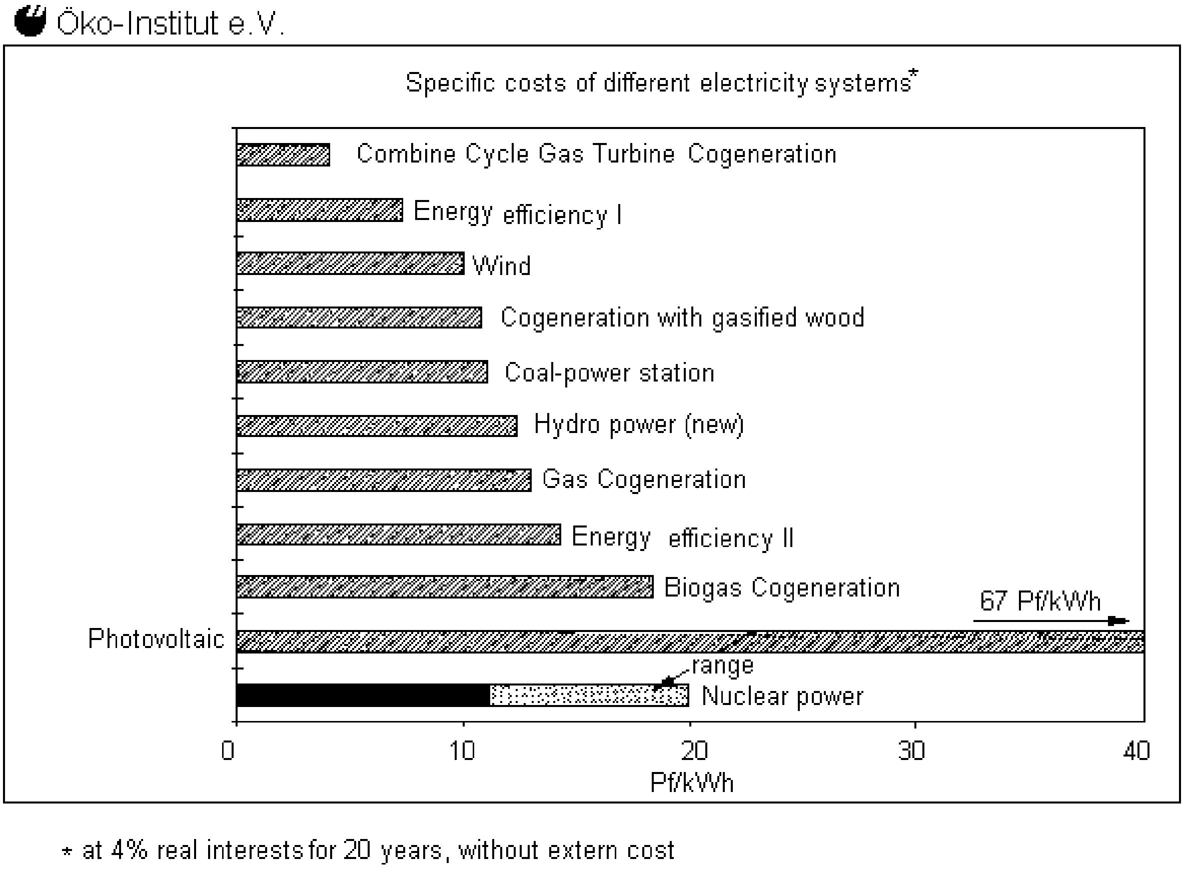
** International Project for Sustainable Energy Paths, El Cerrito CA

*** at 4% Real interest, period: 20 years, no extern costs.

The generation cost of the new nuclear plants differ depending on the study, the range is 9 to 12 Pfennig (Pf or 0,05-0,07 $) per kilowatt hour for current reactor designs.

In GEMIS, a variety of other electricity generation technologies is stored as well. The following figure gives an overview of the production costs of selected alternative electricity systems.

Figure 7: Specific costs (without external costs) of different electricity systems



The figure clearly shows that assertions of low nuclear power costs are no longer valid (see IPSEP 1995 for details). The costs of other alternative systems without particular risks (e.g. cogeneration, DSM) are essentially lower than the low costs margins of nuclear energy today - these systems are competitive. They will be even more favourable if the more realistic upper cost limit for nuclear electricity production is applied. An exception are photovoltaics (direct conversion of sunlight into electricity), though[2].

4 CO_2 Abatement Costs

To determine the costs of CO_2 abatement, one has to select a reference option (e.g., coal- or gas-fired powerplant), and then calculate the emission and cost differences of this reference option to alternative generation technologies.

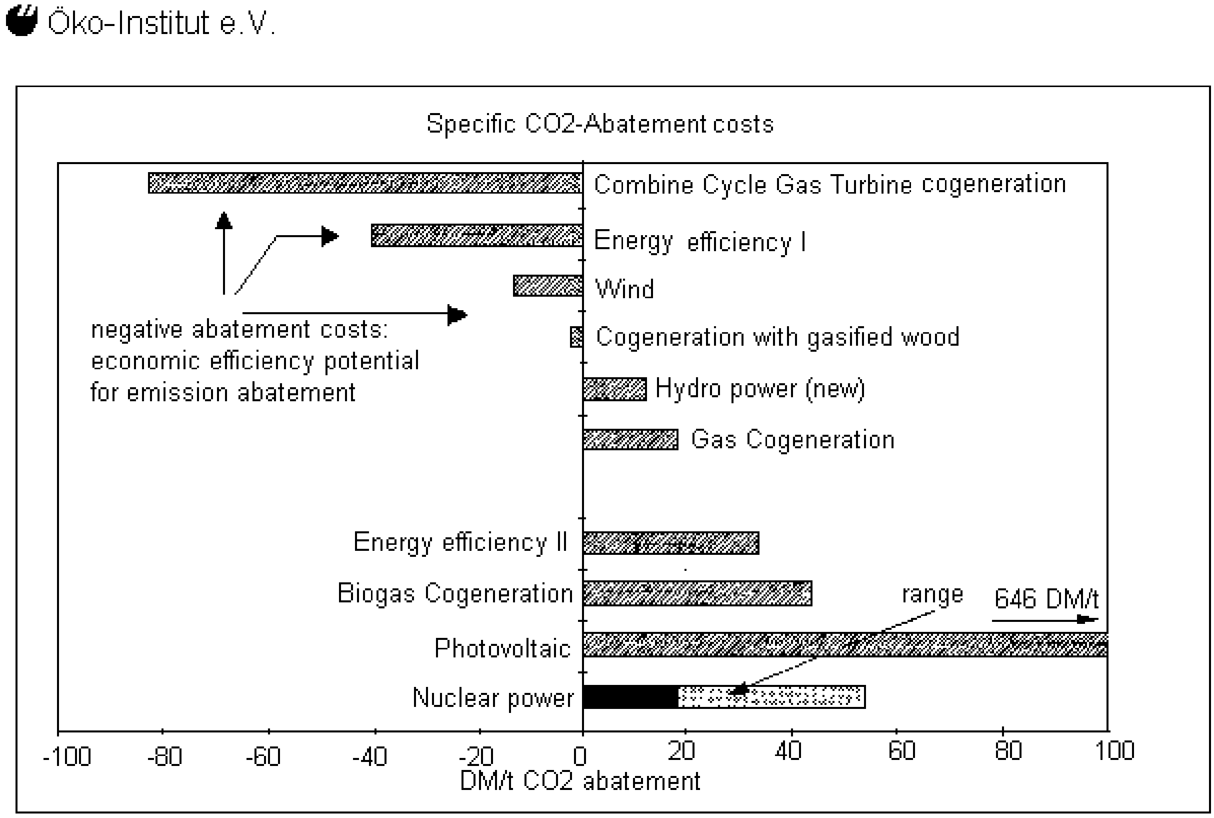
The specific CO_2 abatement costs are calculated as the ratio of the quantity of avoided CO_2 emission and the cost difference to the reference option.

With GEMIS, the specific abatement costs can be calculated easily, because the model determines both the life-cycle emissions, and costs.

2 If photovoltaic cells are produced in large numbers (1.000 to 3.000 MW per year), they will cost less, so that until the year 2005 solar power could be produced in high-solar areas at a cost below 0,15 $/kWh.

In Figure 8, the results of the GEMIS calculation is shown for selected electricity systems.

Figure 8: Specific CO_2 abatement costs for selected electricity systems (from GEMIS)



As can be seen, the combined-cycle gas-fired cogeneration plant, electricity saving technologies, and some of the renewable energy systems offer negative CO_2 abatement costs, i.e. their costs are below the reference option (new coal-fired power station in Germany running on imported hard coal).

More advanced electricity saving technologies, new hydropower and small-scale gas cogeneration have slightly higher generation costs than the reference option, so that their CO_2 abatement costs are positive - between 15 and 45 DM/t of CO_2 avoided.

Nuclear electricity compares to that with a range of 18 - 54 DM/t of CO_2 avoided, depending on the study used to determine the generation cost.

Therefore, a variety of renewable and DSM options (including gas-fired cogeneration with combined-cycles) exists which is more competitive in terms of CO_2 abatement costs, even if no external cost value is allocated to the risks of nuclear electricity.

In a conservative estimate using the low range of nuclear CO_2 abatement costs to compare with the alternatives (cogeneration with combined-cycles) and renewable energy (biomass and wind)), the alternatives show CO_2 abatement costs which are **3-4 times more favourable** than those of nuclear power.

This finding is true not only for Germany, but in general also for other industrial and developing countries, too - the life-cycles do not vary much, and the costs are determined on world-market data.

In the „solar belt“ regions, solar-thermal electricity generation is applicable as well, which would result in CO_2 abatement costs of around 30 DM/t (given today’s costs !).

References

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