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Dynamic life cycle assessment (LCA) of renewable energy technologies

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Abstract

Before new 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 (LCA) approach to future renewable energy systems, one does not distinguish between impacts which are 'imported' into the system due to the 'background system' (e.g. due to supply of materials or final energy for the production of the energy system), and what is the improvement potential of these technologies compared to competitors (e.g. due to process and system innovations or diffusion effects). This paper investigates a dynamic approach towards the LCA of renewable energy technologies and proves that for all renewable energy chains, the inputs of finite energy resources and emissions of greenhouse gases are extremely low compared with the conventional system. With regard to the other environmental impacts the findings do not reveal any clear verdict for or against renewable energies.

Future development will enable a further reduction of environmental impacts of renewable energy systems. Different factors are responsible for this development, such as progress with respect to technical parameters of energy converters, in particular, improved efficiency; emissions characteristics; increased lifetime, etc.; advances with regard to the production process of energy converters and fuels; and advances with regard to 'external' services originating from conventional energy and transport systems, for instance, improved electricity or process heat supply for system production and ecologically optimized transport systems for fuel transportation.

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The application of renewable energy sources might modify not only the background system, but also further downstream aspects, such as consumer behavior. This effect is, however, strongly context and technology dependent.

Keywords: LCA; Life cycle assessment; Forecasting; Renewable energy; Photovoltaics; Geothermal; Hydropower; Biomass; Wind; Solar thermal

1. Introduction

Technological advances in the field of distributed and renewable energy systems, the requirement of climate gas mitigation and electricity system capacity deficits, but also market restructuring and deregulation have led to an increasing interest in innovative energy technologies. Before new technologies enter the market, however, their environmental superiority over competing options must be asserted based on a life cycle approach. Life Cycle Assessment (LCA) investigates environmental impacts of e.g. systems or products from cradle to grave throughout the full life cycle, from the exploration and supply of materials and fuels, to the production and operation of the investigated objects, to their disposal/recycling. With the increasing environmental operation standards of modern energy conversion systems, the upstream and downstream processes, e.g. fuel supply or power plant and infrastructure production, become increasingly relevant [1].

In the prevailing status-quo LCA approach, future developments of the energy systems themselves and of the context in which the systems are to be applied are typically not considered, thus severely distorting the analysis of the environmental characteristics of future energy systems.

In a causal dimension, the following questions arise:

- Which of these environmental impacts can be causally attributed to renewable energies (‘inherent impacts’), and which are ‘imported’ into the system due to the ‘background system’?[1]
- What is the improvement potential of these technologies compared to that of competitors’ technologies, e.g. due to process and system innovations or diffusion effects (e.g. ‘ecology of scale’: lower production impacts due to higher sales numbers) [1]?

These questions also lead to a time dimension:

- How fast will the background system change?
- How fast will the improvement potentials be made accessible?

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[1] In LCAs, background systems are system components that are not directly part of the product systems but which are necessary for the production, use, and disposal of these, e.g. the electricity supply mix for the production of a power plant or the transport infrastructure for fuel transport.

Using a dynamic[2] rather than a static approach helps to identify the inherent environmental bottlenecks. For instance, today under German conditions, producing a polycrystalline solar-grade Silicon photovoltaics system leads to greenhouse gas emissions of 100 g CO_2 equiv./kW h_{el}. From these, a large part is imported into the product system, e.g. because fossil energy is used within the production process. Taking into consideration a future energy mix for production, higher recycling rates, advances with respect to wafer losses, module efficiencies, and a higher lifetime cuts the emissions to approximately 50 g CO_2 equiv./kW h_{el}.

This paper investigates the environmental performance of renewable energy systems particularly in view of future developments.

2. First step: static LCA of renewable energy technologies

2.1. Methodology, goal and scope

The first step of this exercise is to set up LCA models of the respective status-quo renewable energy systems. For this purpose, networks in the LCA software package Umberto (www.umberto.de), which are the basis for life cycle inventory and impacts assessment, are set up. The LCA results are analyzed with regard to critical life cycle segments and materials and compared to conventional systems. To this end, data from manufacturers and system operators is compiled and the extensive IFEU database used, complemented with data from various literature LCAs (wind power [2], solar thermal power plants [3], geothermal energy [4], PV [5], solar thermal collectors [6], biogas [7]). The materials, energy supply chains, transport services, etc. are modeled with the Umberto database (www.umberto.de). A more precise definition can be found in [8].

The functional unit used in the system of electricity generation described in this paper is one 1 kW h_{el} at the power plant[3] for the electricity generating system and 1 kW h at the heat distribution system in a house for the heat generating system.

The geographic reference for the assessment of renewable energy technologies is the Federal Republic of Germany; the time reference is 2010. The most recent LCA data was taken for the assessment. If significant changes are to be expected until 2010, the data is adapted for the general conditions in 2010.

Processes assessed are production, operation and maintenance, and system recycling/disposal. The infrastructure of supply of fuels and power plants was considered with the exception of the utilization of roads due to lorry transports. Unless stated otherwise, recycling is assessed for a closed loop recycling, i.e. it is assumed that recycled material can substitute the use of the primary material to a certain percentage. The expenses of

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[2] In this context, dynamic does not necessarily mean that the development of the product and background system is modelled continuously, but rather it means that a future state of the system is modelled considering the future characteristics of the background and the model system.

[3] This system boundary was chosen deliberately, because the electricity distribution is characterized by significant data uncertainty, particularly with respect to avoided or extra losses due to distributed energy systems and with respect to material input for the electricity grid.

Table 1
Considered impact categories and characterization factors U in streamlined LCAs

Impact category	Inventory parameter	Characterization factor U	Reference	Value U ($kg_{Material}/kg_{Reference}$)
Energy resources		CED	MJ	
Global warming	CO_2	Global warming potential[a]	CO_2 equiv.	1
	CH_4		CO_2 equiv.	21
	N_2O		CO_2 equiv.	310
Acidification	SO_2	Acidification potential	SO_2 equiv.	1
	NO_x		SO_2 equiv.	0.7
	NH_3		SO_2 equiv.	1.88
	HCl		SO_2 equiv.	0.88
Eutrophication	NO_x	Eutrophication potential	PO_4^{3-} equiv.	0.13
	NH_3		PO_4^{3-}equiv.	0.33

[a] Time horizon 100 years.

recycling material processing are allocated to the process. Necessary allocation or credit is described in the respective sections about the technology.

The impact categories include energy resource consumption (also called simplified cumulated energy demand), non-energy resource consumption, and emission of greenhouse gases, eutrophication, and acidification. The characterization factors are summarized in Table 1. Due to the streamlined character of the LCA, only a limited number of inventory parameters are assessed here. However, for all technologies it was checked whether there are specific substances involved that would need to be taken into consideration (e.g. in magnesium production, SF_6 is emitted. If magnesium were involved in any of the systems, the significance of SF_6 to total global warming was checked).

The impact category of land use is not documented. This was considered in greater detail by means of geographic information systems in [8] and will be reported elsewhere.

Finally, the results are normalized. The normalization takes place for electricity generating systems with regard to electricity mix for Germany in 2010 (Table 2). That is, impacts of provision of 1 kW h_{el} by means of renewable energy systems are divided by the impacts of the assumed electricity mix as defined in the business-as-usual development

Table 2
Environmental impacts of the future German electricity and heat mix

		Electricity mix 2010 per kW h_{el}	Heat mix 2010 per MJ_{th}
Iron ore	g	2.6	0.2
(Finite) energy resources	MJ	8.91	1.23
Global warming	g CO_2 equiv.	566	81.5
Acidification	mg SO_2 equiv.	1083	115
Eutrophication	mg PO_4^{3-} equiv.	59.9	7.7

These factors are used for the normalization.

(energy carrier split and average power plant efficiency) according to the reference scenario of the German Enquete commission [9].

In other words, a value higher than 100% implies that in the relevant environmental impacts there is an increase in detrimental effect in comparison to the mix; a value below 100% means a reduction. This normalization serves two purposes. On the one hand, environmental advantages and disadvantages of the electricity consumption can be identified easily. On the other hand, different environmental impacts can be represented in one diagram.

The heating systems are normalized to a heuristic heat mix of 54% natural gas condensing boilers and 46% oil boilers, thus representing the present ratio for oil and gas heating (Table 2).

2.2. Results

The results for selected streamlined LCAs of electricity and heat producing systems are presented in Fig. 1. The results of the inventory and impact assessment are presented in Tables 3 and 4.

Greenhouse gas emissions and the consumption of non-renewable energy resources of renewable energy systems are significantly lower compared to those of conventional systems. The electricity values have a maximum of 20% of the 2010 electricity mix and heat values have a maximum of 15% of the heat mix. In the case of biomass systems obtaining heat and electricity credits, a negative environmental effect arises depending on the system type, i.e. the substitution effect results in the environmental 'relief' for the entire system.

With regard to material resources (iron ore, bauxite), a smaller or similar impact arises as does in the case of conventional systems. Exceptions include photovoltaics due to mounting the modules, solar collectors due to aluminum consumption for the collectors

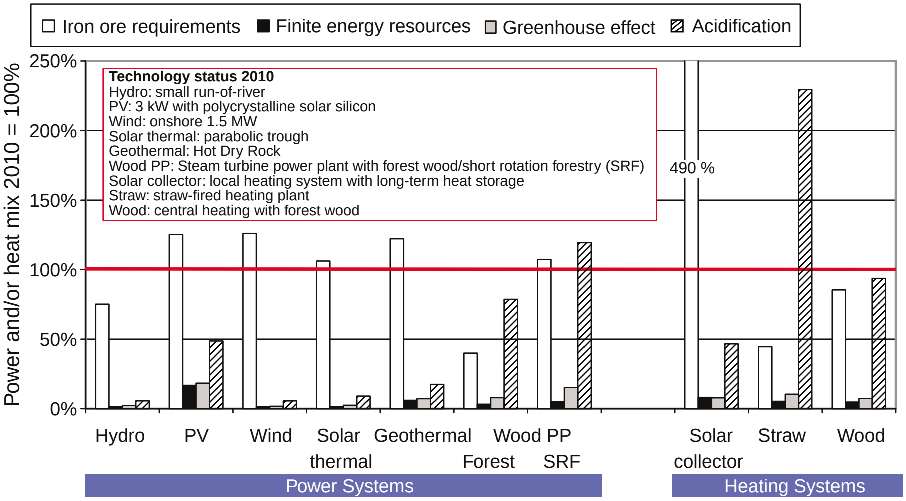

Fig. 1. Normalized LCA of selected renewable energy systems for selected impact categories (full results see Tables 3 and 4).

Table 3
Selected inventory and impact assessment results of renewable electricity systems

Product	Unit	Hydro-power 3.1 MW_{el}	Hydro-power 300 kW_{el}	Wind 1.5 MW (On-shore)	Wind 2.5 MW (Off-shore)	PV (polyc. SOG-Si)	Geother-mal (Hot Dry Rock	Solar ther-mal (Para-bolic trough 80 MW_{el})	Forest wood steam turbine[a]	SRF steam turbine[a]	Waste wood steam turbine[a,b]	Forest wood Co-com-bustion	SRF co-combus-tion	Forest wood recipro-cating engine[a]	SRF reci-procating engine[a]	Biogas[a]
		1 kW h_{el}	1 kW h_{el}	1 kW h_{el}	1 kW h_{el}	1 kW h_{el}	1 kW h_{el}	1 kW h_{el}	1 kW h_{el}	1 kW h_{el}	1 kW h_{el}	1 kW h_{el}	1 kW h_{el}	1 kW h_{el} and 1.7 kW h_{th}	1 kW h_{el} and 1.7 kW h_{th}	1 kW h_{el} and 0.39 kW h_{th}
Ressources																
CED	MJ	0.10	0.14	0.12	0.11	1.5	0.54	0.14	0.28	0.46	0.36	0.18	0.29	0.36	0.53	0.09
Iron ore	g	1.7	2.0	3.3	5.1	3.3	3.2	2.78	1.0	2.8	3.7	0.7	1.8	1.5	3.5	2.5
Bauxite	mg	4	16	4.8		1200	4.7	7.15	29	20	27	19	13	93	81	34
Emissions in air																
CO_2	g	10	13	10.2	8.9	99	37.8	13.4	22	35	31	14	23	27	41	11
CH_4	mg	21	29	24.1	9.8	220	103.4	35.2	17	58	63	21	47	77	124	−19,763
N_2O	mg	0.4	0,7	0.2		1.9	2.6	0.2	73	161	14	41	98	29	130	−743
SO_2	mg	17	28	39.5	35.4	288	61.6	46.7	72	198	315	26	67	74	111	368
CO	mg	59	74	96.8		141	208	85.4	757	820	405	185	226	829	898	723
NO_x	mg	36	49	31.1	20.9	340	188.9	72.9	1064	1192	1320	258	330	1360	1349	575
NMHC[c]	mg	6	11	26.1	2.4	20		2.1	45	40	123	30	27	157	149	166
Particles/dust	mg	26	31	42.2	10.9	119	35.4	40.1	60	95	109	86	109	87	125	38
HCl	mg	0.1	0.2	0.2		2.9	1.1	0.4	41	42	55	5	5	0.2	1	0.1
NH_3	mg	0.04	0.06	0.03		0.71	0.7	0.14	0.1	119	0.1	14	91	0.1	137	1619
Benzene	mg	0.03	0.05	0.02		0.09	0.05	0.22	2.7	2.6	44.9	2.1	2.0	0.5	0.4	0.02
Benzo(a)-pyrene	µg	0.2	0.3	0.48		1.4	0.3	0.36	251	447	502	122	248	272	489	0.4
Impact assessment																
Global warming	g	10	13	11	9	104	41	14	45	86	37	27	54	38	84	−580
Acidifca-tion	mg	42	61	61	50	528	190	98	853	1294	1288	237	473	1026	1313	3814
Eutrophi-cation	mg	5	6	4	2.7	44	24.8	10	138	196	172	38	74	177	223	609

CED, cumulative (non-renewable) energy demand; co-combustion in hard coal power plant; reciprocating engine, gasified wood in Otto engine; SRF, short rotation forestry.

[a] Without allocation/credit.

[b] Incineration plant fired with wood.

[c] Incl. benzene + benzo(a)pyrene.

Table 4
Selected inventory and impact assessment results of renewable heat systems

Product	1 MJ$_{th}$						
	Unit	Forest wood heating plant	SRF heating plant	Straw heating plant	Forest wood central heating	SRF central heating	Solar thermal collectors
Resources							
CED	kJ	61	79	66	60	76	100
Iron ore	mg	108	290	93	178	351	1020
Bauxite	mg	3	2	2	4	3	97
Emissions in air							
CO_2	g	4.2	5.5	4.3	4.1	5.4	6.1
CH_4	mg	8	12	19	17	21	13
N_2O	mg	5	14	12	5	13	0.1
SO_2	mg	10	23	73	19	49	44
CO	mg	62	68	181	75	81	32
NO_x	mg	124	137	212	119	131	15
NMHC[a]	mg	9	8	27	36	36	1
Particles/dust	mg	6	10	7	28	32	13
HCl	mg	4	4	50	7	7	0.19
NH_3	mg	0.03	12	0.03	0.03	12	0.03
Benzene	mg	0.8	0.7	2.8	3.8	3.8	0.01
Benzo(*a*)-pyrene	Ng	25	45	143	191	210	214
Impact assessment							
Global warming	g	6	10	8	6	10	6
Acidification	mg	100	146	265	108	169	54
Eutrophication	mg	16	22	28	15	21	2

[a] Incl. benzene + benzo (a) pyrene.

and steel consumption for the protective design, and wind power due to iron consumption for the steel tower. It is necessary to note that other environmental impacts associated with materials supply are included and that, moreover, material input directly depends on local conditions (e.g. concrete input for hydropower plants, aluminum for photovoltaics depending on roof or façade integration, etc.).

For other environmental impacts no clear trend in results for or against renewable energies arises. In fact, the comparison depends on the technology investigated, the fuel inventory of the used energy carrier (biomass), the specific operational context of the equipment (for example, for the case of photovoltaics, solar insolation, full load hours, topographic site, choice of materials for mounting, etc.), and other relevant factors.

By its nature, environmental accounting for renewable energy systems can only provide information about typical systems. For example, the acidification figures for electricity generating systems are well below or similar to the future reference mix, with the exception of the biogas system, which is above the reference mix owing to the ammonia emissions of the agricultural system. Apart from straw as a fuel, the heat generating systems are also below or similar to the reference mix. Straw-fired heating plants emit more acidifying substances (chlorine and sulphur content, NO_x emissions) than short rotation wood, which in turn emits more than forest wood as a result of the fertilizer and cultivation input and the agricultural emissions.

The pattern for eutrophication is rather different: electricity generating systems excluding biomass are considerably better than the reference mix, but biomass systems are well above the reference mix (exception: systems with co-combustion of forest wood). This is due in particular to the fact that the NO_x emissions of small systems are higher, and that the advantages on the acidification side compared with the reference mix, which result from avoiding the SO_2 emissions of coal-fired power stations, are not apparent when it comes to eutrophication.

On balance, there are thus clear advantages under the headings of greenhouse effect and consumption of finite energy resources. In the other impact categories, the findings reveal no clear trends. Thus, it is not possible to reach an objective decision. If one considers the great importance for energy resource consumption and greenhouse effect and the great specific contribution of the energy system to these environmental impacts, all renewable energy sources demonstrate clear advantages over the conventional variants where these environmental impacts are concerned.

3. Second step: dynamic LCAs of renewable energy systems

3.1. Methodology

The analysis of individual technologies must consider the extremely dynamic development. This concerns the development of products and their production processes as well as their technical performance and the development of so-called background systems (Fig. 2).

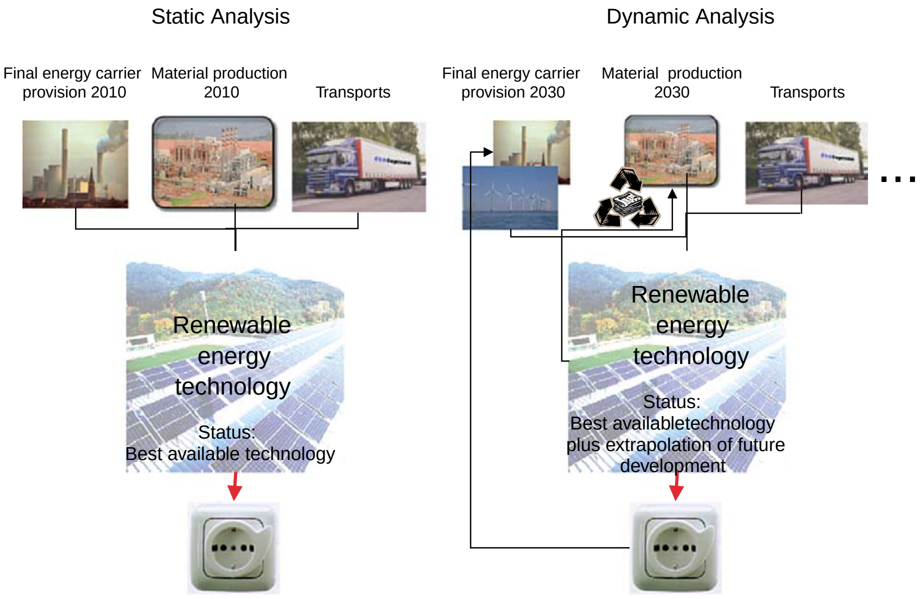

Fig. 2. Dynamic LCAs: principle.

The following renewable energy carriers are presented here as an example of a dynamic LCA:

- Photovoltaics (p-Si);
- Forest timber in central heating;
- Timber from short rotation forestry used in steam turbines.

The following dynamic LCA shall be regarded as an estimate of the order of magnitude of possible impact reductions in the time span, not as an exact forecast. The results are illustrated for the impact categories greenhouse gases and acidification only.

3.2. Dynamic parameters of the background system

The future-oriented dynamic assessments are represented and interpreted in the following sections. To present the influence of the time-dependent parameters, parameter changes are applied for the scenario in 2010 consecutively (cumulative). When interpreting the dynamic assessments one should pay attention to the fact that the results are not commutative, i.e. the order in which the parameters are varied has influence on the reduction effect, because optimizing an already optimized result has a smaller effect than optimizing the default value. Certainly, the final result in absolute amount is independent of the sequence of reduction steps.

For the dynamic LCA, those parameters are extrapolated into the future which are environmentally relevant and at the same time exhibit a significant time–dependency. The assessment of the system is iterated with those input parameters. With this approach, environmental problem areas, which are inevitably connected with renewable energies, can be analytically distinguished from those that are imported into the system by the background system, i.e. supply of energy and materials. The following parameters are varied:

- *Future power plants (electricity mix 2030)*. The development of power plants according to a sustainability scenario, which was developed for the Environmental Protection Agency, is analyzed [10]. This scenario, defined by a climate reduction goal of—80% by the year 2050, is characterized by significant contributions from renewable energy carriers. An extrapolation of the efficiency and emission development from fossil power plants according to [10] is realized alongside the adapted shares of energy carriers.
- *Aluminum*. Future development concerns particularly the reduction of electricity demand for the electrolysis by 7% [11,12]. The recycling share of aluminum depends on the type and composition of the product. On the assembly level, 72% of packaging aluminum, 85% of aluminum in building industry, and 87% of aluminum in electrical engineering are recycled in Germany [13]. 85 and 90% are assumed for 2010 and 2030, respectively.
- *Steel*. The present German recycling quota for steel is at a level of 43%. This comprises both own scrap in the steel mills and purchase of external scrap. The assembly based recycling quota depends strongly on the type of steel, the input, the worldwide scrap

market, etc. The quota of 75% is reported for recycling automobiles. In our assessment, the scrap share is assumed to increase from 46 to 75%. Moreover, the electricity mix 2030 is used for the future steel.

- *Further processes*. Further processes are varied specific to technology (e.g. biomass cultivation methods, fertilizers production, increased efficiency, process losses at silicon wafer production, etc.).

3.3. Example 1: photovoltaics

Future development will lead to a further decrease in production environmental impacts based on the already future-oriented assessment of p-Si, e.g. due to advances in module efficiency, improved casting methods and a lower Silicon demand via thinner wafer, reduced saw losses, other production methods, etc. [5,14].

The dynamic parameters are summarized in Table 5. The improvement of production methods and the favorable conditions for materials supply and energy form the basis of these parameters.

With regard to the greenhouse effect, each of the first three dynamic parameters constitutes a decrease in 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. For the minimization of acidification, the lifetime and module efficiency are of greatest importance (Fig. 3).

Overall, the development of optimization potential and the improvement of materials and energy supply allow a 50% reduction of the environmental impacts. Together with quantified optimization steps, there is a possibility to further reduce environmental impacts, in particular in recycling wafer and module components [15]. The recycling of silica could not be quantified here due to the lack of reliable data.

3.4. Example 2: steam turbine power plant with timber from short rotation forestry

Today, biomass-fired steam turbines often show a very poor performance, with electrical efficiencies around 15–18%. By 2010, we expect that the efficiency of new plants will go up to $\eta_{el} = 29\%$ (without cogeneration) in accordance with [16]. In the 2030

Table 5
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

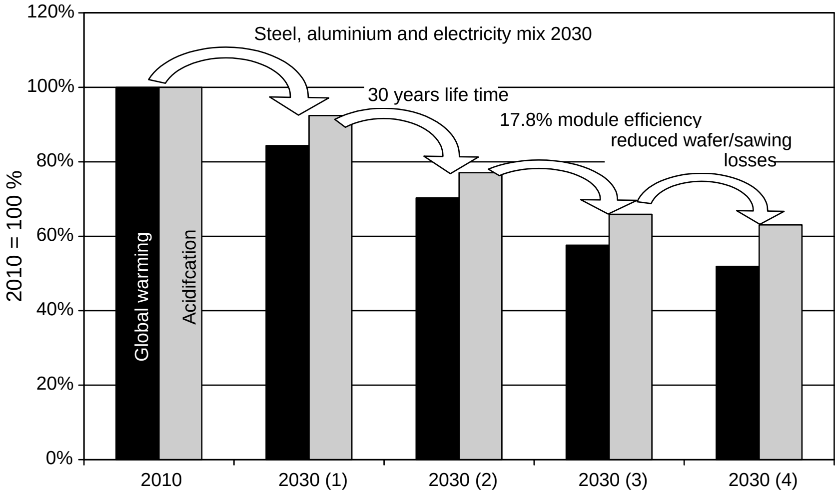

Fig. 3. Dynamic LCA of photovoltaics for selected impact categories.

sensitivity analysis, this will increase only slightly to 31%. Along with the power plant technology improvement, the improvement of the background system is assumed in analogy to the photovoltaics LCA. Improving European fertilizers and implementing possible measures for emissions reduction from the ground due to fertilizers containing nitrogen are extremely important for the agricultural sector (Table 6).

The increase in efficiency and reduction of emissions and fertilizer production reduce impacts by 25% points to the benefit of the greenhouse effect. The first aspect is also the most important step for acidification emissions reduction, which alone is decreased by

Table 6
Parameters varied in the dynamic LCA of steam turbines with timber from short rotation forestry

	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
Efficiency and emissions of steam turbine power plant	CO, NO_x, NMHC, particles emission reduction by 20%[a] $\eta_{el}=29\%$	$\eta_{el}=32\%$[a]
Optimized manure production	Reduction of energy demand for manure production by 30%, of CO_2 and N_2O emissions by 60%[b]	
Technology for application of liquid manure	Reduction of NH_3 emissions from the field by 60%[c]	

[a] Ref. [16].
[b] Ref. [21].
[c] Ref. [7].

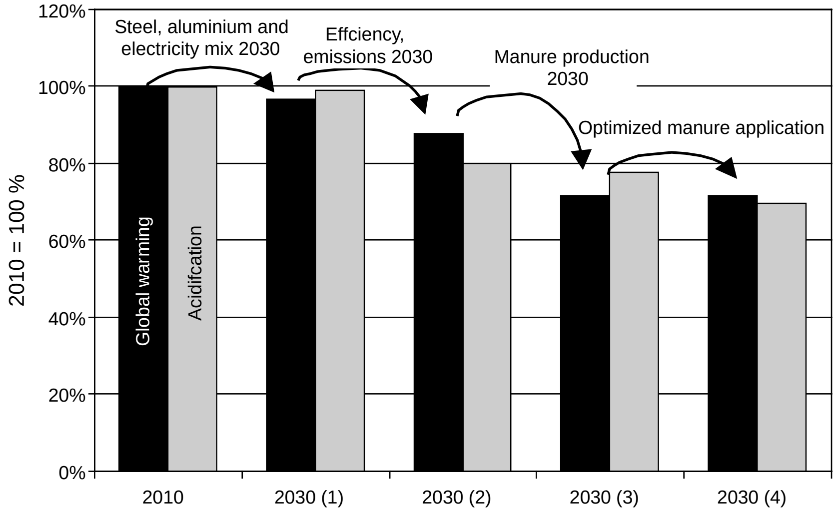

Fig. 4. Dynamic LCA of steam turbines fired with timber from short rotation forestry for selected impact categories.

almost one-fifth. In addition, optimizing the application technology of liquid manure allows an acidification gain of 10% points. The changes for materials and energy are insignificant. In conclusion, the technology-specific development of optimization potential of these environmental impacts allows the reduction of some 30% (Fig. 4).

3.5. Example 3: central heating with forest timber

Similar to electricity production, implementing technical innovations is important for heat delivering biomass technologies. Stricter legal obligations, particularly in the sector of small systems (e.g. through the planned amendment of technical instructions on air quality control) result in greater efforts of manufacturers to reduce emissions of their equipment. Thus, a significant reduction of environmental effects can be achieved, especially for air pollutants.

The limiting value for dust must be reduced to 100 mg/m^3 for devices with a combustion capacity below 2.5 MW that are fed with natural timber from the forest. On the other hand, the required costly flue gas filter technology with electrical filters would generate ‘disproportionately high costs’ instead of cyclone-principle strippers, which are applied to smaller devices.

The dynamic parameters are summarized in Table 7. Like in the case of the above-mentioned energy technologies, an improvement of conditions for material and energy supply is assumed.

In the case of wood timber in wood chips heating, the materials and energy supply have the strongest impact on the greenhouse effect. The development of the efficiency and emissions considerably influences acidification, whereas the changed supply conditions are hardly relevant. In total, the technology-specific development of optimization potential allows a decrease in 20% of these environmental impacts (Fig. 5).

Table 7
Parameters varied in the dynamic LCA of heat production of wood chips boilers with forest wood

	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
Efficiency and emissions of the wood chips boiler	CO, NO_x, NMHC, particles emission reduction by 20%[a] $\eta_{th}=82\%$	 $\eta_{th}=84\%$[a]

[a] Ref. [16].

4. Expanding the system boundary: effects on the consumer

The application of renewable energy sources might not only modify the background system, making ceteris paribus assumptions obsolete. Rather, renewable/distributed energy sources might also modify further downstream aspects, such as consumer behavior. This is particularly the case when renewable energy systems are installed at the customer's premises, e.g. on the roof or in the basement of a private household.

The emissions reduction and resource protection potential of renewable energy systems could then partially be offset by a 'rebound effect', thus implying that environmental benefits achieved by a more benign technology are at least partly compensated, and sometimes overcompensated, by an increase in energy demand. This rebound effect might be due to [17]

- behavioral changes, e.g. new comfort features. For instance, the switch from single coal or wood stoves to central heating in residential buildings leads to increases in energy consumption because users increase the number of heated rooms as well as the average

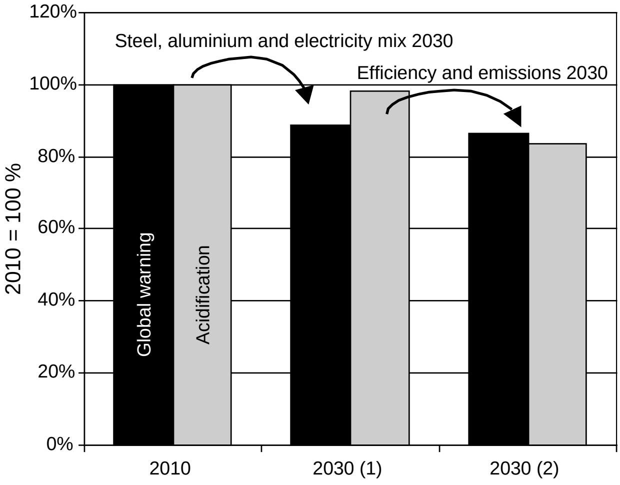

Fig. 5. Dynamic LCA of wood chips boilers with forest wood for selected impact categories.

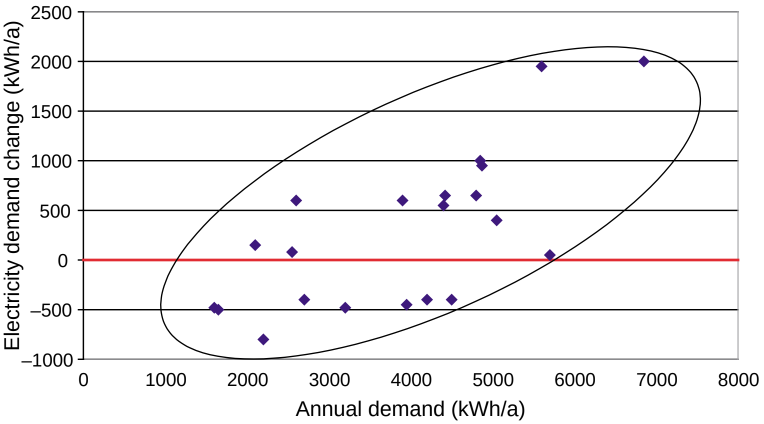

Fig. 6. Influence of PV installation on the change in household electricity demand depending on the annual household electricity consumption [19].

temperature. This level of behavioral change depends, among other things, on the relevance of the user's ecological norms, behavioral consciousness, the degree to which renewable energy system possession is perceived as ecologically relevant, and knowledge of its effects;

- increased expenditure available due to saved energy costs; this aspect is generally not relevant in the case of renewable energy systems;
- off-setting certain symbolic types of environmental action against behavior in other areas (the attitude of 'now I can drive a car because I have a PV system').

On the contrary, installing renewable energy systems could also lead to a stimulated environmental consciousness and enhanced involvement in energy topics. This effect greatly depends on the specific form, timing and detail of feedback, and on the presence of other incentives, such as price incentives, importance of independence, and ecological motives.

Whether the rebound effect or the positive effects on environmental consciousness prevails is, however, difficult to quantify and strongly context-dependent. For example, in the case of photovoltaics, Genennig and Hoffmann [18] and Haas et al. [19] have found that electricity consumption rises in households with low prior consumption and decreases in households with high prior consumption (Fig. 6). Apparently, the 'free' energy is used to raise the comfort level of users who were previously deprived of such comfort. In contrast, Haas et al. [20] find no difference in electricity consumption between households using renewable energies and conventional households. A time perspective on changes in consumption, however, is lacking here.

5. Conclusions

From the LCA results it follows that for all renewable energy chains the inputs of finite energy resources and emissions of greenhouse gases are extremely low compared with the conventional system. The relevant environmental impacts of the renewable energy systems amount to a maximum of 20% of an expected future German mix for electricity, a maximum of 15% of the reference mix for heat, and a maximum of 55% of the future diesel car in the case of fuels. LCA results for renewable energy systems reveals that the use made of the material resources investigated (iron ore, bauxite) is less than or similar to that made by conventional systems with some exceptions. It should be noted that the other environmental impacts associated with the provision of the materials are of course taken into account, and that the input of materials in particular depends heavily on the local situation.

The findings do not reveal any clear verdict for or against renewable energies in the case of other environmental impacts. The comparison depends more on a large number of context-dependent parameters, e.g.

- the technology configuration examined (e.g. polycrystalline, monocrystalline or amorphous silicon or thin-film solar cells, steam turbine or combustion engine CHP units, etc.);
- the type of energy source used, especially in the case of biomass, and its specific properties (fuel inventory, transport distances, etc.);
- the geographical location, topographical situation and local conditions of the plant (crucial for solar radiation, full-load hours, expenditure on barrages for hydropower, etc.) and integration into the local infrastructure.

Future development will enable a further reduction of environmental impacts that are caused by regenerative energy systems. Different factors are responsible:

- Progress with respect to technical parameters of the energy converters, in particular improved efficiency, emissions characteristics, increased lifetime, etc.
- Advances with regard to the production process of the energy converters or fuels, e.g. reduced sawing losses or wafer thickness for solar cells, decreased fertilizer input, and higher yields for biomass cultivation, etc.
- Advances with regard to ‘external’ services originating 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, etc.

On the other hand, the last aspect 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 allow substantial reduction of environmental impacts.

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