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Marginal greenhouse gas emissions displacement of wind power in Great Britain

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ABSTRACT

There is considerable uncertainty over the effect of wind power on the operation of power systems, and the consequent greenhouse gas (GHG) emissions displacement; this is used to project emissions reductions that inform energy policy. Currently, it is approximated as the average emissions of the whole system, despite an acknowledgement that wind will actually displace only the generators operating on the margin. This article presents a methodology to isolate the marginal emissions displacement of wind power from historical empirical data, taking into account the impact on the operating efficiency of coal and CCGT plants. For Great Britain over 2009–2014, it was found that marginal emissions displacement has generally been underestimated with, for example, the emissions displacement factor for wind being 21% higher than that the average emissions factor in 2010. The actual displacement depends upon the relative merit of coal and CCGT, with a greater discrepancy between marginal displacement and average emissions during more normal system operation, suggesting that policies to penalise high-carbon generation can increase the effectiveness of wind at reducing GHG emissions. Furthermore, it was also identified that wind power is almost as technically effective as demand-side reductions at decreasing GHG emissions from power generation.

1. Introduction

Estimates of the greenhouse gas (GHG) emissions reductions from wind power critically inform energy policy and planning applications; however, calculations require estimates of the emissions displacement of wind power, which is currently poorly understood and a matter of some debate. The challenge with estimating this value is that the variable output of wind power is unlikely to displace all forms of generation equally, and may lead to an increase in the emissions intensity of power from conventional plant responding to the fluctuating output of wind farms. The uncertainty over the true emissions displacement of wind power has led to claims that it may increase GHG emissions, or at least be ineffective at reducing them (le Pair, 2011; Lea, 2012). This work presents a realistic picture of the recent historical GHG emissions displacement of wind power in Great Britain (GB), taking into account any negative impact that wind power has on the operation of conventional plant, and compares this to existing estimates.

Current practice in GB is to assume that wind power displaces the annual average emissions of all power generation on the system (Defra, 2013; AEA Technology, 2005; White, 2004): the average emissions factor (AEF). This follows a ruling by the Advertising Standards Authority (ASA), which acknowledges that it is an approximation due to a lack of better information (Advertising Standards Authority, 2007; CAP, 2013). The ASA consulted National Grid, the GB Transmission System Operator (TSO), who observed that a displacement factor for wind power would lie somewhere between the emissions factors for coal and gas generation, but that calculating this value was highly complicated. Due to this complexity, the calculation tool provided by the Scottish Government to estimate the carbon payback period for wind farm planning applications (The Scottish Government, 2014) uses three different displacement factors: the annual average emissions factor, the emissions intensity of coal-fired generation, and the annual average emissions intensity of the fossil-fuelled generation mix (Nayak et al., 2014). Evidently realistic information on displacement will have intrinsic value.

Wind power will displace the output from generators operating at the margin and the emissions displacement factor of wind power therefore depends upon changes in emissions from these marginal generators. Ideally, this would be found by identifying precisely which power plant respond to changes in wind production, with the marginal generation mix varying with demand across the day and year. In GB several generator types will respond to marginal changes in wind output, with coal and Combined Cycle Gas Turbines (CCGT) the most

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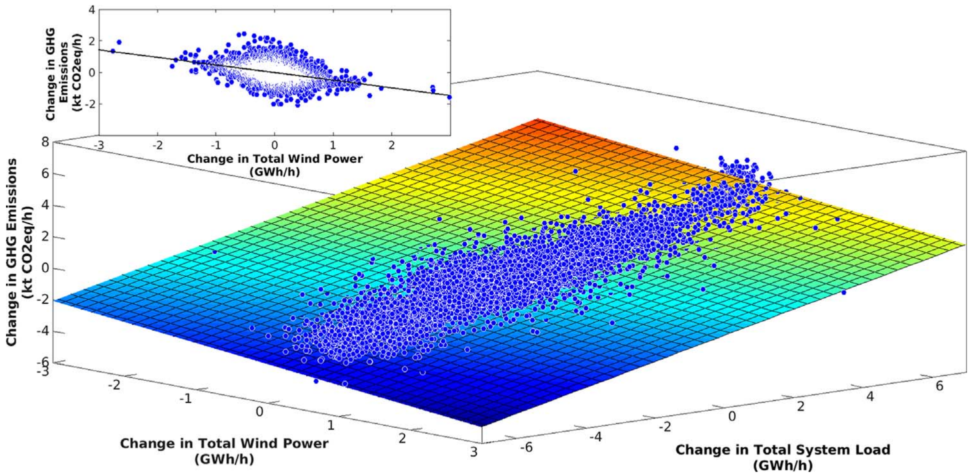

Fig. 1. Relationship between changes in GHG emissions, system generation and wind power output for 2014. Inset shows cases when change in system generation is zero, indicating the MDF.

significant for estimating GHG emissions displacement. In GB, wind variation does not currently affect the output of baseload nuclear generators and, as such, nuclear will influence the average but not the marginal generating mix; therefore the marginal displacement factor (MDF) is unlikely to be similar to the AEF. This conclusion is supported by studies on the emissions associated with marginal changes in demand – marginal emissions factors (MEFs) – which were found to be very different to the AEFs (Bettle et al., 2006; Marnay et al., 2002; Hawkes, 2010; Siler-Evans et al., 2012).

Existing studies on the impact of wind power on the GHG emissions of generation have largely focused on the long-term marginal changes of increased installed capacity, such as those arising from the commissioning or decommissioning of other power stations (Valentino et al., 2012; Delarue et al., 2009; Hart and Jacobson, 2012). These, however, neglect the short-term, operational, marginal impacts of wind power, which account for variations in wind output and forecast accuracy on the dispatch of conventional generators, and corresponding displaced GHG emissions. A few studies have attempted to identify this short-term MDF for other systems (Gil and Joos, 2007; Farhat and Ugursal, 2010; Kaffine et al., 2011; Gutierrez-Martin et al., 2013; Wheatley, 2013; Clancy et al., 2015), but it is system-specific, so the findings do not translate to GB. Furthermore, existing estimates of the MEF of demand (Bettle et al., 2006; Hawkes, 2010; Zheng et al., 2015) cannot be assumed to match the MDF of wind power, as differences such as forecast accuracy mean that conventional generation is dispatched differently in response to wind or demand fluctuations.

A particular challenge in determining the MDF of wind power is that operating fossil-fuelled generation at part-load has an efficiency penalty that increases the fuel consumption and GHG emissions per unit of energy generated; analysis of the MEF of demand fluctuations in the USA found efficiency penalties have a significant impact on emissions reductions (Siler-Evans et al., 2012).

The complexity of estimating the MDF of wind power in GB is compounded by the nature of the British Electricity Transmission Trading Arrangements (BETTA), wherein the operation of the system does not follow the conventional approach of centralised 'optimal' dispatch; a more opaque system of generator self-dispatch makes it very difficult to precisely identify which plant are responding to changes in wind output and the corresponding emissions displacement. Furthermore, such operation is challenging to model accurately, increasing the uncertainty of existing studies of short-term MDF that employ dispatch models (Gil and Joos, 2007; Farhat and Ugursal, 2010; Gutierrez-Martin et al., 2013; Clancy et al., 2015).

In addressing these challenges, this work does not attempt to model the network operation, but instead directly analyses historical operational and market data (2009–2014), while incorporating the effect of efficiency penalties on the emissions of coal and CCGT power stations, in order to provide credible estimates of the marginal emissions displacement of wind power on the GB system, and examine the relationship between increasing wind capacity and operation of conventional plants.

2. Method

2.1. Overview

The approach is based on Hawkes (2010), which calculated the average marginal emissions factor (MEF) of demand from historic GB generation data, identifying a linear relationship between marginal changes in demand and GHG emissions. Here, the analysis extends to isolate the marginal impact of variable wind on emissions, employs more robust power data, and accounts for the part-load efficiency penalties of coal and CCGT plant. The key idea is that any marginal change in system GHG emissions between one time period and the next is a function of the marginal changes in demand, wind output and other system effects (e.g. network constraints, weather, outages, plant warming, reserve requirements, etc.). This is formulated as:

$$\Delta C = a\Delta P_s + b\Delta P_w + c \quad (1)$$

where ΔC is the marginal change in system GHG emissions (t CO_2eq/h), ΔP_s is the marginal change in demand, represented by the change in total system generation (MWh/h), and ΔP_w is the marginal change in wind power output (MWh/h). The three coefficients are: a, the marginal emissions factor (MEF) (kg CO_2eq/kWh); b, the marginal displacement factor (MDF) of wind (kg CO_2eq/kWh); c, a constant representing other system effects (t CO_2eq/h). The change in demand term (ΔP_s) enables the marginal effects of changes in wind generation to be isolated from changes in demand. Multiple linear regression (MLR) identifies the values of the constants that can be visualised as the gradients of a best-fit planar surface, as Fig. 1 shows. The MDF is the gradient of the line where the change in total system generation is zero. Unlike Hawkes (2010), distribution losses (approximately 7%) are not considered as the focus is on emissions displacement of generation; however, the transmission losses are inherently captured within the total system generation. The change in demand is, therefore, represented by the change in total system generation, and includes both domestic demand and exports.

2.2. Analysis

The focus of the analysis is to generate time-series of 'instanta-