Time dependency of emissions from energy generation influencing the life cycle management

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Abstract The analysis of energy usage is an important part of each life cycle inventory analysis (LCI). LCA of certain technologies such as night storage heater having a distinct behavior for their usage time falsify their results by using static data. Hence the approach for using static data for the energy usage in LCAs has to be adjusted by using time dependent values for the consumed energy. The aim of this paper is to present the impact of the time dependency of emissions caused by the energy generation. Using this assignment planning, a time dependent analysis of the resulting emissions is possible. Based on this analysis, the impact on LCAs can be determined using a night storage heater as an example. The enhancement of the common approach broadens the possibilities to optimize processes or productions using life cycle management (LCM).

1 Introduction

The analysis of energy usage is an important part of each life cycle inventory analysis. Therefore, this part of the LCA requires special accurateness. Normally, static data is used for emissions of the power generation such as the German power plant mix with approx. 580 g CO2eq/kWh. However, this approach is only accurate for LCAs analyzing products or services using energy constant over time during each phase of the life cycle. LCAs of certain technologies such as night storage heater having a distinct behavior for their usage time falsify their results by using static data. Hence the approach for using static data for the energy usage in LCAs has to be adjusted by using time dependent values for the consumed energy.

The aim of this paper is to present the impact of the time dependency of emissions caused by the energy generation. Therefore, a power plant assignment planning was used to recreate the emissions in Germany. Each power plant has a geographic location and dependent emissions according to the external circumstances of the power plant. Using this assignment planning, a time dependent analysis of the resulting emissions is possible. Moreover, seasonal effects are observable. During the noon hours the emissions of the German power plant mix are reduced because of the higher percentage of gas plants and solar energy, especially in the summer. Wind energy is not exactly predictable but influences the median of the emissions over the year. Based on this analysis, the impact on LCA can be determined using some examples such as night storage heaters. Moreover, the environmental value of shifting loads into time slots with low emissions can be evaluated. The enhancement of the common approach broadens the possibilities to optimize processes or productions using LCM.

2 Modeling of energy generation in Germany in 2010

The variation of the emissions of the energy mix in Germany originates of the course of the energy load in Germany fluctuating during the day. Normally, the load is low during the night and rises in the course of the day with two peaks during noon and in the evening hours. The existing power plant fleet in Germany has to follow this course while integrating the renewable energy which is produced by wind or hydro energy. The knowledge about the operating time of each power plant is the basis for an ecological evaluation. Therefore, the existing capacity of power plants in Germany and a model allocating these capacities during the day will be described in the following.

2.1 Installed capacity in Germany in 2009

The installed capacity and generated energy in Germany in 2009 is shown in Tab. 1 for each generation type divided into the main primary energy sources. The base load power plants such as nuclear as well as black and brown coal have high installed capacities and long operation hours because of their low energy prices and low flexibility for the matching of the load or generation fluctuations in the grid. Peaking power plants such as natural gas or combined cycles are able to follow the fluctuations in the grid with the results of low operation hours. Renewable energy sources have the highest fluctuations during the energy productions. However, legislative regulations enable them to produce and feed-in their energy whenever it is available using peaking power plants to fill the resulting gaps in the supply.

Tab.1: Installed capacity and generated capacity in Germany [1]

Generation type	Installed capacity [MW]	Generated energy [%]
Nuclear	20.432	23
Black coal	25.257	25
Brown coal	19.345	18
Natural gas	5.812	13
Combined cycle	16.926	
Wind energy	25.700	6,6
Pump storage hydro	6.152	3,5
Run-of-the-river hydro	5.665	
Photovoltaic	16.000	1,2
Others	2.793	9,7
Sum	144.081	100

The location and age of the installed power plants have an impact on their efficiency and their ecological impact. Therefore, the information about age, location and power plant type are integrated into the model. The percentage of renewable energy sources in Germany rises significantly each year. However, for this paper the status quo in 2009 is used.

2.2 Generation model of the German power plant fleet

A generation model uses the installed power plant capacities in Germany to match the load in the grid to ensure the balance between load and generation under consideration of technical constrains. Moreover, the generation has to be as cost efficient as possible to reduce the overall energy costs. In this model, the Merit-Order-Optimization under technical constrains is implemented [2]. The merit-order sorts the power plants according to their marginal costs from the lowest to the highest based on their efficiency, CO2-costs and fuel prices [3]. After the sorting, the load is covered according the list sequentially. The cost per kWh for the last power plant defines the market prices [4]. If the existing power plant fleet is not able to cover the load, energy from neighboring countries is imported and assessed with the average of the country specific emissions and costs.
The developed model is an extension of the pure cost orientated merit order method because of the compliance with technical restrictions for each power plant

time. The most important restrictions are the duration of minimal operation hours, power gradients, revision times and minimal power for each power plant type. Moreover, a malfunction is stochastically integrated to simulate unforeseen breakdowns. The combination of the technical restrictions and the merit-order method permits a realistic estimation of the power plant schedule over the year.
Renewable energy is always integrated into the system without restrictions. It reduces the overall load (residual load) which has to be covered by other power plants. The generation of the renewable energy is not constant because of the dependence of the availability of wind, water or insulation. For the year 2009, the wind availability for each hour for 160 measuring stations in Germany is integrated. Moreover, Germany is divided into 15 regions with typical insulations values influencing the solar energy over the year. Both pieces of information permit a detailed assessment of the generated renewable energy.
The model provides an ex post or ex ante information about the deployed power plants of the German power plant fleet.

3 Daily fluctuations of emissions from the German power generation

The presented model determines which power plant is used to cover the load in Germany. Moreover, the costs and emissions for every hour can be calculated. The detailed life cycle inventory analysis (LCI) is not part of this paper but has been performed with the Umberto software taking into account all technical restrictions and the specific information for every power plant. After the presentation of the LCA results for each generation type, the average emissions on a daily and hourly basis are shown.

3.1 Life cycle assessment phase of the power plants

3.1.1 Emissions of every power plant type

For the life cycle assessment phase, the CML method is used and the result is shown in Tab. 2. Coal fired and oil power plants have, as expected, the highest global warming potential (GWP). Nuclear power plants have very low emissions in every analyzed category. Oil power plants have a high acidification potential because of their high amount of sulfur in the oil.

Tab.2: Emissions per kWh for every power plant type in the model

Generation type	GWP [g CO2-eq/kWh]	Acidification [g SO4eq/kWh]	Eutrophication [g PO4eq/kWh]
Nuclear	10,38	0,07	0,02
Black coal	1093,74	1,69	0,16
Brown coal	1220,69	1,27	0,16
Natural gas	562,73	0,67	0,07
Combined cycle	425,34	0,37	0,05
Oil	1129,04	3,81	0,32
Wind	17,54	0,08	0,02
Pump storage hydro	925,31	1,27	3,65
Run-of-the-river hydro	1,17	0,00	0,00
Photovoltaics	75,44	0,36	0,13

Renewable energy sources have low values in every category with the pump storage hydro power plants as an exception. The reason is the assessment of the energy used for the pumping which is mainly provided by coal power plants during the off-peak hours having high emissions.

3.2 Average daily fluctuations of the emissions in 2009

3.2.1 Average emissions of power plant mix over the year

The average emissions for every category in 2009 based on the developed model are shown in Tab. 3. The emissions for a working day are higher than during the weekend. The values can be used for a typical assessment of the used energy as a part of an LCA and will be used during the use case in this paper as a reference.

Tab.3: Average emissions values over the year

Average Values 2009	Category	g /kWh
Average	CO2eq	580,76
	PO4eq	0,1455
	SO2eq	0,7565
Workingday	CO2eq	596,71
	PO4eq	0,1449
	SO2eq	0,7835
Weekend	CO2eq	540,75
	PO4eq	0,1469

	SO2eq	0,6887

3.2.2 Average emissions of power plant mix during a day on an hourly basis

An average value for the assessment of the energy mix in Germany is only valid if the energy is consumed constantly over the year. In Fig. 1 is shown how variable the CO2eq emissions of the energy mix are during one year.

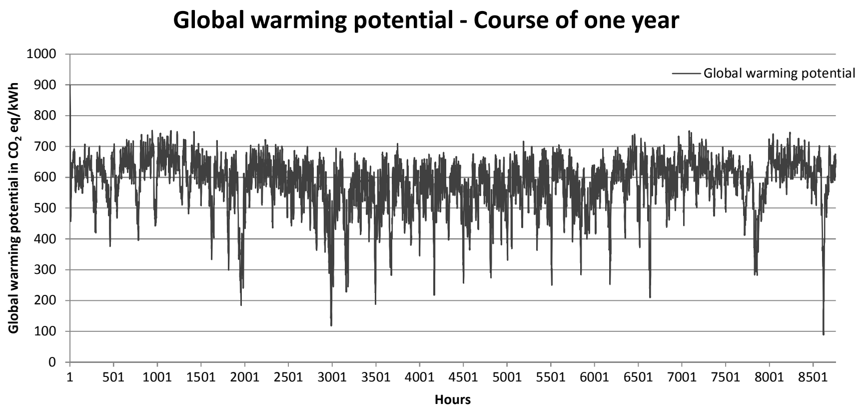

Fig.1: Course of the global warming potential of the energy mix in Germany during one year

The renewable energy sources are able to reduce the emissions of the energy mix significantly for a few hours during the year. However, the fluctuations are not coincidental because the average emissions during the day show a clear reduction of emissions at noon as shown in Fig. 2 for the CO2eq emissions of the energy mix. The average minimum of the CO2eq emissions of the energy mix is from 10 a.m. to 3 p.m. because of the high insulation during the day and the higher appearance of wind during noon generated by the high temperatures differences in different areas.

Fig. 3 and Fig. 4 show the diurnal variations for PO4eq and SO2eq emissions. SO2eq emissions are having nearly the same course as CO2eq emissions during the day. The deviation of the diurnal variations of SO4eq emissions can be partly explained with a higher percentage of pump storage hydro power plants providing energy to the grid to empty their reservoirs for the low tariff times.

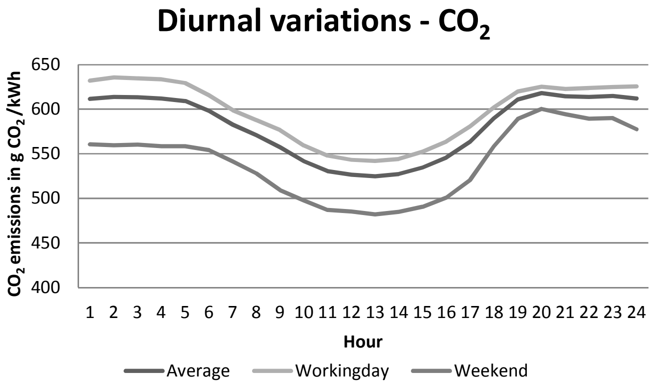

Fig.2: **Diurnal variation of the CO2eq emissions of the energy mix for one day**

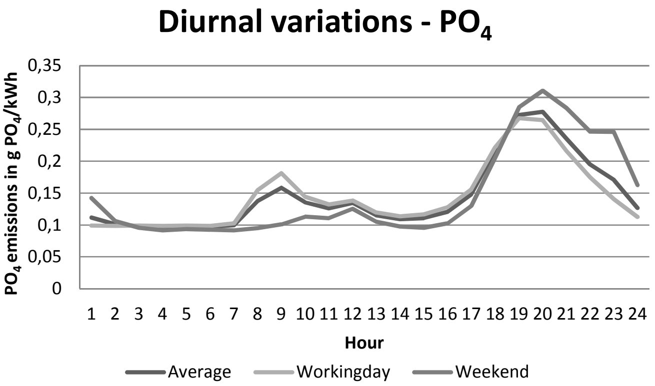

Fig.3: **Diurnal variation of the PO4eq emissions of the energy mix for one day**

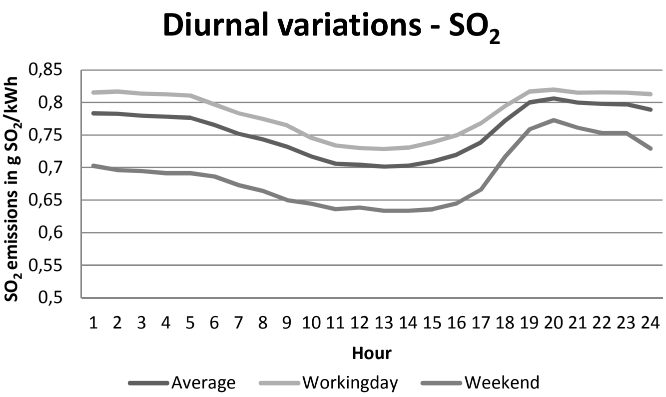

Fig.4: **Diurnal variation of the CO2eq emissions of the energy mix for one day**

4 Use case: Night storage heater

The influence of the shown variation of emissions during the day affects the overall emissions for certain technologies with a distinct behavior during a day. In the following, the night storage heater will be described as a use case to show the effects on the LCA during the usage phase.

4.1 Operating behavior of night storage heaters during the winter

The night storage heater is used to store heating energy during the night using a low energy tariff and to provide the stored energy as heat during the day. During winter, the heat demand is very high so that the whole storage capacity is used as shown in Fig. 5. The maximum power of the heater in this use case is 13.2kW with a total storage capacity of 79.2 kWh. The heater is storing energy only from 2 a.m. to 6 a.m. and provides if afterwards. In this example, 66kWh are stored during the night to match the heat-demand during the day. Therefore, a night storage heater is a useful example for a product only consuming energy during certain times of the day.

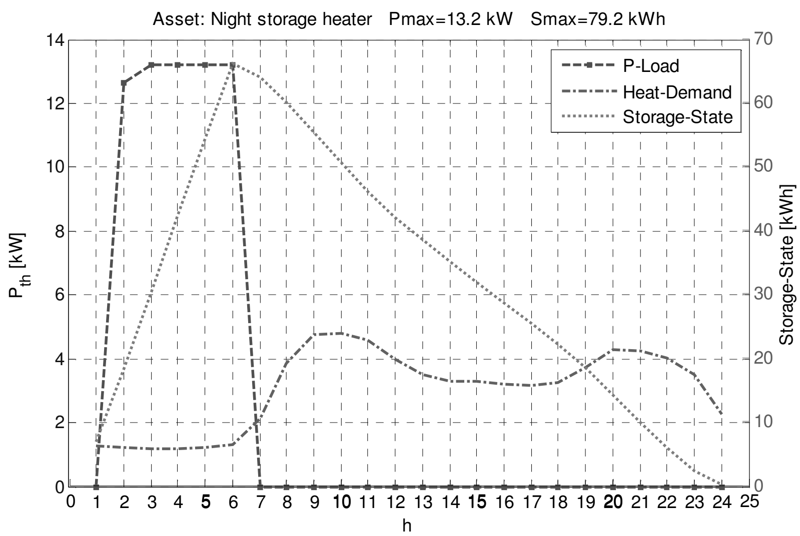

Fig.5: Operating behavior of night storage heaters for a winter day

4.2 *Impact of using average energy values compared to using a hourly resolution*

Due to the time restriction of the energy storage of the night storage heater, the approach of using average values leads to a falsification of the consumed energy and therefore to wrong assessment of the emissions. The comparison of the caused emissions of a night storage heater is shown in Tab. 4 for both approaches: using average emissions over the year and using the detailed energy mix for each hour.

Tab.4: Average emissions values over the year

Category	Average	Hourly basis	Difference [%]
CO2eq [g CO2eq/d]	38330,27	40214,83	4,92
PO4eq [g PO4eq/d]	9,60	6,47	-32,60
SO2eq [g SO2eq/d]	49,93	51,25	2,64

The difference for CO2eq and SO2eq emissions is with around 5% and 2.6% relatively small. The effect of the PO4eq is with a reduction potential of 32.5% significant.

5 Discussion

The influence of the different approaches of assessing the consumed energy for a product or a process could be shown in the example of the night storage heater. The effect is relatively small for CO2eq and SO2eq today but will rise in the future because of the rising percentage of renewable energy sources strengthening the effect of the diurnal variation of the emissions during the day.

The approach using hourly emissions for an LCA is only reasonable for products or processes with a very distinct time behavior as shown in the example. Moreover, if the load of the analyzed product or process is very high and therefore able to influence the power generation, this approach cannot be used with fixed values for the emissions during the day but has to be extended into an iterative process to provide variable emissions according to the new load curve.

6 Summary

The emissions of the energy mix in Germany are not constant during the day but vary significantly due to a high percentage of renewable energy sources. An ecological assessment of the consumed energy of processes or products with a very distinct time behavior has to be conducted with an approach using hourly emissions rather than with average values. Depending on the time behavior, the impact for certain impact categories can be very high. The impact on the LCA results will rise in the future due to the rising influence of renewable energy sources.

7 References

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