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Environmental Impacts of Future Energy Systems

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Abstract

New energy technologies are currently investigated in R&D and promoted in the political arena. Before these technologies enter the market, their environmental superiority over competing options must be asserted based on a life cycle approach. However, when applying the prevailing status-quo Life Cycle Assessment approach to future energy systems, some drawbacks arise. This paper investigates the environmental performance of several future energy systems (carbon capture and storage, micro cogeneration and photovoltaics) and describes associated methodological issues and instruments for dealing with the future dimension of these technologies.

1 Introduction

A number of new energy technologies are currently entering the energy market or are, at least, investigated with respect to their diffusion opportunities into the energy market. Technological advances in the field of distributed and renewable energy systems, the requirement of climate gas mitigation and electricity system capacity deficits, as well as market restructuring and deregulation have led to an increasing interest in these innovative technologies.

The environmental compatibility of such systems is an essential prerequisite for a positive assessment. Typically, the environmental performance of products in general and energy systems in particular are measured using Life Cycle Assessment. The two key elements of LCA are

- assessment of the total life-cycle (“cradle-to-grave approach”) of a given energy conversion technology, including the exploration, processing, transport of materials and fuels, the production and operation of the investigated energy conversion units, and their disposal/recycling; and
- assessment of different environmental impacts on resources, human health, and ecosystems.

An LCA basically consists of four steps: (1) a goal and scope definition, (2) an inventory analysis involving data collection and calculation procedures, (3) an assessment of potential impacts of the inputs and outputs of the inventory analysis, categorizing and aggregating the environmental interventions. For that purpose, impact categories, such as global warming, eutrophication, acidification, toxicity or summer smog are defined and characterisation factors are calculated, which describe the contribution of different substances to that particular impact category (e g. CO_2, CH_4 or N_2O to global warming).

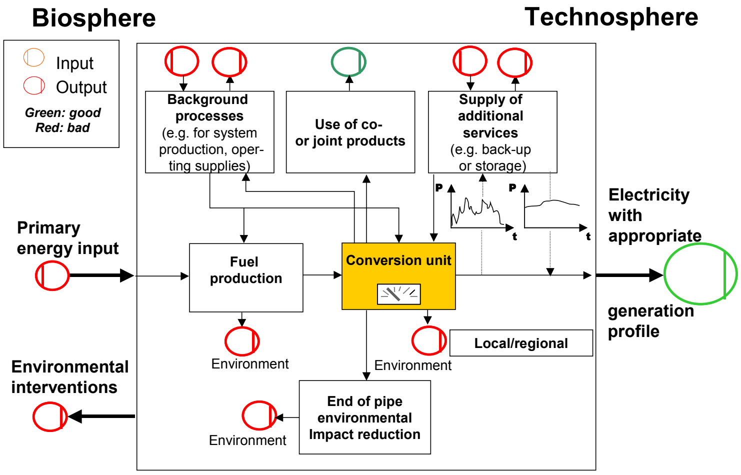

Fig. 1 Environmental interventions of future energy systems

(4) Through interpretation, the findings of the inventory analysis and the impact assessment are combined in order to draw conclusions or formulate recommendations.

However, the assessment of environmental impacts of *future* energy systems on a life cycle basis (**Fig. 1**) cannot follow the standard approach. Uncertainties, data gaps, modified energy system layouts and different physico-technical properties of the system make adaptations in the methodology necessary (**Table 1**):

- *Future character of the foreground system.* In LCA terminology, foreground systems are defined as consisting of processes, which are under control of the decision-maker for which an LCA is carried out. (Frischknecht 1998; Grunwald and Langenbach 1999) The future character of the foreground system can develop in different respects:
  Many of the systems under investigation have not yet been realised on a large scale, if at all. For instance, the performance of small Stirling engines for single-family applications has not yet been monitored with statistical significance (chapter 3). Likewise, in carbon capture and sequestration processes with chemical absorption, one – environmentally significant – step, the solvent regeneration, is still burdened with large uncertainty (chapter 2).
  Thus the following question arises: What is the improvement potential of these technologies compared to competitors, e. g. due to process and system innovations, progress of technical performance and production processes of systems, fuels and ancillary materials (e. g. wafer losses, biomass cultivation, etc.), diffusion effects (e. g. “ecology of scale”: lower production impacts due to higher sales numbers), and increasing complexity of the systems, e. g. due to more integrated system design (use of co-products)? Ultimately, the uncertainty with respect to the development of these different dimensions leads to data gaps in the LCA model.

- The often distributed nature of the energy systems requires further activities to monitor not only life cycle, but also regional and *local environmental impacts*. For instance, in the case of reciprocating engine micro CHP (chapter 3), not only the overall pollutant emissions, but also local air quality issues need to be taken into account. Toward this end, analyses of local air quality are required. The distributed location of some of the future energy systems (e. g. photovoltaics) might also have impacts on consumer behavior, e. g. increased awareness for energy consumption and rebound effects (Pehnt 2005).

- Future energy systems will often exhibit low direct emissions from the use phase (e. g. pollutant emissions). Therefore, the environmental contribution of the other life cycle stages, namely the *production* of fuel and power plants, increases in relative importance. Also, the more sophisticated design of future power plants might involve more environmentally problematic materials. For example in fuel cells, catalyst materials (platinum group metals) and graphite (PEFC), nickel (MCFC) or rare earth materials are among the more environmentally costly materials (Pehnt 2003).
- The transformation of the overall "*background system*" (which is not part of the actual object under investigation, but which provides, for instance, auxiliary materials, energy, etc.) significantly impacts the assessment of the energy systems under study. However, not taking these transformation processes into consideration could lead to self-fulfilling prophecies (for instance, assuming electricity mixes for Si wafer production for solar cells leads to significant impacts which are not inherent to solar cell production, but imported into the system from the fossil system; chapter 4). The changing background system might also concern the competing technologies. For instance, today a micro CHP system competes with a gas condensing boiler rather than with an average heating system. The question of the development of the background system also leads to a time dimension: How fast will the background system change?
- The differing *generation characteristics*, e. g. of fluctuating renewable electricity generation systems, require modelling of feed-in, storage, and back-up systems.
- Another time aspect of assessing future energy systems is the *time span* which is covered by the analysis. Consider, for instance, a system with a certain leakage rate of a substance (such as CO_2 from a geological carbon storage formation). The question arises: Which is the appropriate integration interval of this assessment?

To deal with these issues, different approaches have to be chosen. Forecasting is necessary whenever environmentally relevant processes or components have to be assessed based on systems of an immature technology standard. Very often, the forecasting of the use phase, i. e. the performance, emission factors etc., can be derived either from process modelling, target data from manufacturers information, or emission levels required by environmental legislation.

It is more difficult, however, to determine the impacts from the production of future energy technologies which are, at the time of the LCA, very often produced on a lab-scale only. Different cost estimation methods have been developed in management sciences, such as subjective assessment methods, regression analysis, or system modelling (Pehnt 2003). Other approaches include interactive technology foresight processes integrated into LCA (Borup and Andersen 2003), expert panels which deliver input data for Monte-Carlo simulations (Contadini et al. 2002), and scenario technology (Weidema et al. 2002).

In the following chapters, the focus will not be on the methodological aspects, but rather on the application of the methods to three concrete examples of electricity-generating systems: carbon capture and storage, micro cogeneration, and photovoltaics.

Table 1: Aspects regarding the assessment of future energy systems

Examples	Carbon Capture and Storage (CCS)	Micro CHP	Photovoltaics
Physico-technical properties of the system			
Decentralised systems	-	Emission source closer to recipient, impacts on local air quality	Decentralised installation: higher awareness for energy consumption
Low emissions in operation phase	-	Fuel cells or Stirling engines: lower direct emissions, therefore increasing relevance of system production and fuel supply	No direct emissions, therefore high (relative) relevance of system production
Fluctuating energy supply → requirement of backup services			Regulating energy and load-levelling
Future character of the product (foreground) system			
System innovation, progress of technical performance (life time, efficiencies, emissions, etc.)	Progress in carbon capture and power plant technologies (e. g. improved solvents, IGCC) lowers specific energy demand	Condensing operation, improved burner design (e. g. FLOX burners), better thermal integration	Increased life-time and efficiencies of PV modules
Progress of the production processes of systems, fuels and ancillary materials		Fuel cell micro CHP with lower catalyst loading	Reduced wafer losses, solar Silicon, EDFG, etc.
Diffusion effects, "ecology of scale", up-scaling technologies		Lower production impacts due to higher sales numbers (fewer fixed impacts per unit)	Lower production impacts due to higher sales numbers (fewer fixed impacts per module)
Increasing complexity of the systems, e. g. due to more integrated system design		Combined production of heat and electricity	
Future development of the background system			
		Changing benchmark technologies (e. g., micro CHP today competes with condensing boilers rather than low efficiency boilers)	Electricity for wafer production, steel and aluminium for module support

2 Future Character of the Foreground System: The Example of Carbon Capture and Storage[1]

Carbon dioxide capture and storage (CCS) is the capture of the CO_2 from the a flue gas stream from any point emission source, such as power plants, its compression, transportation, and subsequent storage in carefully selected storage sites, such as depleted oil and gas fields, aquifers, coal formations, and other geological reservoirs. CO_2 capture processes can be divided into three general categories: pre-combustion separation, oxy-fuel combustion, and post-combustion separation.

CCS has only rarely been implemented, mostly in the context of enhanced oil recovery. Therefore, coal power plants with CCS are a good example of future technologies that are characterized by a high degree of technological and infrastructural uncertainty. A detailed life cycle analysis (LCA) of the carbon sequestration paths was performed at IFEU (Idrissova 2004). The investigation involved analyzing the environmental characteristics of carbon dioxide capture and storage from fossil-fired power plants as a

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[1] This chapter is based on a thesis supervised by IFEU (Idrissova 2004).

means of greenhouse gas mitigation in comparison with conventional and advanced power generation. Additional environmental aspects, such as local risks due to sudden releases of CO_2, groundwater issues, micro-seismic activities, etc. cannot be covered with LCA.

The LCA model was developed for a conventional lignite power plant (LPP), lignite power plant with CO_2 recovery by chemical absorption, an integrated gasification combined cycle (IGCC) power plant without CO_2 recovery and an IGCC with CO_2 separation by physical absorption. From the impact categories implemented in the model, here we report only the cumulated Energy Demand (CED), based on the lower heating value of fossil fuels and the fission heat of nuclear materials, and the Global Warming Potential in CO_2 equivalents.

The 600 MW_{el} conventional lignite power plant was set as a reference power plant with a net efficiency of 41 %. Further power plants that were investigated included a 600 MW_{el} IGCC power plant with an efficiency of 43.6 % without CCS and an IGCC plant with CCS. The CO_2 from the conventional lignite power plant is captured by an already mature and commercial technology of chemical absorption, a very energy-intensive process due to solvent regeneration. In the case of the IGCC, the more favorable physical absorption in terms of energy can be applied. For the recovery of CO_2 from the solvent in the regeneration tower, thermal energy in the form of steam is obtained from the steam cycle of the power plant. This results in a decrease of power production (energy loss), and the thermal energy can be converted into an “electric equivalent” taking into account the decrease in the performance of the steam turbine. For the scenario in this model the energy requirement for the 20 % solvent concentration is estimated as 0.38 kWh_{el} per kg CO_2 (Göttlicher 1999), and is considered as a “base” case.

Due to the complexity of the chemical absorption, there is a certain degree of uncertainty in the estimation of the energy penalty. The variation of the solvent concentration in the chemical absorption changes the energy requirement and thus affects the total performance of the power plant. This is a typical uncertainty of high relevance and high time-dependency and thus requires further consideration. Here, we used chemical process calculations for the capture process with different solvent concentrations, as carried out by Göttlicher (1999), and implemented these data points in a sensitivity analysis.

The captured gas is then compressed to the required density level suitable for transportation and is directed via pipelines to the storage site. The length of the pipelines is another parameter for the sensitivity analysis (variation from 300 km to 900 km) due to the additional energy required for compression along the pipeline in order to compensate the pressure drop.

The storage site is assumed to have a zero leakage rate in this particular study. However, this is a question of further investigation and research in terms of integrity and availability of storage reservoirs, as well as of the acceptable duration of the storage and the subsequent monitoring of the site. The overall complexity of geological underground storage of CO_2 thus does not allow estimating a “general” leakage/seepage rate which could then be used in LCA or similar studies, as it is a parameter defined specifically for each storage location. Different studies are being carried out to address this issue. (Hepple and Benson 2003; Chalaturnyk and Gunter 2004). The important factor is the rate of surface seepage that could be acceptable in order to ensure the effectiveness of CCS. As long as the leakage rate is above zero, the result of the greenhouse gas assessment obviously depends on the upper integration limit: If we assume a leakage rate of 0,001 % per year, then after 1000 years, 1 % of the CO_2 will have leaked into the atmosphere. Ultimately, with an extreme long-term perspective, the full amount of CO_2 stored underground will be released.

The LCA results using 0 % leakage and including the infrastructure (pipeline, carbon capture equipment, etc.) can be seen in **Fig. 2** in which all four power generation options are considered and two selected impact categories are compared. As seen from that figure, the lignite power plant with CO_2 recovery has the highest cumulative energy demand (CED) in comparison with the reference power plant. The implementation of the advanced IGCC power plant with its higher efficiency would make it possible to reduce global warming (GWP) by 7 % compared to the conventional lignite power plant. Integrating CCS by chemical absorption in the conventional power plant would cause a 67 % increase in energy demand, whereas a CO_2 removal by physical absorption in the IGCC increases energy demand by only 20 %. This difference can be explained by higher energy demand of chemical absorption on the one hand and the higher IGCC efficiency on the other hand. The higher energy demand of CO_2 sequestration paths implies subsequently higher environmental impacts that are associated with coal mining, such as deterioration of area, ground water issues and so forth.

Whereas the energy penalty in the power plant due to CCS and the leakage rate are significant parameters, the effect of other life cycle stages (e. g. compression along the pipeline) and system components (e. g. construction of the pipeline) are only of minor importance. The results for other impact categories will be part of a separate publication.

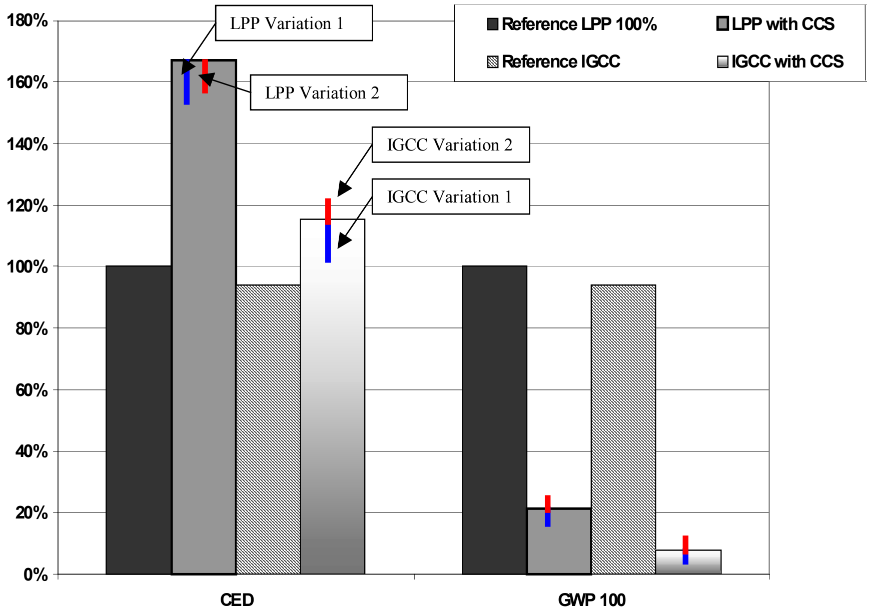


Fig. 2: Cumulative Energy Demand (CED) and Global Warming (GWP) of four power generation options (conventional lignite power plant LPP and integrated gasification combined cycle IGCC with and without CCS). LPP Variation 1: increase in solvent concentration to 40 %, variation 2: pipeline length increase to 900 km. IGCC Variation 1: plant efficiency increase to 50 %, variation 2: pipeline length increase to 900 km.

3 Localized Environmental Impacts: The Case of Micro CHP

Micro CHP (combined heat and power production) or micro cogeneration is the simultaneous production of heat and power in a single building (Harrison and Redford 2001) based on small energy conversion units (e. g. reciprocating or Stirling engines, fuel cells). The heat produced is used for space and water heating and possibly for cooling; the electricity is used within the building or fed into the grid.

A detailed Life Cycle model of micro CHP, including the production of the power plant and the fuel supply, is devised and described in Pehnt et al. (2005). To take into account the co-product heat, an "avoided burden approach" was chosen. That is, we regard electricity as the main product, while generated heat is credited, and we analyze the replacement of a gas condensing boiler by a variety of micro CHP systems. The question answered through this substitution perspective is: Which environmental impacts do micro CHP systems have if we install them instead of a modern gas condensing boiler?

The micro CHP case study demonstrates two future aspects: data gaps due to uncertain system properties and more localized environmental impacts. Whereas the latter is dealt with further below, the first is particularly relevant for fuel cells as the least mature among the micro CHP technologies. Since they are still in the field-testing phase, the environmental performance of these technologies is still unclear. For instance, the estimates of total efficiencies range from 80 to 90 %. In the LCA presented in **Fig. 3**, this is covered by using default estimates and bandwidths to characterize the uncertainty of the data.

As far as the reduction of GHG emissions is concerned, the assessment shows that most micro CHP systems which are operated with natural gas are superior not only to average electricity and heat supply, but also to efficient and state-of-the art separate production of electricity in gas power plants and heat in condensing boilers (**Fig. 3**). This is true, despite the strong dependence of the results on the electrical and thermal efficiency of micro CHP technologies and further parameters such as methane emissions from reciprocating engines. In fact, lower GHG emission levels can be achieved at an electrical capacity of up to five orders of magnitude smaller than large gas combined-cycle power plants. Even larger reduction effects could be achieved if heating systems based on more carbon-intensive fuels, such as diesel oil, were to be replaced. The GHG advantages of micro CHP plants are comparable to district heating with CHP.

The performance of micro CHP technologies with respect to climate and resource protection depends mainly on the total conversion efficiency (including the thermal output of the system) that can be achieved. In some cases, an unfavorable heat integration of micro CHP systems may lead to operation at the lower end of the assumed bandwidths of total efficiency. In such cases, CHP systems come rather close to the GHG emissions of electricity production in modern combined cycle plants without CHP. Optimizing micro CHP implementation thus involves careful integration into the supply object.

Under the assumption that gas-condensing boilers are the competing heat-supply technology, all technologies (fuel cells, reciprocating and Stirling engines) are within a very narrow range, with the exception of the small Stirling engine, which features lower electrical and total efficiency. For reciprocating engines, the values for methane emissions due to unburned natural gas vary considerably. Therefore, the error bar for this technology is larger.

Environmental impacts other than those related to climate and resource protection relate more specifically to technology. Whereas emissions of air pollutants are extremely low for fuel cells and Stirling engines (as long as these use innovative flameless burner technologies), reciprocating engines emit more significant amounts of NO_x, CO, and hydrocarbons. Furthermore, the emission factors of reciprocating engines depend heavily on operation characteristics (lean operation or λ=1, partial load or full load, etc.), and on the age and maintenance of the systems (catalyst exchange, engine characteristics, etc.). Thus, large bandwidths characterize this system. As a consequence, acidifying emissions of small reciprocating engines (considering the heat co-product) are somewhat higher than those of centralized gas power plants, due to more efficient emission control in the latter (**Fig. 3**).

When interpreting the LCA results for pollutant emissions, it is equally important to evaluate the impact of these emissions on the recipients' side: How does the *local air quality* change due to the emissions? This is even more important because we talk about a decentralized energy system with the emission source being close to the potential damage location. To address this question, the environmental relevance of the additional NO_x emissions of reciprocating engines were assessed. For this purpose, a dispersion calculation for a virtual residential area was carried out, based on the software package AUSTAL2000 (2003). For this calculation, it was assumed that, in a residential area based on multi-family residences, one third of the houses would be equipped with a reciprocating engine. This corresponds to 100 systems in a 1 km^2 area. In addition, avoided air pollutant releases due to the substitution of an alternative gas heating system are accounted for.

With respect to technical parameters, we conservatively assumed 5000 hours of full load operation per year, an NO_x emission factor of 300 mg/Nm^3 (expressed as NO_2), and a share of 10 % NO_2 of primary NO_x emissions. This latter assumption is of great importance, because NO_2 is of primary environmental concern. A site that has a flat topography and relatively critical weather conditions was selected: non-uniform wind distribution, large share of stable weather situations, and low wind speed, which tend to lower the dispersion of pollutants. The surface texture corresponds to that of an urban area.

Fig. 4 depicts the additional annual average concentration of NO_2 in the residential area due to net emissions from reciprocating engines. The annual average of 0.6 $\mu g/m^3$ can be compared to the permissible level for the annual average NO_2 concentration; the German limit is 40 $\mu g/m^3$. The air concentration associated with the installation of the 100 units is very low – below a level of irrelevance, which is by German law defined as 1.2 $\mu g/m^3$.

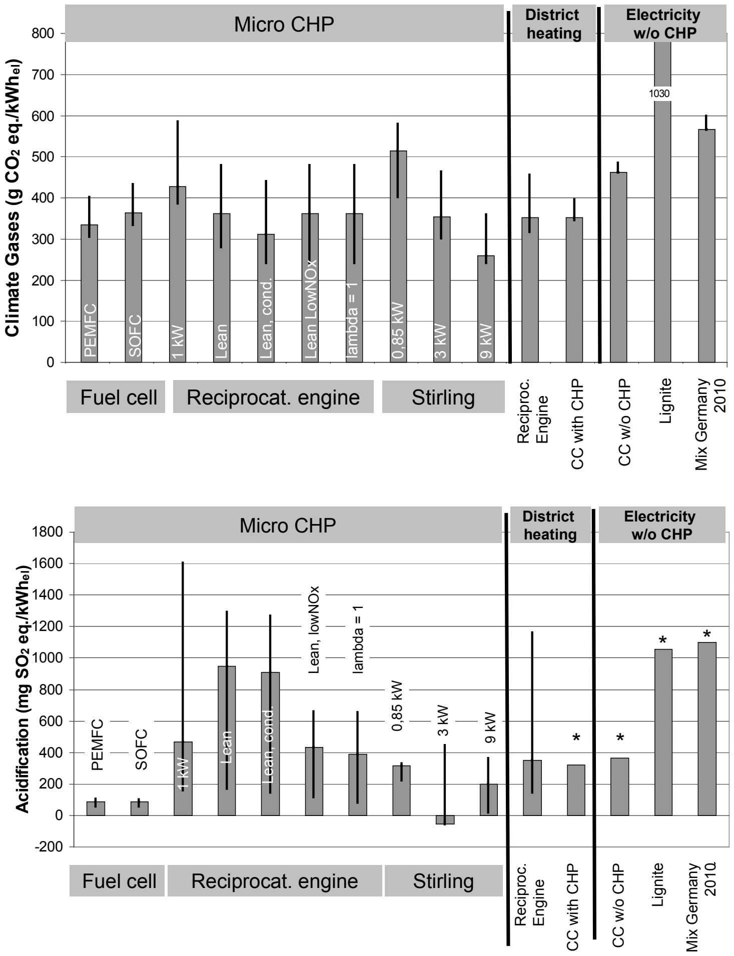
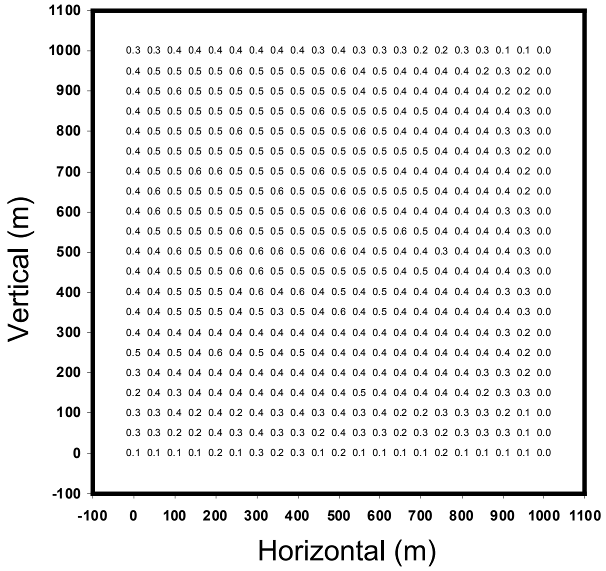


Fig. 3. Life cycle GHG (above) and acidifying (NO_x, SO_2, NH_3) emissions of micro CHP technologies compared to large CHP and conventional electricity production in the year 2010.

Functional unit 1 kWh electricity at low voltage level. CHP co-produced heat is credited with a gas condensing boiler ("avoided burden").



0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.3	0.4	0.3	0.3	0.3	0.2	0.2	0.3	0.3	0.1	0.1	0.0
0.4	0.5	0.5	0.5	0.5	0.6	0.5	0.5	0.5	0.5	0.6	0.4	0.5	0.4	0.4	0.4	0.4	0.2	0.3	0.2	0.0
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0.4	0.5	0.5	0.5	0.5	0.6	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.6	0.5	0.4	0.4	0.4	0.4	0.3	0.0
0.4	0.4	0.6	0.5	0.5	0.6	0.6	0.6	0.5	0.6	0.6	0.4	0.5	0.4	0.4	0.3	0.4	0.4	0.4	0.3	0.0
0.4	0.4	0.5	0.5	0.5	0.6	0.6	0.5	0.5	0.5	0.5	0.5	0.5	0.4	0.5	0.4	0.4	0.4	0.4	0.3	0.0
0.4	0.4	0.5	0.5	0.5	0.4	0.6	0.4	0.6	0.4	0.5	0.4	0.5	0.4	0.4	0.4	0.4	0.4	0.3	0.3	0.0
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0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.3	0.2	0.0
0.5	0.4	0.5	0.4	0.6	0.4	0.5	0.4	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.2	0.0
0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.3	0.3	0.2	0.0
0.2	0.4	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.4	0.4	0.4	0.4	0.4	0.2	0.3	0.3	0.0
0.3	0.3	0.4	0.2	0.4	0.2	0.4	0.3	0.4	0.3	0.4	0.3	0.4	0.2	0.2	0.3	0.3	0.3	0.2	0.1	0.0
0.3	0.3	0.2	0.2	0.4	0.3	0.4	0.3	0.3	0.2	0.4	0.3	0.3	0.2	0.3	0.2	0.3	0.3	0.3	0.1	0.0
0.1	0.1	0.1	0.1	0.2	0.1	0.3	0.2	0.3	0.1	0.2	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.0

Fig. 4. Annual average concentration of NO_2 in ambient air ($\mu g/m^3$) in a residential area due to installation of 100 reciprocating engines per km^2 (permissible level: 40 $\mu g/m^3$).

Consequently, with respect to the impact on ambient air quality, reciprocating engines are not critical under the given circumstances. Other emission sources, particularly from transportation, dominate the overall level of air quality. However, complex terrain (e. g. a narrow valley) might cause higher pollutant concentrations in certain places as calculated here.

4 Transformation of the Background System and Dynamic LCA: The Case of Photovoltaics

Not only the product system itself, but the background system which provides materials and services to the system under investigation can be in a process of transformation. The combination of changes in the foreground and background system could ultimately lead to a substantial change in the environmental performance.

As an example, **Fig. 5** shows results of a dynamic LCA for a polycrystalline photovoltaic system and the influence of various optimisation parameters. The example is taken from a project which investigated the (environmental) implications of a widespread implementation of renewable energy carriers (DLR, IFEU, WI 2004).

The following parameters – which are both environmentally relevant and strongly time-dependant – are varied:

- *Future power plants*. Production of photovoltaics requires large amounts of electricity. Rather than using an average electricity supply mix as input, we assume that the power plant portfolio develops according to a “sustainability scenario”, meets a climate reduction goal of -80 % by the year 2050 and exhibits significant contributions from renewable energy carriers. We analyze a long-term development, taking the year 2030 as reference. An extrapolation of the efficiency and emission development from fossil power plants according to DLR, IFEU, WI. (2004) is realized alongside the adapted shares of energy carriers.

- *Aluminum and steel.* Future development concern particularly the reduction of electricity demand, the respective power plant mix for the production electrolysis and the recycling rate (EAA 2000; Rombach et al. 2001).

- *Technology parameters.* Further time-dependant parameters cause an increase in module efficiency and life time, reduced wafer thickness and process losses at silicon wafer production.

Table 2: Parameters varied in the dynamic LCA of p-Si photovoltaics

	2010	2030
Steel production	Scrap share 46 %, electricity 2010	Scrap share 75 %, electricity 2030
Aluminum production	Scrap share 85 %	Scrap share 90 %, reduced electricity demand for electrolysis
Electricity production	Business as usual electricity mix 2010	“Sustainable“ Electricity mix 2030
Life time PV system	25 years	30 years
Module efficiency	13.4 %	17.8 %
Wafer thickness / Sawing loss	300 µm/200 µm	150 µm/150 µm

With regard to the greenhouse effect, each of the first three dynamic parameters constitutes a decrease of about 20 %. Although the production of Silicon substantially contributes to the greenhouse effect, the smaller wafer thickness only makes a smaller difference. This is also due to the fact that the improvement step is applied to an already optimized system. Life-time and module efficiency are of the utmost importance for minimizing acidification.

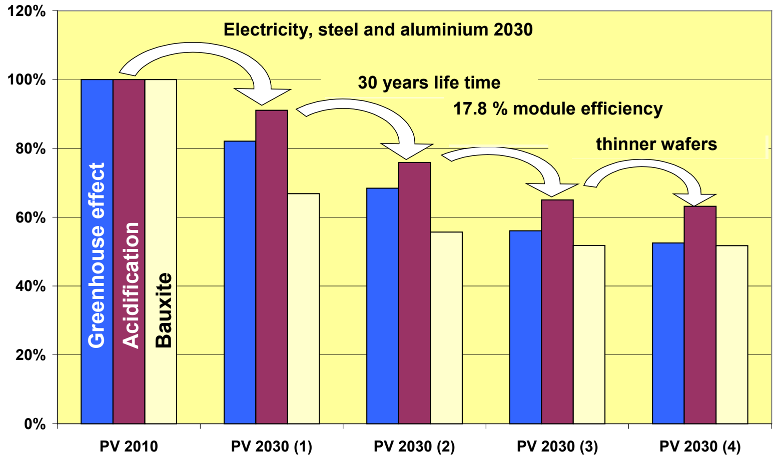

Fig. 5: Dynamic LCA of renewable energy systems, taking photovoltaic as an example. The representation is based on the environmental impacts of the non-dynamic system (=100 %).

Overall, the development of optimization potential and the improvement of materials and energy supply produce a 50 % reduction of the environmental impacts. Together with quantified optimization steps, it is possible to further reduce environmental impacts, particularly by recycling wafer and module components (Frisson et al. 1998).

It is interesting to note that advances with regard to “external” services that originate from conventional energy and transport systems, for instance, improved electricity or process heat supply for system production, ecologically optimized transport systems for the biomass transportation, could potentially lead to higher ecological impacts, because the attainable credits for by-products (“avoided burden”), e. g. glycerin in bio diesel production, are also lower.

Nevertheless, the combined effect of the three progress (advance) factors will bring about a substantial reduction of environmental impacts. A dynamic LCA perspective, thus, appears essential in the overall assessment of future energy technologies.

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