



Implications of integrating electricity supply dynamics into life cycle assessment: A case study of renewable distributed generation



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ABSTRACT

Electricity supply is frequently cited as a significant hot spot in life cycle assessment (LCA) results. Despite its importance, however, LCA research continues to overuse simplified methodologies regarding electricity supply modeling. This work aims to demonstrate the usefulness of electricity trade analysis (proposed model) for integrating the short-term dynamics of electricity supply and refining LCA results. Distributed generation using renewable energy is applied as a case study to demonstrate how electricity trade analysis provides more refined estimates when environmental impact abatements are assessed compared with the conventional (simplified) approaches in LCA. Grid-connected photovoltaic panel (3 kWp mono- and poly-crystalline) and micro-wind turbine (1, 10 and 30 kW) environmental impact abatements are investigated by determining the displaced marginal electricity production on an hourly basis. The results indicate that environmental impact abatements calculated using the developed short-term time horizon approach can be significantly different (up to 200% difference) from those obtained using a simplified approach. Recommendations are provided to LCA practitioners to address this issue of differing results.

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1. Introduction

LCA researchers agree that there are two main approaches to life cycle assessment (LCA): attributional LCA (ALCA) and consequential LCA (CLCA) [1,2]. ALCA aims to describe the environmentally relevant physical flows to and from a life cycle and its subsystems [3], whereas CLCA seeks to describe how environmentally relevant physical flows will change as a consequence of the analyzed decisions [4]. The distinction between ALCA and CLCA is more distinct in the process of resolving methodological debates, such as the choice of data [5]. Average data (used for ALCA) represent the average environmental burdens for producing a unit of good or service in the system [5], whereas marginal data (used for CLCA) represent the effects of a small change in the output of goods or services in the environmental burdens of the system [4]. The differences between average and marginal data can be seen in the following example of electricity supply presented below.

1.1. Electricity supply modeling in LCA

1.1.1. Electricity supply modeling using attributional approaches

Electricity supply is often highlighted as a significant hot spot in LCA results [6,7]. LCAs are typically performed using attributional approaches, and thus, electricity production has been modeled using average data, called grid mix data. These data represent all power plants producing electricity at a given period of time and a geographic delimitation such as a country or a region [7]. The major assumption behind modeling these data is that any increase or decrease in electricity demand results in an increase or decrease in supply from all power plants supplying a given geographic delimitation proportional to their averaged contribution.

The second assumption is that all power plant supply comes from a given geographic delimitation. Indeed, a common method of modeling electricity supply considers the national grid mix, such as the US average mix, which unrealistically simplifies the complexity of the grid [8–10]. In a comparison of the results of recent studies modeling US state consumption mixes (i.e., state generation mixes including imports) with the results of different commonly used geographic delimitations (i.e., US average mix and state generation

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mixes), significant variations (more than 100%) were observed for the LCA results (environmental impacts) [9–11].

1.1.2. Electricity supply modeling using consequential approaches

From the CLCA perspective, a distinction is made between short- and long-term marginal data for electricity supply. Short-term marginal data represent changes in the use of existing power plant production (i.e., generation changes from the available power plants) [4,12]. The long-term marginal data represent changes in the production capacity and/or the technology itself. In other words, long-term marginal data are an estimate of the next power plant likely to be built in the case of a growing market with all potential constraints (e.g., economic, political, and resource) [4,12]. The major assumption behind marginal data modeling is that a power plant that operates at the margin to provide electricity is more likely to respond to a change in electricity demand than the average contribution of all power plants to the grid.

Beyond the distinction between the short- and long-term perspective, marginal data for electricity supply are often considered too complex to model [4,10]. Therefore, LCA publications often assume one single marginal technology [13,14], whereas several technologies are at the margin at different periods of time. A stepwise procedure has been proposed to avoid unjustified assumptions [12]. This procedure consists of determining the scale and time horizon of the studied change, the market delimitation and trend, the production constraints and the technologies most responsive to change.

Beyond avoiding unjustified assumptions, this procedure still highlights only one marginal technology [12]. Earlier work has identified long-term marginal electricity production technologies for the Nordic and the German electricity systems as a function of time by using an energy system analysis model in combination with LCA [15,16]. The obtained results clearly demonstrated how long-term effects include consequences for investments in multiple technologies rather than one marginal technology. From a short-term perspective, the consequences of increased electricity demand are likely to concern a mixture of technologies producing peak load and base-load electricity [4,10]. As a matter of fact, power plants that turn on to deliver power on the margin use different fuels, which change as a function of the electricity demand [9,10].

Despite a frequent focus on the short-term perspective [12], LCA studies taking into account the time varying nature when modeling short-term marginal data for electricity supply are surprisingly sparse in the literature. The few identified papers integrating temporal aspects of electricity supply possess different limitations, such as approximating the dispatch order of power plants [17] or not accounting for the energy flows between electricity markets [18,19].

Price bids from generators, defining the supply curve, and hence the “marginal” power plant, would be ideal for the analysis. However, in a context of increased deregulation, price bids are not always publicly available. In the absence of such data, a procedure for integrating the short-term time variations of marginal technologies is missing. Such a procedure could play an important role in increasing the robustness of LCA studies and refining their estimates of environmental impact abatements, as we will illustrate in this work by using the case study of renewable distributed generation.

1.2. LCA of distributed energy systems

Distributed generation (DG) using renewable energy systems (RES) is often proposed as a sustainable solution to comply with current energy policies such as reducing greenhouse gas emissions and adding supply to meet increasing demand [20]. Recent work

modeling DG life cycle environmental impacts using RES and, more precisely, grid-connected photovoltaic panels and micro-wind turbines in the province of Quebec indicated an abatement of environmental impact when oil electricity emissions are avoided¹ in Quebec adjacent markets (i.e., Northeastern American market) from a short-term perspective [21]. However, the latest work did not consider the temporal variations of the short-term marginal electricity production technologies. As previously introduced, ignoring these variations could reduce the relevance of the study results, and that is the main hypothesis of this work.

1.3. LCA of distributed energy systems

This paper's objective is to assess the implications of incorporating temporal patterns of electricity supply into LCA. Environmental impact abatements of distributed generation (DG) using renewable energy system (RES) are estimated and compared to conventional LCA approaches. More precisely, temporal variations of electricity supply are modeled, and the results are used to estimate the displaced types and quantity from the short-term marginal electricity production. It is anticipated that the obtained results will help in answering the following questions. What are the potential abatements in terms of environmental impact as a consequence of RES production when a time varying marginal electricity production technology is taking into account? How do these estimates differ from those obtained using the conventional approach, from a short-term perspective?²

2. Materials and methods

One of the RES deployment objectives is the reduction of greenhouse gas (GHG) emissions related to electricity production. Given the time-varying output of RES and the diversity of fuel types for electric generators providing electricity at different moment of time, there is significant uncertainty regarding avoided emissions and thus the actual environmental benefits of RES.

Using historical generation information to estimate units that would have reduced their electricity production in response to the variable output from RES provides a good picture of the current grid operation and also good insight into the efficiency of distributed generation as a new energy program for policy makers [22]. Indeed, distributed renewable generation has recently gained support from the province of Quebec, Canada. Therefore, using historical generation information, and hence a short-run time horizon, is particularly well-suited for examining the impact of adding a small quantity of electricity to the electricity-generating system, as is the case for a new energy program such as distributed generation. However, historical generation information is rarely publicly available, which consequently justify a procedure development to identify the short-term marginal electricity production.

This procedure is explained in more detail in the following five subsections (steps) below: 1) Estimating RES hourly production, 2) Identifying the short-term marginal electricity production, 3) Matching RES production with the right marginal production for a

¹ By avoided emissions, we refer to the emission increase that would have occurred, given the current generation mix, if renewable DG had not been injected to the grid.

² A short time horizon choice was made in this manuscript to solve a methodological issue in LCA modeling: the identification as a function of time marginal technology and in a context of electricity trade. Beyond this methodological issue, a short-run time horizon perspective is important for policy makers as provides a good picture of the environmental benefits and efficiency of the new energy policy, as is the case with renewable distributed generation.

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