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Temporal variations in the primary energy use and greenhouse gas emissions of electricity provided by the Swiss grid

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ABSTRACT

It is a frequent practice nowadays to use mean annual conversion factors (*CF*s) when performing life-cycle assessment (LCA) of processes and products that use electricity supplied by the grid. In this paper, we conduct an hourly assessment of the greenhouse gas (GHG) emission factor, along with the conversion factors for the cumulative energy demand (CED) and its non-renewable part (CEDnr), of electricity supplied by the Swiss grid and its direct neighboring countries (France, Germany, and Austria; Italy being neglected). Based on an hourly inventory of energy flows during a one-year period (2015–2016), this attributional approach allows performance of various certification procedures of process or product manufacturing, and comparison of energy and carbon intensities of different national mixes. Hourly calculation allows evaluation of the order of magnitude of errors made when considering an annual mix. Visualization techniques are used to better understand the obtained data and to detect when strategies involving timing optimization of electricity use may be efficient. A case study is chosen to illustrate the relevance of hourly *CF*s when performing LCA associated to the exploitation of a given building. Moreover, mean annual *CF*s of interest are discriminated by electricity end-use sectors. This could be of great help for system designers willing to improve the assessment accuracy when hourly *CF*s are not readily available.

1. Introduction

Life-cycle impacts of electricity depend mainly on the production process. At a national level, electricity is either produced domestically or imported from surrounding countries, and generated by various production technologies that induce different environmental impacts. The share of the technologies used to generate electricity varies continuously, due to energy resource availability and in order to adapt the power supply to an ever-changing demand. Therefore, each kWh at the consumer's disposal does not have the same environmental impact over time. However, the specific nature of the alternating current does not allow a physical tracking of electrons from a given power plant to the final consumer, and therefore an environmental labelling of each kWh remains conceptual. Through life-cycle electricity generation inventories, the correct understanding regarding the origin and responsibility level of each contributor is a fundamental key that grid managers and policymakers could use for efficient energy transition toward the decarbonization of electricity (see Ref. [1–3]).

This study deals with a limited selection of environmental impact categories, with the aim of providing to engineers and practitioners the necessary input data to various assessments of processes and products using electricity; this is particularly needed in the construction sector for certification procedures (e.g. Ref. [4,5]) and for sustainability assessments needed for quality label, such as LEED [6], HQE [7], or BREEAM [8]. Therefore, the scope of the study focuses on the hourly assessment of the greenhouse gas (GHG) emission factor, along with the conversion factors for the cumulative energy demand (CED) indicator and its non-renewable part (CED_{nr}), associated with the electricity supplied by a given national grid. These factors—respectively CF_{GHG}, CF_{CED}, and CF_{CEDnr}—are important when assessing GHG emissions, as well as energy use efficiency and the amount of energy from sources that may be depleted by extraction, when using an electric grid as power supply. These factors consider the whole life-cycle (cradle-to-grave boundary, see Ref. [9] of a mean representative unit of electricity supplying a national grid at a given time. The GHG emission factor CF_{GHG}—also called simply emission factor [10], $CO_{2\text{-eq}}$ footprint [11], or carbon footprint [12] in the current literature—is

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expressed in [kg $CO_{2\text{-eq}}$ kWh^{-1}]. Both CF_{CED} and CF_{CEDnr} are expressed in [$MJ_{oil\text{-eq}}$ kWh^{-1}]. Choosing a functional unit of 1 kWh of electricity production mix at extra-high voltage (380 kV or 220 kV), and integrating transport and distribution losses enable comparison with other national grids.

Two assessment methods can determine time-dependent conversion factors of electricity mix. Ex post data, with an *attributional* approach ([13] for France; [11] for Belgium) are used when the objective is to depict the potential impacts of using a given national grid (e.g. certification procedure). By knowing the dynamic patterns and the variation amplitudes of the conversion factors assessed within an attributional approach, this knowledge can inform when timing optimization of electricity use could be applied for energy and/or GHG emission mitigation [14]. However, when the goal is to evaluate the impacts of a certain change in a system (for example, in the electricity generation mix), the potential of mitigation occurring with this change is assessed with a marginal approach, which is compulsory in *consequential* studies (See [15] for France; [16] for Sweden, [10] for Finland). The applicability of both the attributional and consequential approaches is discussed in more detail in Soimakallio et al. [17]. In the present study, *CF*s are evaluated on the base of a time-resolved attributional LCA, with hourly averaged energy produced per each generation technology.

In current life-cycle impact assessment, it is common to use yearly averaged conversion factors of a national electricity mix (e.g. Ref. [18]). In this study, yearly averaged conversion factors are referred to as the "conventional method". The lack of temporal resolution generates inaccuracies in assessments, especially when the electricity consumption and the conversion factors of the grid are highly variable over time (see Refs. [19,13,14]). This is problematic, notably in buildings where operational performances are under the scope of norms, standards, and various certifications (e.g. Ref. [4,5]). Temporal variability needs to be included in the environmental footprints of electricity for various reasons. Hourly conversion factors allow not only more accurate energy and emission assessments to be guaranteed even when the electricity demand varies over time, but also to detect when a timing optimization of electricity use may be efficiently deployed (see Refs. [10,14]). These kind of strategies can be neither assessed nor deployed with a yearly-averaged *CFs* of a given national grid. Another benefit of introducing hourly conversion factors is related to the massive introduction of decentralized electricity generation and building energy storage, which enable managing a shift between production and consumption. Consequently, the challenge is no longer to fulfill a given amount of harvested and stored energy, but to understand the life-cycle qualities of this renewable energy, which should ideally be better than those of the grid mix. A last example is given in the context of the constant decay in building energy consumptions. As a consequence, the relative accuracy of life-cycle assessments significantly decrease if more robust impact assessments techniques are not introduced.

The Swiss grid is very interesting considering its high share of exchanges with neighboring countries, and it is considered as the main subject of interest of this study. In Switzerland, the CED, the CEDnr, and the GHG emissions are highly important, since they have been selected as the main indicators of the 2000W society vision [20]. Hourly conversion factors related to these three indicators are not yet available for the Swiss mix. In this paper, we first present the methodology and discuss the data availability for Switzerland as well as for its surrounding countries. We then present the obtained results, consisting of the hourly conversion factors $CF^{h}{}_{GHG}$, $CF^{h}{}_{CED}$, and $CF^{h}{}_{CEDnr}$ for the Swiss, Austrian, French, and German grids. In the second part of the study, the traditional method of energy and emission assessment (dealing with mean annual conversion factors) is compared with a method using hourly conversion factors, using a case study consisting of a highly-efficient building in central Switzerland that represents future construction trends. Furthermore, we address the relevance of conversion factors discriminated by end-use sectors of electricity in the building taken as the case study. The expected audience of this study is composed of LCA practitioners, energy engineers and researchers, and electric grid managers and policymakers.

2. Methodology

The LCA methodology used in this study to assess the Swiss grid follows the ISO 14040/14044 guidelines [21,22] and the ILCD handbook [12]. We consider a spatially-homogeneous quality of electricity in a given country. When considering the electricity delivered to the national grid of a country *c*, given a category indicator *m* in a time interval *i*, the assessment of an impact score $IS_{c,m,i}$ is obtained as follows:

$$IS_{c,m,i} = IS^{DP}_{c,m,i} + IS^{I}_{m,i} - IS^{E}_{c,m,i} \quad (1)$$

where $IS^{DP}_{c,m,i}$ is the impact score of domestic production; $IS^{I}_{m,i}$ is the impact score resulting from the imports of electricity from surrounding countries; and $IS^{E}_{c,m,i}$ is the impact score related to electricity exports. They are evaluated in the present study, respectively, in the following manner (Eqs. (2)–(4)):

$$IS^{DP}_{c,m,i} = \sum_{f} GE_{c,f,i} \cdot CF_{m,f} \quad (2)$$

with $GE_{c,f,i}$ being the net generated electricity by technology type *f*, and $CF_{m,f}$ being the technology-specific conversion factor of a given category indicator *m*.

$$IS^{I}_{m,i} = \sum_{n} E^{I}_{n,i} \cdot CF_{m,n,i} \quad (3)$$

with $E^{I}_{n,i}$ being the imported electricity from a neighboring country *n*, and $CF^{E}_{m,n,i}$ being the country-specific conversion factor of a given category *m*.

$$IS^{E}_{c,m,i} = E^{E}_{c,i} \cdot CF_{c,m,i,} \quad (4)$$

with $E^{E}_{c,i}$ being the sum of exported electricity from the exporting country *c* to its surrounding countries, and $CF_{c,m,i}$ being the national conversion factor of a given impact category *m*:

$$CF_{c,m,i} = \frac{IS^{DP}_{c,m,i} + IS^{I}_{m,i}}{\sum_{f} GE_{c,f,i} + \sum_{n} E^{I}_{n,i}} \quad (5)$$

When applying this description to a region of interest, a domino-chain reaction occurs in the sense that a surrounding country *n* subsequently becomes a country of main interest *c*. In other words, each grid (with its own set of conversion factors) is influenced by the features of the surrounding grids from which electricity is imported. In this study, we limit the data inventory by introducing a simplification concerning electricity imports from surrounding countries *n*. Instead of Eq. (3), we consider the share of imports in the national grids surrounding *c* to be time-independent and with conversion factors equivalent to those of the European Network of Transmission System Operators for Electricity (*ENTSO-E)* mix supply. Therefore, Eq. (5) applied to a surrounding country *c* becomes: