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Spatial and temporal variations of marginal electricity generation: the case of the Finnish, Nordic, and European energy systems up to 2030

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ABSTRACT

Assumptions related to energy generation often play a decisive role in abatement studies for estimating the effects of demand-side interventions. However, there can be significant geographical and temporal variation in the emission intensities of electricity generation in different regions. The aim of this article is to describe how spatial and temporal variations related to a particular energy system may affect an electricity generation unit operating on the margins. The approach takes the generation mix within interconnected electricity markets and the exchange of electricity between these markets into account. The short-term (2009–2010) and long-term (until 2030) hour-by-hour marginal electricity generation unit and marginal emission intensities are identified for electricity use, using the Finnish, Nordic and European energy systems as actual cases. The estimated marginal electricity generation technology and marginal emission intensities for electricity use differed significantly within the studied time horizon and between the studied countries and energy systems. Furthermore, due to the projected structural changes in the energy systems, i.e. changes in the fuel mix and electricity generation technologies, the carbon dioxide (CO_2) intensity of marginal electricity generation will decrease in the Nordic countries and in the EU in the long-term. However, the approach used for calculating the effect of change in electricity exchange on the margin increased the variability of the results considerably for some Nordic countries, such as Sweden and Norway, whose export of electricity was high and whose marginal generation mix differed significantly from the European system. Furthermore, the spatial and temporal variations of marginal electricity generation will increase in the future. This variation, combined with the interconnections between market areas for exchanging electricity in the EU will require improved understanding of the impacts of exchanged marginal electricity generation on the possible emission leakage between EU countries to better inform policy decisions.

1. Introduction

Assumptions related to energy generation often play a decisive role when estimating the environmental impacts in life cycle assessment studies (LCA) (Curran et al., 2005). Typically, in LCA studies the aim is to provide a coherent and holistic support for decision-making affecting the environment (Rebitzer et al., 2004). For instance, LCA method is often used in abatement studies for estimating the effects of demand-side interventions, such as different energy efficiency and policy measures, for mitigating climate change. In order for a policy measure to be effective, energy system stakeholders and policy makers need coherent information on the response likely to be achieved by the interventions in the energy system. Therefore, as a tool for decision-making, the research method should be such that the real-life effects are revealed. In recent years, LCA methods have developed towards identifying the environmental consequences of changes.

The development of LCA method has led to a definition of two distinctive LCA categories: attributional and consequential (European Commission et al., 2010). The different focuses of attributional and consequential LCA are related to the data used in the modelling of subsystems of the life cycle, and allocation and related system boundaries.

Attributional LCA (ALCA) has been defined as a method “to describe the environmentally relevant physical flows of a past, current, or potential future product system” (Ekvall et al., 2005; Tillman, 2000). ALCA describes the average emissions in a static energy system, often derived from national statistical data for

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electricity generation and fuel use (Weber et al., 2010). ALCA can be utilised as a tool for decision-making, and it is frequently used in abatement studies. However, it is not suitable for describing the environmental impact of a change in demand, since the method implicitly assumes that all components of the electricity system respond proportionally to the change, and that all components of the electricity system are located in a given geographic delimitation (Rinne and Syri, 2013; Soimakallio et al., 2011). Furthermore, emissions from the electricity generation units on the margin can deviate from average emissions over the entire load-generating base (Bettle et al., 2006; Hawkes, 2010).

Consequential life cycle assessment (CLCA) is defined by its aim to describe how environmentally relevant flows will change in response to possible decisions (Curran et al., 2005; Ekvall et al., 2005; Finnveden et al., 2009). Furthermore, decisions lead to consequences through chains of cause—effect relationships which can have the properties of timing, duration and magnitude. Marginal consequences are the response of the system to a marginal change in demand. In the merit order dispatch of generation, electricity generation units with the lowest marginal costs are committed first. This means that a marginal change in the consumption of electricity influence the marginal generation unit, i.e., electricity generation unit currently running with highest marginal cost. Thus in CLCA, the marginal generation unit and magnitude of such an operating margin should be specified (Ekvall and Weidema, 2004; Weidema et al., 1999). CLCA method often includes markets affected by decisions and when identifying these markets, the methodology recommends that the analyses are simplified by defining the main marginal technology affected.

The main challenge regarding CLCA method stems from identifying the marginal consequences in an energy system. The marginal generation unit is often identified using static models of an energy or electricity system. An often-used approach to defining the marginal generation unit is to identify the long-term change in electricity generation capacity and assume that the marginal supply will be fully produced with such capacity (Ekvall and Weidema, 2004). This method follows the assumption that a short-term change in demand can affect the timing and nature of new investments and lead to a long-term change in generation capacity. Investment decisions are further influenced by a number of factors reflecting the potential future market trends or by socio-political decisions to regulate market externalities. Traditionally, it is common to define either coal or natural gas condensing power as a marginal generation unit (Dotzauer, 2010; Schmidt et al., 2004; Schmidt and Weidema, 2008). However, a marginal change in capacity will have to operate as an integrated part of the energy system, and therefore, it does not necessarily represent the marginal change in electricity supply, which is likely to involve a mixture of different generation units (Lund et al., 2010).

Studies of the marginal changes of electricity demand have increasingly recognised the importance of the variability of electricity generated at different points in space and time (e.g. Graff Zivin et al., 2014; Kopsakangas-Savolainen et al., 2015; Roux et al., 2016). The changes in annual electricity and heat demands can affect the dynamics of supply dispatch of electricity differently from one hour to the next. Depending on the magnitude of such short-term change in demand, the marginal electricity generation unit can vary significantly at different points in space and time. This can be due to a strong diurnal or temporal variation in electricity and heat demands. For instance, the marginal generation unit generating peak load and base load electricity may vary between day and night and summer and winter, due to the level of utilisation of the generation units (i.e. electricity supply portfolio) which fluctuates with aggregate load on the electricity network (Amor et al., 2014; Hawkes, 2010; Holttinen and Tuhkanen, 2004). Furthermore, electricity generation units operating on the margin can use different fuels, which can change as a function of the electricity demand (Marriott et al., 2010; Weber et al., 2010).

Energy systems are typically interconnected and exchange electricity (and in some cases heat and gas) on the external electricity market, depending on the costs of the marginal electricity generation. A change in internal electricity demand in one country may affect the exchange of electricity on the external market, which in turn implies that generation in another region, country, or countries may change. Hence, there is no definitive way of locating where electricity demanded at a particular location and time was actually generated. For several OECD countries, the generation-based and consumption-based carbon dioxide (CO_2) emissions of the final electricity consumption deviate significantly (Soimakallio and Saikku, 2012). Thus, a country can have a significant amount of CO_2 emissions embodied in its imports or exports, even if the net electricity trading of the country is at a low level. However, while no accepted method for addressing electricity exchange between countries or regions has emerged, allowing the marginal producer to be located anywhere in the corresponding grid interconnection can yield significantly different estimates of the electricity generation units operating on the margin (Graff Zivin et al., 2014). Electricity has been increasingly exchanged between EU countries and due to further market couplings between European electricity markets, the risk of significant emission leakage between countries may become an important issue (International Energy Agency, 2012a).

The consequences of a marginal change in electricity demand may be more far-reaching in space and time. The currently often-used approach to identify a single marginal electricity generation unit without taking into account the exchange of electricity on the external market may not be adequate to reveal the real-life effects in a complex energy system. Despite the increased focus on the long-term perspective for identifying marginal electricity generation, studies taking into account the time-varying nature when modelling long-term marginal data for electricity consumption are sparse in the literature (Hawkes, 2014; Lund et al., 2010; Mathiesen et al., 2009). According to the authors' knowledge, although many local and national studies on marginal electricity generation have been carried out, existing literature does not take into account the energy flows between electricity markets when identifying marginal electricity generation units.

The aim of this article is to describe how spatial and temporal variations related to a particular energy system may affect the electricity generation unit operating on the margin, using the Finnish, Nordic and European energy systems as actual cases. The method utilised in this study is based on energy system analysis, and this article mainly concentrates on identifying the marginal changes in electrical energy generation. The hypothesis is that due to the constraints and fluctuations in electricity supply and demand, the hour-by-hour de facto marginal electricity generation unit can differ from the annually pointed single marginal electricity generation unit (traditionally coal or natural gas). The energy system analysis focuses on the hour-by-hour operation of installed capacities, that is, the method considers the temporal variations in demand and resource availability and how the electricity generation unit operating on the margin may change from a short-term or long-term perspective when structural changes occur in the energy system. Furthermore, the method presented in this article takes into account the interconnections in the electricity markets, which can mean that generation units on the margin may operate beyond the boundaries of a particular energy system, i.e. the choice of region and imports/exports. In this regard, two different methods for identifying the hour-by-hour de facto marginal electricity generation unit are presented in this article.