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Estimating marginal CO_2 emissions rates for national electricity systems

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ABSTRACT

The carbon dioxide (CO_2) emissions reduction afforded by a demand-side intervention in the electricity system is typically assessed by means of an assumed grid emissions rate, which measures the CO_2 intensity of electricity *not* used as a result of the intervention. This emissions rate is called the "marginal emissions factor" (MEF). Accurate estimation of MEFs is crucial for performance assessment because their application leads to decisions regarding the relative merits of CO_2 reduction strategies. This article contributes to formulating the principles by which MEFs are estimated, highlighting the strengths and weaknesses in existing approaches, and presenting an alternative based on the observed behaviour of power stations. The case of Great Britain is considered, demonstrating an MEF of 0.69 $kgCO_2/kW$ h for 2002–2009, with error bars at +/−10%. This value could reduce to 0.6 $kgCO_2/kW$ h over the next decade under planned changes to the underlying generation mix, and could further reduce to approximately 0.51 $kgCO_2/kW$ h before 2025 if all power stations commissioned pre-1970 are replaced by their modern counterparts. Given that these rates are higher than commonly applied system-average or assumed "long term marginal" emissions rates, it is concluded that maintenance of an improved understanding of MEFs is valuable to better inform policy decisions.

1. Introduction

Given international concern regarding climate change, energy security, and energy-cost competitiveness, development of strategies for transformation of national energy systems is topical, as exemplified in DECC (2009a). These strategies usually focus on the supply-side of the system, and demand is seen as an inelastic necessity to be met, albeit with broad assumptions regarding efficiency improvements. However, it is increasingly recognised that consideration of the potential of both supply-side and demand-side simultaneously is necessary to obtain a better understanding of system change, and that coordinated action on both sides could lead to a much more cost-effective solution. In essence, the full potential of the demand-side can only be realised if it is not seen as the junior partner to supply-side transformation, and can take an active role in delivering useful outcomes. Amongst an array of issues, one important step in properly incorporating the demand-side is the development of techniques to accurately assess the impact of interventions in terms of their CO_2 reduction. This could lead to an improved basis of industry and political support for more promising measures. Ultimately it could be a building block of demand-side interventions becoming a more integrated part of system change, because better information would be available regarding the dynamics of their interaction with the supply-side of the system.

When policy makers consider demand-side interventions, there are two assumptions regarding their CO_2 performance that could be improved. Firstly, performance is usually "deemed". This means that a certain fixed CO_2 reduction is assumed to occur as a result of the intervention, but there is no guarantee this will actually be achieved in practice. Whilst deeming is administratively undemanding, it can lead to poor-quality measures being supported, and certainly does not lend itself to incorporation of an active demand-side. Secondly, the impact of an intervention is often assessed against the CO_2 content of either *grid-average* electricity or a speculative marginal emissions rate. However, a change in demand does not act upon all elements of the electricity system proportionally and as such a system-average emissions factor (AEF) could be misleading, as could a poorly chosen marginal rate. In reality, specific generators respond to system demand changes, and it is the CO_2 intensity of these generators that dictates the actual CO_2 reduction brought about. The metric that estimates the CO_2 intensity of a demand change is called the *marginal emissions factor* (MEF), and it is a function of specific CO_2 intensity of the individual generators that respond to that change.

This article reviews existing research regarding the estimation of CO_2 savings from electricity-related interventions, and then presents an alternative methodology that builds upon previous efforts. Specifically, in this article MEFs are calculated based on the observed dispatch of large generators in the electricity system, rather than modelling or attempting to observe the merit order of these generators. A key controversy in appropriate choice of emissions factors for performance assessment is then investigated; the

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contribution of commissioning and decommissioning of power stations. The methodology developed is then applied to study MEFs over a specific period of operation of the electricity system in Great Britain and compare them to corresponding AEFs. Characterisation of the nature of MEFs is then explored, followed by a projection of how they might be expected to change over the coming 5–15 years, along with suitable analysis of uncertainties. Finally, the calculated MEFs and AEFs are applied to assess the CO_2 performance of two topical demand-side interventions; micro-combined heat and power (micro-CHP) and air source heat pumps, and to discuss the timeframe over which such factors may be applicable. These two technologies are of interest because residential heating can account for a significant portion of final energy demand in mild to cool climates, and they both have mass market potential.

The results serve to aid debate regarding the best way to assess the performance of demand-side interventions, provide critique of methods currently applied in formulation of policy instruments, and offer evidence to weigh up the relative merits of passive versus active demand-side management of technologies such as micro-CHP, heat pumps, and electric vehicles.

2. Selected literature review

A number of attempts have been made to quantitatively characterise the marginal emissions factor. Amongst these are Marnay et al. (2002); Voorspools and D'Haeseleer (2000a,b); Bettle et al. (2006); Rekkas (2005), and Hadland (2009). The approaches developed generally revolve around the observation that three timeframes are important when considering the marginal electricity system in a liberalised market:

1. Short term 'balancing' impact—seconds to 1.5 h ahead.
2. Systematic energy trading impact—energy is traded 1 h to 1 year ahead.
3. Long term infrastructure impact—5 to 15 years ahead.

The short term impact (1) relates to the elements of the incumbent system, if any, that respond to unpredictable changes in demand. These can be very short-lived responses, stemming from events such as intermittency of some generator types or unplanned power station outage, where the system operator performs actions to balance the system in real time. In contrast, systematic impacts (2) relate to changes in the supply mix that occur after a predictable change in demand, where (for example) the specific power stations online at a particular time change due to a consistent change in aggregate demand. Finally, long-term systematic changes (3) in demand can also lead to particular infrastructure investment choices, where alternative technologies may be chosen or investment deferred or avoided based on consistent long-term changes in demand. An example of a long-term infrastructure impact is the deferment of build of a new power station due to insufficient increase in peak electricity demand.

All previous studies have found that the marginal impact of interventions can be significantly different to that calculated using grid-average metrics; Bettle et al. (2006) applied a marginal emissions calculation methodology that indicated up to 50% greater CO_2 reductions than a system-average methodology. However, it was also noted that results could change due to market liberalisation, where dispatch strategies may alter according to market structures. Marnay et al. (2002) demonstrated that the same is true of California's power sector in that use of grid-average factors could lead to significant underestimates of emissions reductions. Voorspools and D'Haeseleer (2000a) studied the impact of a selection of interventions on CO_2 reduction in Belgium, but specifically focused on the influence of changes in the generation mix due to plant commissioning or decommissioning. In contrast to the previously mentioned studies, this demonstrated the possible impact of plant commissioning/decommissioning on the marginal emissions result, coming to the conclusion that it is a critical part of the analysis and could justify marginal emissions factors that are lower than system-average rates (where new generators have lower CO_2 intensity than the existing fleet).

2.1. Merit order based approaches

The majority of existing studies have developed a merit order based approach to examine the marginal emissions problem. Merit order is defined as the order of dispatch according to cost of operation, with the underlying assumption that the cheapest generators are dispatched first, followed by more expensive systems, until system demand is met in a given time period. When combined with a load duration curve, one may observe which generator and fuel type is on the margin (i.e. next to be brought online or taken offline) for a given level of system load, as per Fig. 1. The CO_2 intensity of this generator is the MEF for that system load level, and as such it follows a step function (see Fig. 1, right axis). This method can be applied to arrive at annual, monthly, or time-of-day technology-specific MEFs based on the knowledge of system demand at times when the demand-side intervention is impacting on demand. Bettle et al. (2006); Voorspools and D'Haeseleer (2000a,b); and Marnay et al. (2002) all used at least one approach based on merit order, although the specifics of how this order was generated and applied differed between them.

For example, rather than developing a merit order based on the generation cost, Bettle et al. (2006) used historical data from the England and Wales power system for the year 2000 (i.e. just before full market liberalisation) to develop a merit order. This was based on the observed utilisation factor of generators of each technology type, with highest utilisation assumed to be lowest in the merit order. It was then used to investigate emissions reduction scenarios for a set of interventions assuming certain changes to the underlying mix of available power stations over time (i.e. plant commissioning and decommissioning were also included in depiction of the marginal energy system). Conversely, Voorspools and D'Haeseleer (2000b) did not use historical data to form the merit order, but instead developed a set of possible

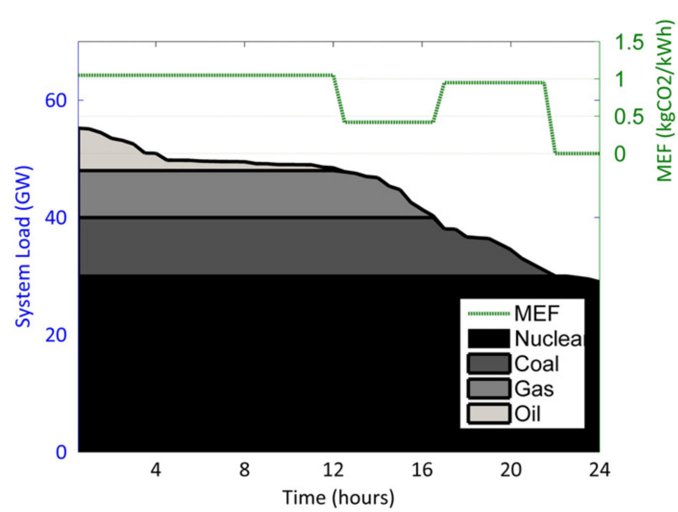

Fig. 1. Conceptual load duration curve (LDC) demonstrating predicted dispatch of generators according to their merit order, and corresponding marginal emissions factor (MEF). Resulting MEF is a step-function of system load.