Impact of dynamic CO$_2$ emission factors for the public electricity supply on the life-cycle assessment of energy efficient residential buildings

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Abstract. Climate change and its effects are the reasons for the energy transition in Germany and lead to an increasing exploitation of renewable energy sources. At the same time, energy efficient buildings reduce the heat demand significantly and allow for the operation of electricity based heating systems. With the aid of dynamic CO$_2$ emission factors, the life-cycle assessment (LCA) for buildings can be adapted to reflect the fluctuating nature of renewable energy sources and the dynamics of heating power demand during the use phase more precisely. A case study using dynamic building simulation and static as well as dynamic emission factors for the year 2017 shows deviations of 3.4 % in the building’s GHG emissions. Furthermore, two emission factors for 2030 and 2050, which reflect the national 80 % carbon dioxide reduction target, are developed and applied to the case study. For these emission factors, the overall building’s GHG emissions decline drastically, whereas the deviation between the LCA using static or dynamic emission factors increases significantly. It can be seen that the application of a more dynamic approach for LCA adds substantial value to the investigation. However, further investigation on a broader set of dynamic input parameters for the LCA of energy efficient buildings seems to be reasonable.

1. Introduction

Climate change and its effects are threatening the lives of millions of humans globally. Since the beginning of industrialization in the end of the 19$^{th}$ century, an anthropogenic greenhouse effect caused by carbon dioxide and other greenhouse gases has led to an increase of the global mean temperature and a more frequent occurrence of extreme weather phenomena. In order to prevent major impacts on the
livelhood of mankind, climate change needs to be limited to a maximum increase of around 1.5 °C compared to pre-industrial ages. [1] This is why the German federal government has set the ambitious target to reduce greenhouse gas emissions about 80 % to 95 % compared to the base year 1990. As the largest part of German greenhouse gas emissions is caused by the combustion of fossil energy carriers in the electricity sector, the German Energiewende initially concentrated most of its efforts on increasing the share of electricity generation from technologies based on renewable energy carriers. Today, Germany’s energy transition affects the three sectors electricity, heat and mobility, equally. [2, 3] At first glance, Germany has succeeded in enhancing the electricity generation from renewable energy sources significantly. In 2017, more than one third of the national gross electricity consumption was covered by renewable energies. However, the corresponding GHG emission factor for the public electricity supply in Germany reflects this progress only in part. [4] A stronger penetration with renewable energy sources in all sectors and the implementation of innovative, highly efficient cross-sectoral technologies will help to accelerate the reduction of energy-related GHG emissions. Therefore, sector coupling is considered to be a prerequisite for the next phase of energy transition. [5, 6]

Against this background, it is still uncertain which technologies in which sectors may come up with particularly low GHG emissions if the share of volatile renewable energy sources in the German electricity mix increases steadily until 2030 and beyond. To some extent, this uncertainty can be ascribed to the current methods for the evaluation of environmental impacts of products and processes. The common approach to use static emission factor for the electricity mix, which are defined as an average ratio regarding the produced electric energy over the period of one year, does not lead to realistic results as it neglects the real operation of building technology when assessing the annual energy consumption. Moreover, the integration of more flexible innovative technologies for the power and heat supply asks for more dynamic approaches. As a consequence, any future environmental assessment has to consider the dynamics of both energy supply and consumption.

For this reason, the authors developed a methodology to create electricity generation profiles for Germany in a temporal resolution of 15 minutes, which are transformed into a time series of GHG emission factors in a subsequent step. These dynamic emission factors provide the opportunity for realistic evaluations under consideration of real operation. Furthermore, the high temporal resolution is suitable for complex dynamic simulations. [7]

The paper is organised as follows: Chapter 2 starts with a brief description of the life-cycle assessment (LCA) framework and the adaptations necessary to incorporate dynamic emission factors, followed by an overview of the approach mentioned to develop dynamic emission factors based on [7]. In the end of Chapter 2, future scenarios for the public electricity mix in 2030 and 2050 are presented. In Chapter 3, a case study depicts the application of dynamic emission factors in the course of an LCA. The applicability of the dynamic GHG emission factors for building LCA and the benefits are discussed in Chapter 4. Finally, Chapter 5 gives an outlook on how to further develop dynamic building LCA methods.

2. Methodology
The following chapter gives an overview of methods and databases that are the basis for the authors’ approach to develop dynamic emission factors for the German electricity mix together with a brief description of the developed technique itself: For further details about the complex methodology to process given electricity generation data and to convert it into emission factors please refer to [7].

2.1. Environmental evaluation of buildings and the built environment

2.1.1. Life-cycle assessment (LCA) and building-related LCA. The methodological basis for the calculation of emission factors for the public electricity supply is the life-cycle assessment (LCA) technique, a well-established methodology to account environmental impacts of products and services along their life-cycle. Common principles of LCAs are the definition of a specific research subject for each assessment as well as the definition of a functional unit to enable a comparison of different products.
or processes on the basis of their benefit for the user. In the context of fuel combustion related to electricity generation, calculated emission factors either just consider the environmental impact of fossil fuels while burning the fuel or also the upstream chain from fuel extraction and transportation, which corresponds to the LCA approach. [8, 9]

In accordance with the general LCA, building-related LCAs facilitate the evaluation of the environmental impacts during the construction, use, renovation, reutilization and demolition phase of buildings. Amongst others, the German Sustainable Building Council (DGNB) established a methodology for a holistic assessment of the sustainability of buildings, which contains a building-related LCA as major part of the ecological assessment criteria. Therefore, relevant environmental impact categories (e.g. GHG emissions) from building construction, use and reuse, recycling as well as disposal are calculated over a period of 50 years. There exist multiple databases that contain various environmental product declarations (EPDs) for building materials. In addition, numerous data sets feature mean values for a certain category or technology of construction related components like the Sustainable Construction Information Portal ÖKOBAUDAT. [10, 11]

While data sets can easily be used for the calculation of construction, transport and disposal related impacts, the use phase of a building – and in particular the energy supply for heating, domestic hot water and electricity – require additional information, input parameters and demand calculations. Besides information about the technical equipment, e.g. heat generators and storages, the final energy demand for the chosen energy carriers has to be determined. This final energy demand can be calculated according to different energy balance schemes, which in turn serve as a requirement for the issuance of energy performance certificates. [12] Anyway, all of these calculation methods usually deliver the total final energy demand per year as an input to the building-related LCA, which is then converted into a certain environmental impact using the current impact or emission factor for the corresponding energy carrier. The overall impact for the use phase is projected by multiplying the annual impact based on the final energy demand with the duration of the use phase.

2.1.2. Adapted environmental impact analysis for the use phase. In order to incorporate dynamic emission factors with a higher temporal resolution than one year, some adaptations to the described application of the building-related LCA have to be made. First and most important, the established energy demand calculation methods cannot be used any longer. Instead, dynamic building simulations replace traditional energy balance schemes giving the opportunity to simulate profiles for the space heating and the electrical power demand in a higher temporal resolution of 15 minutes. As a basis for this simulation, a building model must be elaborated that reflects the energy related behaviour of the building assessed using the LCA. Afterwards, the multiplication of the energy demand $q$ in each time step $i$ with the corresponding emission factor $f_{GHG}$ leads to a dynamic profile for the environmental impact, e.g. GHG emissions $c$ per time step $i$ (see Eq. 1). The input to the LCA is the sum of all greenhouse gas emissions $c_{total}$ during the period under review which is calculated from the sum of GHG emissions ($c_{annual}$) for all time steps multiplied by the number of years ($n_{years}$) of the period reviewed (cf. Eq. 2).

$$c_{GHG,i} = q_i * f_{GHG,i}$$  \hspace{1cm} (1)

$$c_{total} = c_{annual} * n_{years} = \sum_i(c_{GHG,i}) * n_{years}$$  \hspace{1cm} (2)

2.2. Dynamic emission factors for the German electricity mix

2.2.1. Power generation and energy-related emissions. The basis for the calculation of dynamic emission factors for the public electricity supply in [7] is a set of different data on German electric power generation and consumption. For this reason, aggregated data from the transparency platform of the European Network of Transmission System Operators for Electricity (ENTSO-E) serves as the main input. [13] The data is available in 15 minute time steps and represents a mean value of the power generation from 17 different types of electricity generation. However, the data has to be processed to
comply as good as possible with German national energy and emission balances. As a result, a dataset is available which shows the power generation from different types of energy carriers and power plants in the same temporal resolution on the one hand and with the correct sum of produced electricity over one year on the other.

Finally, the electricity generation time series needs to be converted into dynamic GHG emission factors, which is done by using specific environmental impact factors for different types of electricity generation provided by [14]. The resulting dynamic emission factors refer to the total consumed electric power in each of the time steps and, hence, can be used to assess the electricity demand of a building as part of a building-related LCA.

2.2.2. Modelling of future emission factors. The methodology described above is applied to calculate the German public electricity supply on the basis of actual power generation data and assessments of the environmental impact of technologies reflecting the status quo (cf. [7]). To evaluate how an increasing share of electricity generation from renewable energy sources impacts the LCA results and the dynamic approach, in particular, requires the modelling of future emission factors. This modelling is subject to certain simplifications and estimations: a) A major simplification is that the LCA results for all power generation technologies are considered to be constant, i.e. the environmental impact of a unit of electricity generated from a certain technology in the future will be the same as it is today. b) A scenario for the increasing installed capacity and power generation from renewable energy technologies is used to obtain the annual power generation from these renewable sources as well as from conventional technologies. c) The profile of feed-in of electrical power from renewable energies for the future has the same pattern as in 2017. This means, the increased annual power generation in the future leads to a scaling of the respective profile for the year 2017. At the same time, conventional power production is restricted to gas-fired power plants only, which are modelled as combined-cycle power plants capable for base load and gas turbine power plants in order to cover peak loads.

With these simplifications and principles, dynamic emission factors for the years 2030 and 2050 were derived from scenarios developed in [15]. While [15] discusses multiple scenarios, only the scenarios aligned to the German policies on climate change reflecting a 80 % reduction of CO₂ emissions compared to the base year 1990 will be used in this paper. Table 1 summarises some of the key parameters of the model. The GHG emission profiles for 2017, 2030 and 2050 are illustrated for a period of one week in Figure 1.

| Parameters of the most important energy carriers of the model of dynamic emission factors. |
|---------------------------------|----------------|----------------|----------------|
| Annual power generation (in TWh) |
| Net annual production | 619.4 | 578 | 627.1 |
| Photovoltaics | 39.3 | 70 | 100 |
| Wind-Onshore | 87.6 | 136 | 188 |
| Wind-Offshore | 17.6 | 63 | 208 |
| Biomass | 46.7 | 46.8 | 36.8 |
| Other renewable | 26.3 | 27.2 | 27.3 |
| Conventional fossil | 401.9 | 235 | 67 |
| Consumption weighted annual GHG emission factor for the public electricity supply (in g CO₂ eq/kWh) |
| direct | 524.5 | 340.6 | 77.6 |
| incl. upstream chains | 594.1 | 401.4 | 119.6 |

Figure 1. Dynamic GHG emission factors in a temporal resolution of 15 minutes for the years 2017, 2030 and 2050 in the period of 1st October to 7th October.
3. Case study
The following case study shall demonstrate the application of dynamic GHG emission factors on the building-related LCA. Remarks focus on those variations in results that occur from applying dynamic input parameters instead of static emission factors. Furthermore, the sensitivity of the simplified LCA approach becomes evident when comparing the results based on today’s public electricity supply with those referring to a scenario with higher shares of renewable energies.

3.1. Building Model and simulation environment
In order to carry out the LCA, the experimental design of this study case is based on a generic building model. Its geometry is derived from [16] and used to set up a simulation model for the dynamic simulation software IDA Indoor Climate and Energy 4.81 [17]. The aim is to simulate the building’s final energy demand in a high temporal resolution. Afterwards, the details on the building construction as well as the energy demand profile are used as inputs for the adapted LCA described before. [10] has already proved the general applicability of the chosen generic building models in the course of a profound scenario analysis. For the case study of this paper, a residential single family home will be investigated, which was modelled by [10] in accordance with the minimum requirements of the latest Energy Saving Ordinance (EnEV). In the building model, an air-to-water heat pump covers the building’s space heating demand in combination with a floor heating system. Table 2 outlines the most relevant model parameters and boundary conditions of the simulation.

Table 2. Simulation and building model parameters.

| Building design | 2 floors |
|-----------------|----------|
| Net floor area  | 197 m²   |
| Gabled roof     |          |

| Heat transmission coefficient of the building envelope | Wall | 0.19 |
|--------------------------------------------------------|------|------|
| Wall                                                   |      |      |
| Roof                                                   | 0.20 |      |
| Floor                                                  | 0.15 |      |
| Windows (glazing / total)                              | 0.60 | 0.74 |
| Thermal bridges                                        | 0.05 |      |

| Sun shading | External sun blinds |
|-------------|---------------------|

| Infiltration | Air change rate per hour |
|--------------|--------------------------|
| Fixed natural infiltration | 0.21 |

| Ventilation | Window opening |
|-------------|----------------|

| Internal loads | Residents 4 / MET 1. |
|----------------|---------------------|
| Equipment      | 370.2 W             |

| Location, climate data, simulation year | Potsdam |
|----------------------------------------|---------|
| Test reference year 2010               |         |
| 2014                                   |         |

| Heat generation | Air-to-water heat pump |
|-----------------|------------------------|
| Nominal power   | 9.28 kW                |
| COP / Annual performance ratio | 3.5 / 2.95 |

| Heat transfer | Floor heating |
|---------------|---------------|

| Room temperature | Heating period | min. 20 °C |
|------------------|---------------|-------------|
| Cooling period   | max. 26 °C    |             |

Among others, the case study in this paper is subject to the following boundary conditions: a) First, the simulation model includes both, heating demand for zone conditioning and hot water demand. The latter is implemented as a hot water demand profile for a household of 4 persons calculated with DHWcalc. [18 in 10] b) A base load of approximately 370 W reflects the household’s internal heat source due to
electrical equipment, which leads to an annual electricity consumption of approximately 3,240 kWh. The power demand for lighting is not modelled in detail, but is part of the base load power consumption. 

c) The ecological assessment follows a simplified approach compliant with the DGNB certification system and [19] which comprises the thermal envelope of the building and the technical equipment for heating and ventilation. Building components that do not have any direct influence on the energy performance of the building are left aside for this case study. Furthermore, the impact of doors or other opaque openings is not reflected. 

d) The review period is 50 years.

e) The environmental impact assessment is based on [11] and focuses on the GHG emissions of the building. Other impact categories are neglected, since the emission factors developed in [7] cover carbon dioxide and GHG emissions only. 

f) The dynamic GHG emission factors used for the assessment of the electrical power consumption include the impact of upstream chains for the electrical power generation.

3.2. Simulation and LCA results

The annual building’s energy consumption is about 6,420 kWh. Because of the fact, that the heat generator is an electrically powered heat pump, the only energy carrier consumed is electricity. The overall consumption comprises 3,180 kWh for heating and auxiliary equipment as well as 3,240 kWh for the household’s power consumption. Figure 2 depicts the distribution of power consumption for the heat generation and the household’s power consumption on a monthly basis. It is obvious, that most of the power consumption for heating occurs from October to April during the heating period.

As shown in Figure 3, the results of the simplified LCA reveal that the construction and disposal of the building causes 5.6 kg CO$_2$-eq per square meter floor area\(^1\) and annum. At the same time, the consumption of heat and electrical power during the use phase of the building accounts for 20.2 kg CO$_2$-eq per square meter floor area and annum over a period of 50 years. The heat generator accounts

\(^1\) The reference area is the gross floor area less the area for construction of external walls.
for less than 1 % of the GHG emissions of the building and is not of major importance for the LCA. A comparison of LCA results using the static method against the approach based on dynamic GHG emission factors shows a deviation of the specific emissions of about 3.4 %. This means, the GHG emissions of the energy consumed in the use phase of the building are higher than estimated by the standard calculation method. The reason for this situation is quite clear: While the static emission factor averages the annual emissions from all power generation technologies and renewable energy sources despite their varying seasonal distribution, the electrical power consumed for heating during the heating period lacks a high share of (almost carbon-neutral) photovoltaic power generation. Nevertheless, the deviation is quite small, when taking into account that many of the LCA input data sets reflect average values for components and materials.

3.3. LCA using dynamic emission factors for 2030 and 2050
As already demonstrated for the LCA results with 2017 GHG emission factors, a deviation from the static to the dynamic approach exists. To evaluate how the increasing share of electricity generation from technologies based on renewable energy carriers will impact the adapted LCA of buildings, 2030 and 2050 emission profiles are used for the investigation.

| Year | Scenario | Construction | Building Technology | Heat/power demand | Deviation |
|------|----------|--------------|---------------------|-------------------|-----------|
| 2017 | static   | 5.61         | 0.17                | 19.31             |           |
|      | dynamic  | 5.61         | 0.17                | 20.15             |           |
|      | Total    |              |                     | 25.93             | 3.4 %     |
| 2030 | static   | 5.61         | 0.17                | 13.05             |           |
|      | dynamic  | 5.61         | 0.17                | 14.14             |           |
|      | Total    |              |                     | 19.92             | 5.8 %     |
| 2050 | static   | 5.61         | 0.17                | 3.89              |           |
|      | dynamic  | 5.61         | 0.17                | 4.74              |           |
|      | Total    |              |                     | 10.52             | 9.8 %     |

Figure 4. LCA results for GHG emissions profiles of the years 2017, 2030 and 2050

Very clearly, Figure 4 shows the reduced GHG emissions of the electrical power consumed during the use phase of the building, provided that the share of renewable energies in the public electricity supply increases until 2030 and 2050, respectively. In this case study, the LCA input parameters for the construction and disposal phases are not adapted for the scenarios. Thus, only the electricity demand during the use phase changes according to the calculated dynamic GHG emission factor profiles. For the static LCA approach, the GHG emissions of the use phase decreases from 25.1 kg CO₂-eq to 18.8 kg CO₂-eq in 2030 and 9.7 kg CO₂-eq per square meter floor area and annum in 2050 (Table 3). This corresponds to a 25 % and 61 % reduction of GHG emissions, respectively. The comparison of static and dynamic LCA results shows that the deviation between both calculation methods is increasing with the rising share of power produced from renewable energy sources. While the deviation is 3.4 % with
emission factors for the year 2017, it increases to 5.8 % in 2030 and 9.8 % in 2050, respectively (cf. Table 3).

4. Conclusion
In this conference paper, dynamic emission factors for the public electricity supply have been applied in a high temporal resolution to the life-cycle assessment of buildings. The paper shows that a dynamic simulation instead of an energy balance can be used as a methodological adaptation to the LCA. The impact of the adapted LCA approach is demonstrated in a case study, which reveals an increase of LCA results about 3.4 % for the building’s life-cycle GHG emissions with a dynamic emission profile for the year 2017. In addition, the calculation of future GHG emission factors for 2030 and 2050 and their application to the LCA shows that although the overall GHG emissions for the use phase of the building decrease, a tripling of the deviation between the static and the dynamic LCA approach occurs. The building model investigated in the case study follows an electricity-only concept. Thus, deviations are higher than for a conventional setting with a non-electric heat generator. However, the combination of an increasing share of houses equipped with heat pumps in Germany along with higher efficiency requirements for buildings to achieve emission targets and the overall need for integrated energy systems underline the necessity that corresponding LCA results should match reality as good as possible. In contrast, the results of the conducted case study show the imperative to improve established assessment methods if LCAs shall help to achieve the emission targets on building level as well as on the level of national and global GHG inventories, respectively.

5. Outlook
Three main aspects regarding a building-related LCA that considers the fluctuating character of electricity from renewable energy sources have not yet been considered in this study. First, other dynamics in the power consumption of households (e.g. power demand for lighting) are not taken into account. German standard load profiles show winter-summer dynamics, which could also lead to higher emissions when incorporating them into a LCA with dynamic emission factors. In addition, the study case does not consider mechanical ventilation and, in particular, cooling in summer time. Most probably, the electrical cooling demand will have a reverse effect on the total GHG emissions compared to the heating loads when using dynamic load and emission profiles. Second, the building-related LCA uses dynamic load and emission profiles to assess the environmental impact of the use phase. However, the LCA is still restricted to multiplying the annual GHG emission in a certain year of investigation with the number of years reviewed (cf. Eq. 2). An approach for a more realistic evaluation of a certain building could be the use of a scenario model, which determines dynamic emission profiles for each year of the review period. Third, the overall impact of energy transition and lower emission factors for the public electricity supply is not reflected in this case study with regard to building components and materials that have a high electricity demand in the production phase. Scenario-specific data sets of LCA input parameters for components and materials, which reflect a decreasing emission factor of the German electricity supply would enable a profound evaluation of environmental impacts of future buildings. In this context, the potential of using dynamic CO₂ and GHG emission factors for reducing the overall environmental impact could be investigated more comprehensive.

Acknowledgments
Part of the research presented in this conference paper was financial support by the DFG in the framework of the Excellence Initiative, Darmstadt Graduate School of Excellence Energy Science and Engineering (GSC 1070).
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