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Environmental performance assessment of the use stage of buildings using dynamic high-resolution energy consumption and data on grid composition

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ABSTRACT

During the use stage of buildings, their consumption of electricity has proved to influence considerably their environmental performance. The impacts associated with using electricity are directly related to the electricity grid that delivers the power and hence are also closely associated with the impacts induced by the production of each kWh delivered to the grid. Life cycle assessment (LCA) usually does not account for the variations in the energy sources that supply an electricity grid every day, month and year. This study addresses the dynamic nature of electricity grids and accounts for the source variations in electricity production using electricity grid data at high temporal resolutions. The study compares inventory data on electricity grid composition at hourly, daily and monthly resolutions with the conventional yearly average grid compositions from the ecoinvent database. The high-resolution electricity grid inventory data are subsequently paired with data sets for electricity consumption by buildings with matching resolutions in order to quantify the differences in the environmental performance of buildings resulting from the application of temporally high-resolution grid data. Finally, environmental building performance (EBP) calculated using high-resolution grids is compared to EBPs generated from conventional data resolutions. The results indicate that the contribution to global warming potential is closely related to the data resolution of the grid composition and that the EBP may be overestimated by up to a factor of two when compared with conventional grid inventory data with yearly (i.e. low) data resolutions.

1. Introduction

1.1. Dependence on electricity

Electricity is an essential part of modern society. Our dependence on electricity has its origin in the industrialization of the western world, where the large-scale introduction of electricity accelerated global industrialization by providing “easily available, cheap, and reliable energy from non-renewable fossil fuels, such as coal, oil, and natural gas” [1], [2]. Fossil fuels are still a major component of the global energy mix, with larger shares in emerging and developing economies.

The energy crisis of 1973 left Denmark and other Nordic countries in a situation that forced them to rethink their national energy supplies not only by moving away from being solely reliant upon fossil fuels, but also by reducing their dependence on the energy resources of foreign countries. This resulted in an ambition to develop renewable domestic energy sources suitable for the political and geographical situation of each Nordic country. In Denmark this led to the large-scale construction of infrastructure to harness wind power, while Norway decided in favour of hydro-power, and Sweden and Finland opted for biomass from their vast forests, which they combined with nuclear power. Today all these countries still import energy, but at a much lower scale than in the 1970s, and mainly from neighbouring countries.

Current opinion globally is that it is not enough for a country to meet its total energy demand solely by replacing non-renewable energy sources with renewable ones [2]. It is also necessary to reduce global energy consumption drastically, thus countering the misconception that humanity's potential to produce is limitless [3].

In Denmark, total energy consumption was 744 PJ in 2017, of which electricity consumption represented 122.5 PJ or around 16.5% [4]. Fig. 1 shows the distribution of total electricity consumption in seven selected sectors in Denmark. The office buildings assessed in this study fall under the category “public service” buildings, which in 2017 consumed 8% of Denmark's total electricity consumption.

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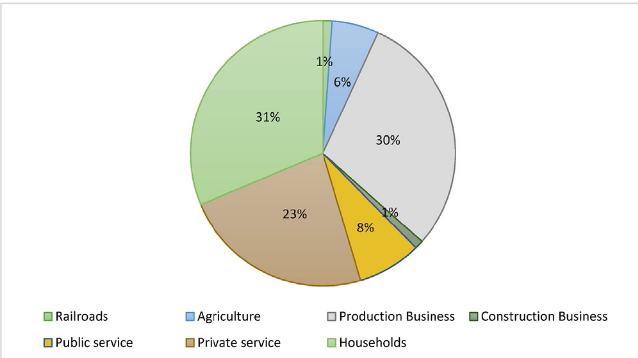

Fig. 1. Distribution of electricity consumption in Denmark in 2017.

1.2. EBP optimization through LCA

Life-cycle assessment (LCA) is often used to gain understanding of the environmental impacts associated with the manufacture or maintenance of a given service, product or system. It is common to perform an LCA on a building to assess the impacts of all the stages in the life-cycle of a building [5], [6]. According to EN 15978 [7], the building life-cycle covers four stages: product, construction, use and end of life. The use stage of a building is its operational and maintenance period and includes operational energy consumption.

In the total life-time of conventional buildings, it is the use stage that has most of the negative environmental impacts [3]. In EBP assessments of various building types (residential, commercial, agricultural etc.), the impacts induced during the use stage generally play a predominant role. Earlier research showed that the use stage may represent as much as 90% of the aggregated impacts of buildings [5], [8].

In the use stage, the main contributor to the overall environmental impact is energy consumption [9]. Since energy consumption plays such a crucial role in the EBP, it is clearly essential that quantifying the environmental impacts induced by energy consumption is as representative as possible.

Currently, when it comes to the EBP of buildings, the usual method is to apply a static power grid that does not vary throughout the lifetime of the modelled building system, combined with yearly estimates of annual average power consumption [10]. The combination of these two parameters allows the environmental impacts resulting from the building's energy consumption to be quantified [11].

Given how important energy consumption is for the EBP, and as Sohn et al. have demonstrated [12], using only static power grids and relying on yearly averages may not be the correct way to present the actual performance of the building in question. However, the neglect of temporal differentiation is one of the most significant drawbacks of LCA, one that has been addressed several times in published research on it [13–15]. Furthermore, Anand and Amor [16] argue that some of the gaps in the LCAs of buildings can be covered by incorporating more dynamic aspects for tracking the potential changes over a long period. Also, Roux et al. [17] argue that current LCA practice based on a documented reference year should be replaced by the temporal variability of electricity production within a year. For example, they found that the discrepancy between the annual and hourly impact results could be over 40% for some indicators. This article therefore examines the LCA application of high-resolution dynamic energy data in office buildings, taking into consideration parameters like temporal variations in the composition of the power grid, as well as the building's location, age and size.

The aim of the present article is thus to quantify the importance of accounting for the variations in electricity production throughout the year. This task is accomplished by quantifying the environmental impacts induced by electricity consumption in office buildings with an hourly data resolution to account for changes in consumption and grid composition simultaneously. The purpose is to quantify the variations in the impacts per kWh consumed throughout the year and to combine these time-dependent impacts with actual electricity consumption data in order to obtain the most accurate EBP assessment of the building's use stage as possible [18].

The energy grid data and energy consumption data for buildings are compared at different resolution scales in order to analyse the differences in the EBPs so that recommendations can be made as to which method is most pertinent.

Lastly, the high-resolution energy calculations are compared with a standard, static system assessment approach, where, in respect of energy consumption, the EBPs are calculated using the standard method, and the degree to which these results differ is quantified.

1.3. Dynamic LCA

As a concept, dynamic modelling in LCAs has emerged over the past few years, the intention being to counteract some of the shortcomings inherent in traditional, static LCAs. Where traditional LCA practices are more rigid in their structure, dynamic system models and/or system inventories allow for the inclusion of parameters that change throughout the temporal scope of the LCA, thus reflecting more accurately the real-life circumstances of the system being assessed [19].

Dynamic system modelling often includes temporal variations in unit processes, and in some cases this consideration leads to results that differ from their static counterparts [12], [14].

Dynamic LCAs differ from conventional ones through the inclusion of temporal and spatial variations in the system modelling [20]: just as the temporal considerations have major implications for the accuracy and representativeness of the LCA as a whole, so can spatial variations influence the results of an LCA and thus the conclusions drawn from it. With regard to building LCAs, a key aspect of the overarching results is occupant behaviour, which, over the course of a buildings' long life-span, has great potential to affect the EBP [15], [21].

Naturally there are limitations to the application of dynamic modelling practices in LCAs. While the temporal considerations potentially yield significantly greater accuracy in the impact modelling, they also necessitate vast amounts of data. In most cases the data required to perform the LCAs at the highest resolutions (i.e. temporally and spatially dynamic) are not available, limiting their representativeness [20]. In scenarios in which the data necessary to perform dynamic LCAs are available, these data can relieve the uncertainties from the static product system models that might otherwise arise.

Even though dynamic LCA practices have already been proved to yield informative results, the full extent of their implementation is not yet known, and the methods are still relatively new. The application of dynamic frameworks has the potential for far-reaching implications in the field of LCA, and such frameworks are continually being developed further. Recent studies have evaluated the applications of dynamic characterization, showing that the different impact categories do not react identically to temporal dynamic frameworks [22]. In the sensitivity analysis presented by Shimako et al. [22], it is shown that, for both climate- and toxicity-related impacts, the temporal considerations influence the results when compared to static systems. Furthermore, Shimako et al. [22] show that the time increment (i.e. the temporal resolution) one choses has the greatest effects on the toxicity-related impacts, while the climate change-related impacts are not affected by the temporal resolution. This observation is assumed to be related to the time scale of the related impacts. That is, toxicity-related impacts have a maximum time-scale of months or a few years, while climate change-related impacts have time scales of decades or even several centuries, depending on the method of characterization.

As shown above, the implementation of dynamic LCAs has proved to be of major significance for projects where such an approach to assessment is feasible data-wise. Applying a dynamic framework therefore has the potential to influence the final results of an LCA