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

- updated version* -

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1 Introduction

The political, societal, and scientific debate on nuclear energy has a long history: Starting in the early 1970ies with concerns about low-level radiation, nuclear accidents, and final disposal of spent fuel, the late 1970ies focused on limited energy resources for which nuclear promised relieve in applying reprocessing with breeder cycles. In this time frame, associated proliferation risks were discussed as well.

In the 1980ies, the debate focused on the economics of nuclear power, and of its alternatives.

In the 1990ies, global concerns regarding the greenhouse effect peaked in the Rio Convention on Climate Chance, and the Kyoto Protocol to limit greenhouse-gas emissions from industrialized countries which entered into force in February 2005. Accordingly, proponents argue that nuclear electricity is favourable in terms of its “zero” greenhouse-gas emissions.

Since September 11, 2001, issues of nuclear terrorism are under discussion as well.

In parallel to this debate, nuclear expansion slowed down due to rising costs, and a *de-facto* moratorium in OECD countries after the Harrisburg (1981), and Chernobyl (1986) accidents could be observed. Disregarding voices calling for a nuclear “renaissance” in the 1990ies and after, several European countries endorsed nuclear *phase-out* policies. In other parts of the (developing) world, nuclear electricity continued a rather slow expansion[1].

As the issue of nuclear risks in its various forms – from radiation released during uranium mining to severe reactor accidents, and leakage from fuel reprocessing and repositories for spent fuel - is beyond the scope of this paper, we concentrate the following analysis on the more recent issues for which a scientifically “reasonable” range of data is available.

In that respect, two arguments favouring nuclear electricity can be identified:

- It is *allegedly “free”* of CO_2, and
- It is *allegedly low cost*.

In this paper, we address both, presenting results of life-cycle cost and emission analyses of energy systems with respect to current technologies[2].

We discuss the results with respect to other findings in the literature, and also indicate the cost-effectiveness of CO_2 abatement in the electricity sector.

The scientific work from which this paper draws was sponsored by a variety of sources, including the German Federal Ministry for Environment, Nature Protection, and Nuclear Safety (BMU), German Federal Ministry for Research and Education (BMBF), The Federal Environment Agency of Germany (UBA).

1 For details on the status and prospects of the world-wide nuclear industry, see Schneider/Froggatt (2004).

2 The original paper of 1997 was updated with the most recent GEMIS data. Also, currency data were converted from the original DM and US$ figures (in 1995 values) to $Euro_{2000}$ figures.

2 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 and processing, enrichment of uranium, fuel fabrication etc. – this is the so-called *upstream* fuel-cycle. Nuclear is not the only energy source needing upstream activities before electricity can be generated in a plant: also fossil fuels and biomass need extraction, processing, conversion, and transport. There are also *downstream* (post-plant) activities needed to process and store (nuclear) wastes. Furthermore, steel, concrete, and other materials are necessary for the *construction* of both the nuclear power plants, and the facilities in the up- and downstream fuel-cycle. If those are included, the analysis comprises the whole *life-cycle* of the nuclear system.

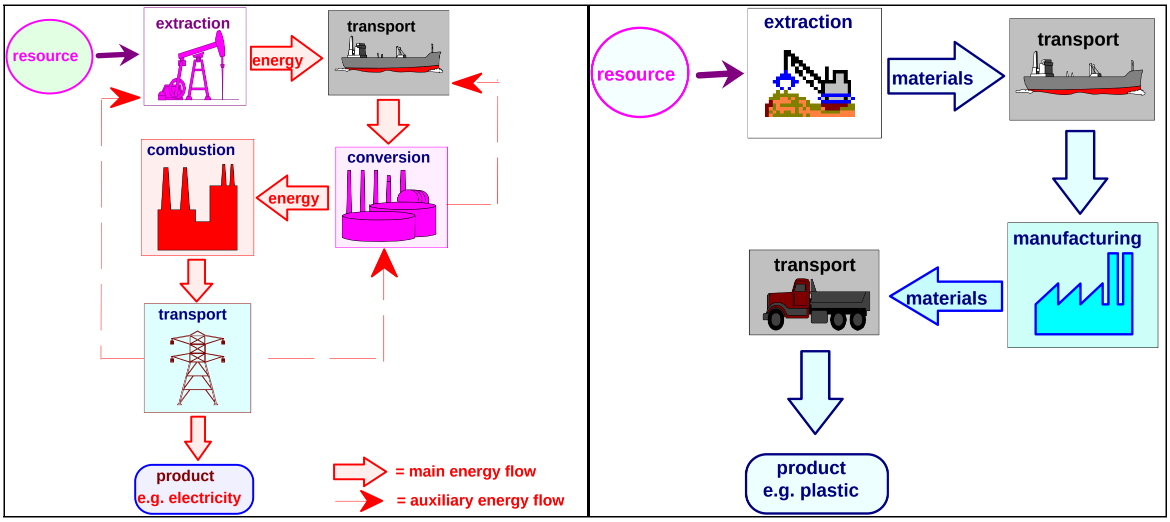
The energy used for these purposes is partly produced by fossil energy (which causes greenhouse-gas emissions), and some additional greenhouse-gas emissions result directly from chemical reactions during material processing (e.g. cement production).

Thus, nuclear powerplants – as well as other energy facilities - *indirectly* emit CO_2, as well as other greenhouse gases.

3 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 when considering or comparing greenhouse-gas emissions from energy processes. To do so, one has to follow all relevant steps along the life-cycles 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) in the left part, and material cycles in the right-hand part:

Figure 1 Processes and Links in Energy (left) and Material (right) Cycles



Along the energy flow, emissions and other environmental impacts can occur in every step (“process“) of the cycle, depending on the technology and fuel characteristics.

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: 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 (including transports), and
- indirect impacts from manufacturing materials used during the *construction* of all processes.

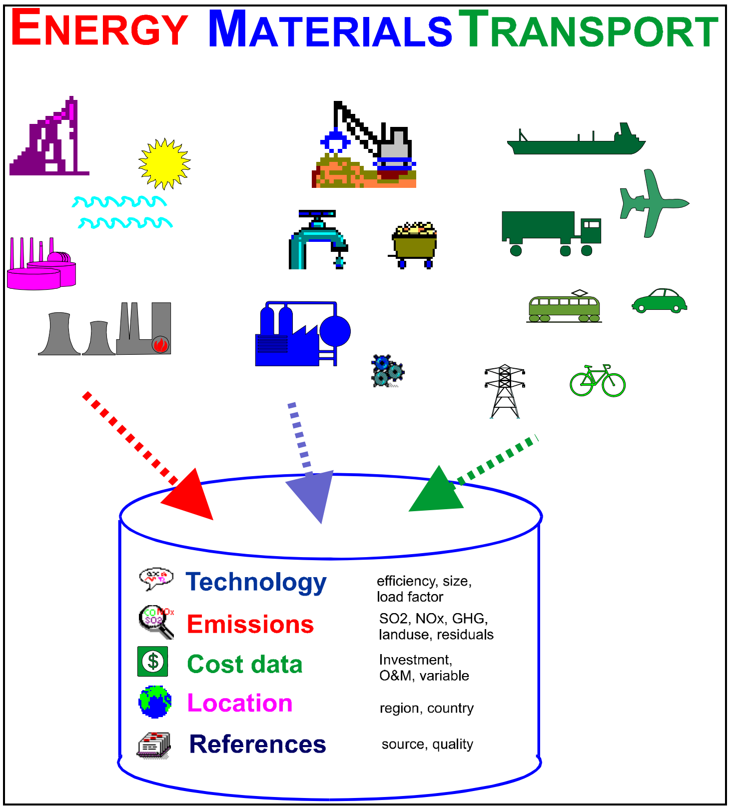
In reality, these levels are *interlinked* (e.g., electricity for steel making comes from a powerplant made of steel), so that life-cycle analysis considers the interactions between all processes.

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

Öko-Institut maintains since 1987 a computer model called GEMIS (Global Emission Model for Integrated Systems)[3], in which this data is compiled, and continuously updated and expanded. The GEMIS database is shown in the following figure:

3 GEMIS is a multilingual model and database. For more information, see www.gemis.de

Figure 2 Principal Structure of the GEMIS Database



4 Life-Cycle Analysis: Results for Nuclear Electricity

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

According to these data, the GEMIS model calculates some 31 grams of CO_2 per kWh of electricity generated in nuclear power plants in Germany. These calculations are based upon data for the whole life-cycle (complete production process including ore extraction, transformation, enrichment, and construction of all facilities).

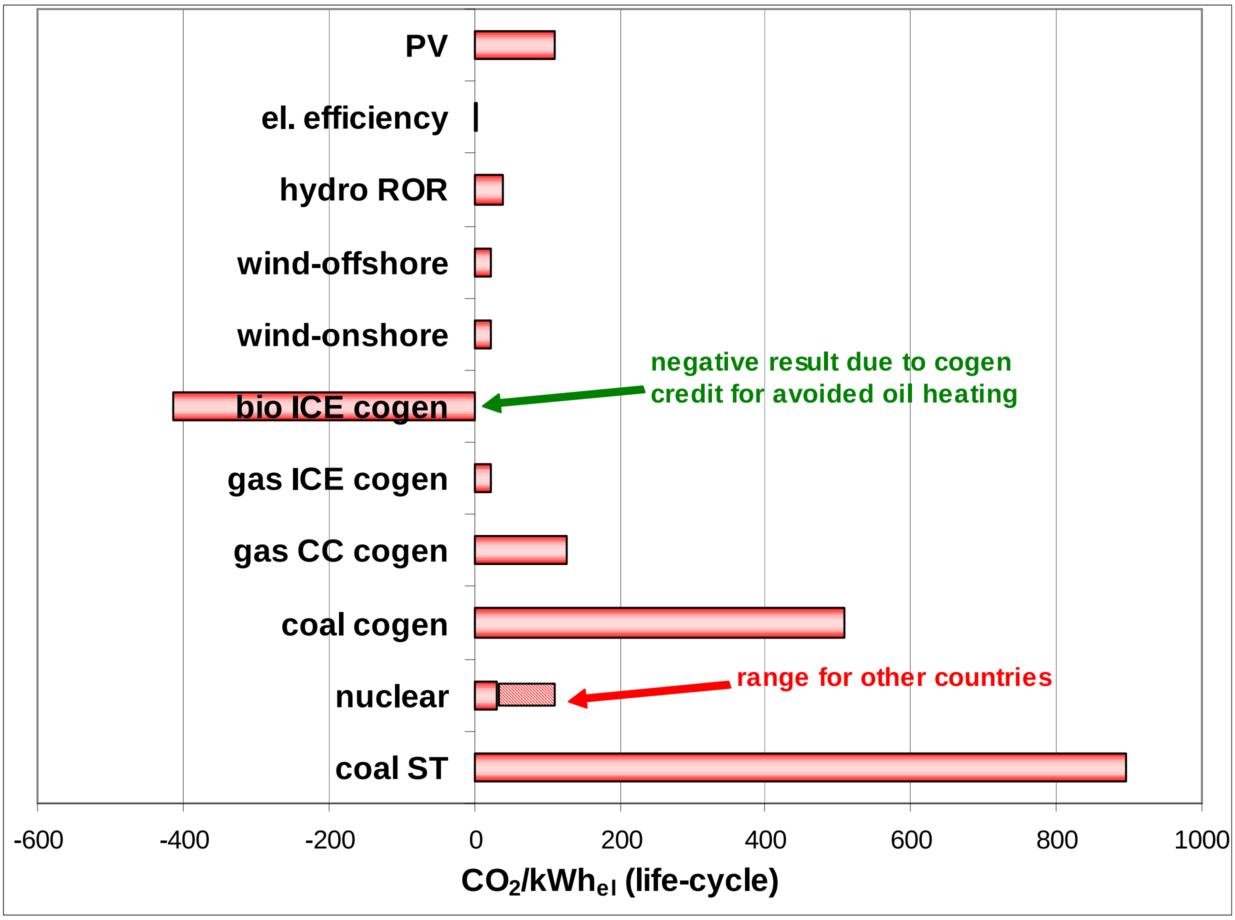
As not only CO_2 is emitted along the nuclear life-cycle, other greenhouse gases contribute to a total of some 33 g of CO_2 equivalents per kWh_{el} from nuclear.

The results of other international studies show higher CO_2 figures: 30 to 60 g/kWh_{el} (IEA 1994; CRIEPI 1995) up to 120 g/kWh_{el} for 0.1-1% ore grades (van Leeuwen/Smith 2004).

In total, a nuclear power station of standard size (1250 MW, 6500 h/a) *indirectly* emits some 250,000 t (German conditions) per year.

In comparison with the specific CO_2 emissions (per kWh) of alternative systems, e.g., cogeneration, renewable energies, and electricity saving, nuclear electricity is *not* the "winner" (see figure below).

Figure 3 Life-Cycle CO_2 Emissions from Electricity Generation (GEMIS data)



Source: own calculation with GEMIS 4.3

The “negative“ emissions of cogeneration are the results of the following approach:

When comparing electricity-*only* options like nuclear, wind etc. with *combined* heat and power (CHP) generation (i.e. cogeneration), one must deal with the additional *non*-electric - but still useful - heat output supplied by the cogeneration system. To do so, first the *total* CO_2 emissions of the cogeneration system (i.e. the emissions from generating both electricity *and* heat) are determined. Then, the emissions of a heating system delivering the *same amount* of heat are subtracted (“credited”), because the cogeneration system not only generates electricity, but also replaces heat supply from another system – say, an oil heater – and, hence, replaces also its emissions.

For example, the production of 1 kWh of electricity in a gas-fired internal combustion engine (ICE) cogenerator substitutes about 2 kWh of heat which does not have to be produced separately. The CO_2 emissions thus saved are credited to the cogeneration system.

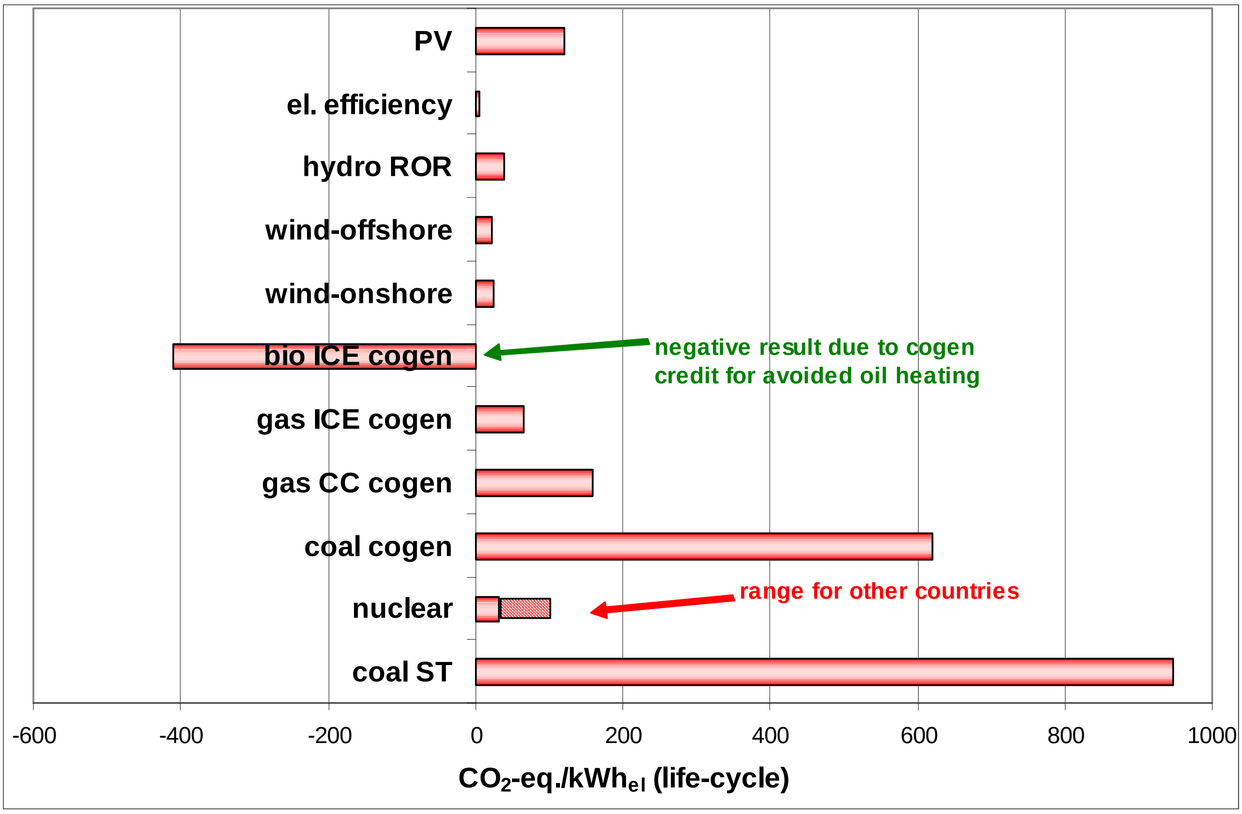
The *net* CO_2 emissions of electricity from gas-fired ICE cogeneration plants are *lower* than the CO_2 emissions of electricity produced in nuclear power plants. For biogas cogeneration, the negative net figures are even higher, as biomass is CO_2-neutral.

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

Besides CO_2, the upstream fuel cycles of fossil and biomass energy systems also cause other greenhouse-gas emissions (notably CH_4 and N_2O), so that a more comprehensive comparison must take these non-CO_2 greenhouse gases also into account.

The following figure shows the overall greenhouse-gas (GHG) emissions, expressed in CO_2-equivalents[4].

Figure 4 Life-Cycle GHG Emissions from Electricity Generation (GEMIS data)



Source: own calculation with GEMIS 4.3

The inclusion of the non-CO_2 GHG does not effect nuclear life-cycle emissions, but increases those of coal, and natural gas systems.

All in all, renewable electricity, and electricity efficiency have lower GHG emissions than nuclear electricity. Small-scale gas cogeneration plants are close to nuclear, while biogas-fired cogeneration clearly has far lower emissions than nuclear plants[5].

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4 The CO_2 equivalents are calculated using the IPCC global warming potentials for CH_4, and N_2O, i.e. their relative radiative forcing compared to CO_2 (mass-based, for a time horizon of 100 years).

5 This is also true for other biomass-fired powerplants and cogenerators – even if they biomass from dedication energy crops such as short-rotation forestry, miscanthus, or switchgrass.

5 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.

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

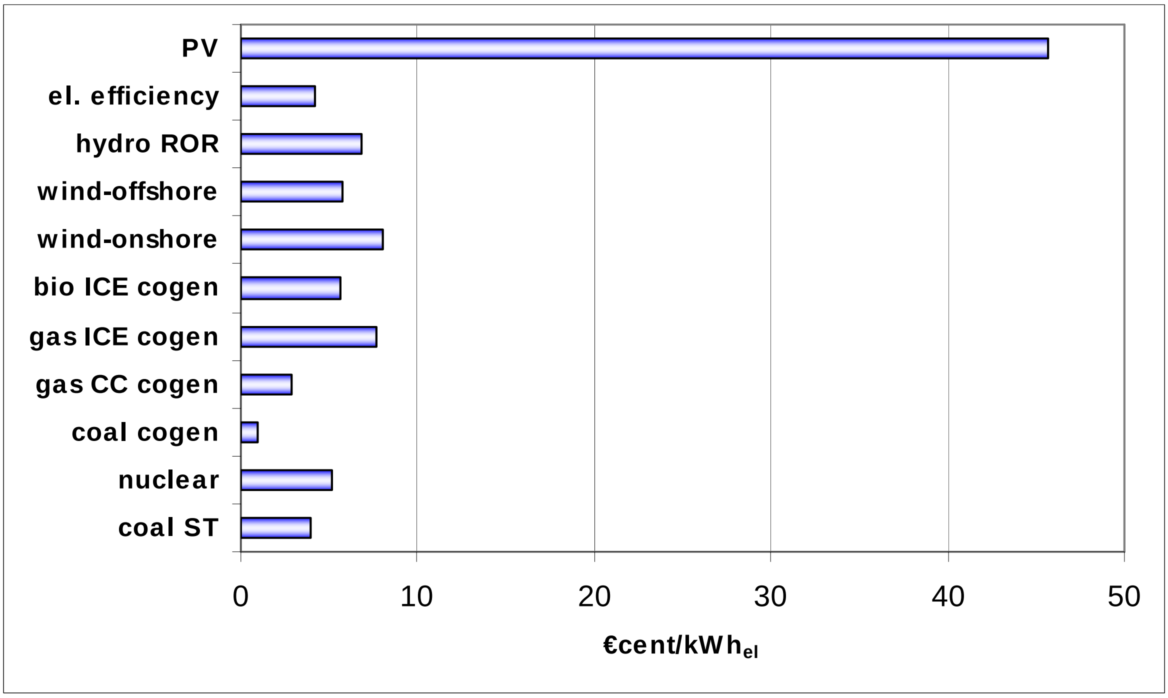
		NEA/IEA (2005)		
Parameter	**Units**	**Min**	**max**	**GEMIS**
Investment	€/kW_{el}	1500	2500	2050
fixed O&M	€/kW*a	40	94	61,5
Fuel & disposal	€/MWh_{el}	3.3	7.5	5.1
Operating time	h/a	6000	7000	6500
Lifetime	a	20	30	25
generation cost*	€cent/kWh_{el}	4.5	6.5	5.3

*= @ 7% real interest rate

The generation costs of new nuclear plants differ depending on various parameters. The range is 4.5 to 6.5 $€cent_{2000}$ per kilowatt hour for current reactor designs, with GEMIS data for Germany in the order of 5 €cent/kWh_{el}.

In GEMIS, a variety of other electricity generation technologies is available as well for emission and cost comparisons. Figure 5 shows the costs of selected other electricity systems.

Figure 5 Specific costs (without external costs) of German electricity systems



Source: own calculation with GEMIS 4.3

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 *new* nuclear plants. These systems are competitive and their costs are also lower. They will be even more favourable if the upper limit cost of nuclear electricity is assumed.

6 CO_2 and GHG Abatement Costs

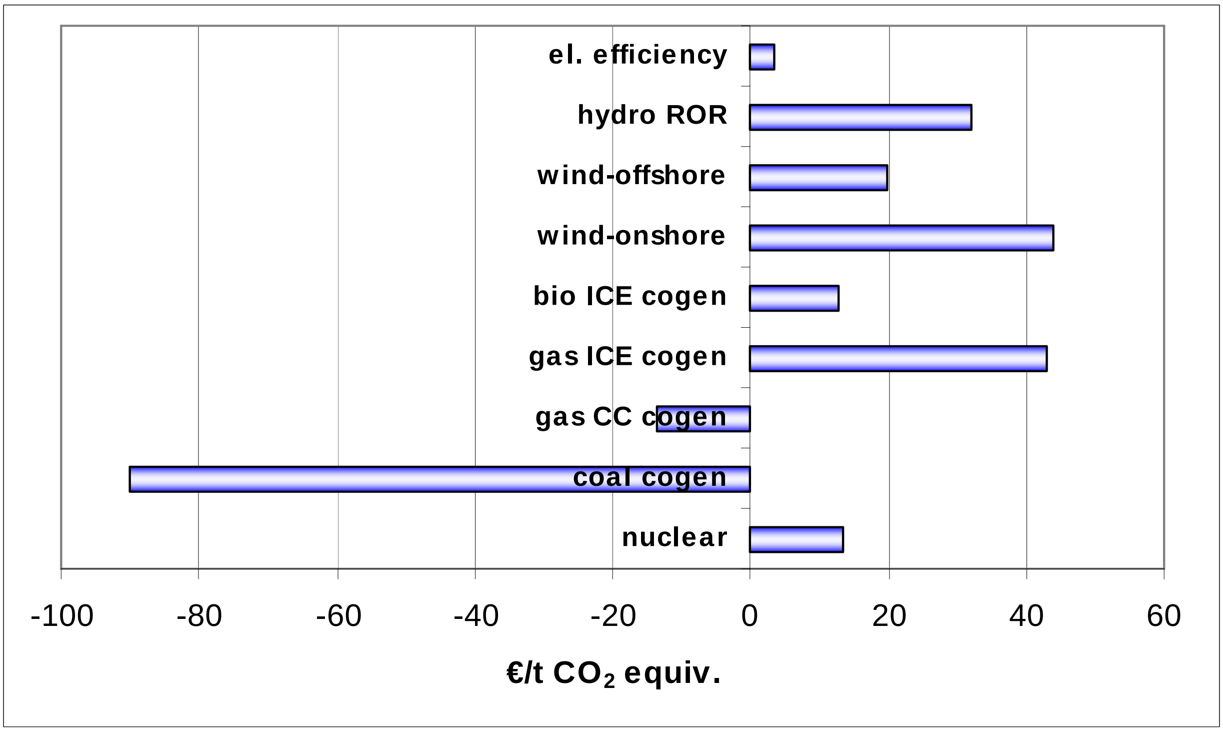
To determine the costs of CO_2 (or more general: GHG) abatement, one has to select a reference option (e.g., coal- or gas-fired powerplant), and then calculate the emission and cost differences of this reference option to alternative generation technologies.

The specific GHG abatement costs are then calculated as the ratio of the quantity of avoided GHG 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.

In Figure 6, the results of the GEMIS calculation is shown for selected electricity systems.

Figure 6 Specific GHG abatement costs for selected electricity systems



Source: own calculation with GEMIS 4.3

As can be seen, the coal-fired cogeneration plant, the gas-CC cogen system offer *negative* CO_2 abatement costs, i.e. their *costs are below* the reference option (new coal-fired power station with world-market hard coal), and also their emissions. Thus using those options instead of a coal plant, one could save costs while reducing GHG emissions.

GHG abatement costs for electricity efficiency technologies, and biogas-fired ICE cogen plants are below those of nuclear electricity, while wind (offshore) is in the same order of abatement cost. Small-scale gas ICE cogen plants, wind-onshore, and new hydro run-of-river plants have higher generation costs than the reference option, so that their GHG abatement costs are positive - between 35 and 45 Euro/t of CO_2 equivalent avoided.

Nuclear electricity compares to that with a range of 15 - 50 Euro/t of CO_2 equivalent avoided, depending on the study used to determine the generation cost, and the country-specific life-cycle emissions.

If we are optimistic and use the low range of nuclear GHG abatement costs to compare with the fossil alternatives (cogeneration) and renewable energy (biomass and offshore wind) as well as some electricity efficiency, the alternative mix offers GHG abatement costs *three to four times lower* than those of nuclear power.

This brief comparison clearly shows that renewable and DSM options (including gas-fired cogeneration with combined-cycles) are more competitive in terms of GHG abatement costs, even if no external cost value is allocated to the risks of nuclear electricity.

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.

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