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Estimating the Reduction of Generating System CO2 Emissions Resulting from Significant Wind Energy Penetration

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***Abstract*— This paper presents ways of estimating CO2 reductions of wind power using different methodologies. The paper discusses pitfalls in methodology and proposes appropriate methods to perform the calculations. Results for CO2 emission reductions are shown from several countries. This paper is an international collaboration of IEA Wind Task 25 on wind integration.**

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I. Introduction

In the majority of electricity systems in which it is incorporated, wind power primarily displaces generation from fossil fuels, reducing fuel use and emissions. One primary policy driver for wind power uptake in recent years has been CO2 emission reduction in support of environmental policy objectives. Wind power is a renewable electricity generation source that does not itself emit CO2 in operation, and has very low life cycle CO2 emissions when compared with the life cycle emissions of fossil fuelled generation. This paper will examine methods for estimating avoided CO2 emissions in the power system, since those constitute by far the biggest share of the total lifecycle emissions of the whole power generation chain. Research elsewhere has examined the other elements of lifecycle CO2 emissions for both wind power and fossil fired plant. In principle the methods to estimate the emission reductions should be the same for any power source or change in demand and there is previous literature on the subject). However, in this analysis we concentrate on the particular application of these methods to CO2 abatement by wind power.

When wind power replaces electricity from legacy (older) coal power plants, the CO2 emission savings in power generation can be more than 1000 g/kWh. If generating plant other than coal power plant is displaced, the emission savings will be less. Due to a scarcity of examples of complete power systems with high wind power penetrations, a majority of the early studies examining the CO2 emissions reductions levels from wind power in electricity systems have been for hypothetical future scenarios with controlled assumptions on system operation. More recently, with high penetrations of wind power being achieved in several power systems internationally, it has been possible to quantify the actual CO2 emissions levels within these systems. Attributing decreased CO2 emissions from electricity generation to wind power in real historical power system operational contexts presents several challenges and a number of approaches have been used.

II. Methodologies for Estimating CO2 Reductions

In order to estimate CO2 reductions caused by wind power, one should isolate the impact of wind power from all other changes in the system and compare the system with wind power to the situation that would have prevailed in its absence. However, the complexity of the electricity system makes estimation of fossil-fuel and CO2 emissions an intricate task. The primary parameters affecting emissions intensity can vary significantly across short timescales and no 'natural experiment' exists to facilitate analysis.

Regarding operational impacts of wind power, an ideal natural experiment would involve two identical systems having the same generation portfolio, demand profile, forecast accuracy, dynamic fuel price changes, generator and interconnector availability, interconnector trade flows and network constraints in each time period across a year. In other words, one should change only those things that would change with vs. without wind power. The CO2 emissions on the system with renewable energy generation could be compared to the system without any renewable energy in order to determine the impact.

However, there is no fully objective way to establish the comparative cases and therefore at least the assumptions need to be clearly laid out. The difficulty in establishing the base case or the counterfactual scenario is one reason for divergent methodologies and results concerning CO2 reductions due to any power source.

Extra complexity is introduced when estimating emission impacts for a region that is part of a larger market area – in all cases where exchange of electricity is significant. Emission reductions also occur in the neighbouring region where electricity is exported to. Also, in a more comprehensive, long term approach, the changes caused by wind power to power plant fleet and to other power system components during the life time of wind power plants would be taken into account.

Four main categories of methods have been used to show the impacts of renewable energy on fossil-fuel displacement and CO2 emissions reduction. These vary in complexity and approach and are outlined below.

A. Displacement estimation

The simplest approach to estimate CO2 reduction is to assume that wind power replaces the average annual emissions of the power system, which are often readily available as statistics. The Clean Development Mechanisms (CDM), the system used to issue Certified Emissions Reductions (CERs) for electricity production renewables in developing countries, uses the average carbon intensity of the existing electrical generation capacity as a benchmark to estimate the avoided CO2 emissions from wind and other renewables. Basing the calculations on the carbon intensity of a generation mix will generally give a lower figure for avoided CO2 than is realistic Part of the generation is such that wind will not replace it (like 0 emission technologies hydro or nuclear power in most cases). It is also an oversimplification as wind power does not generate electricity in tandem with electricity demand. It would be more correct to weight the CO2 emissions of each scheduling period with wind power output, but even this suffers from the assumption that wind power replaces all forms of generation.

A more accurate way is to make assumptions on the type of fossil-fuel that renewable energy is likely to replace and the conversion efficiencies of this electricity generation. The Primary Energy Equivalent (PEE) method equates the energy produced from renewable sources with the amount of primary fossil-fuel energy required to generate the same amount of electricity.

The PEE approach requires an assumption of the efficiency of the fossil-fuel plant being displaced by renewable electricity sources and the type of fuel used. A weighted average approach can be used by assuming that fossil fuel generation is displaced in proportion to the individual shares in the fossil-fuel mix [2]. This method may over- or underestimate the fossil-fuel and CO2 displacement as the impact of renewable energy tends to be focused on a subset of the generation portfolio, typically the more expensive or marginal generators. As fuel costs are the main contributor to the cost of generation, the marginal units tend to be of the same fossil-fuel type. Using the proportional approach spreads the displacement effect over more fuel types and does not account for the marginal displacement effect.

The assumption can also be based on time series about marginal units, if that data is available. However, depending on the amount of wind energy during operating hour and the amount of energy from marginal unit at that time, there may be other units displaced also that are likely to have a different emission rate.

A further complication is that wind power may displace thermal power production in neighbouring countries. The marginal CO2-emission reduction benefit on a system-wide basis and a national basis might differ considerably, because of international power markets.

The data of the PEE method is usually easily available and computational requirements are light. PEE provides a relatively straightforward and understandable way to estimate fuel and emissions displacement. However, the simplifying assumptions can introduce some inaccuracy, even if care is taken to use the fuels that wind is replacing only. The PEE method cannot account for any additional dynamic changes that renewable electricity may introduce into the system. Fossil-fuel units may operate in less efficient modes and may be subject to additional start-ups.

B. Empirical statistical methods applied to historical data (Econometric methods)

Empirical econometric methods have applied statistical tools to (hourly) data on emissions production, changes in electricity demand, renewable electricity generation, and weather conditions. By establishing the marginal reduction in emissions as the share of renewable electricity rises, inferences are made on the displacement effectiveness of renewable electricity.

These methods seek to isolate the impact of renewable electricity generation by accounting for variables that are statistically related to emissions. The problem is that CO2 emissions can be highly sensitive and non-linear.

C. Detailed simulation: Dispatch models

The dispatch model method uses detailed information on components of the electricity system to establish a representation of how the electricity system operates. Data and information on the full range of influencing factors prevailing over a particular historic or future period may be included. Scenario analysis compares identical systems with and without renewable electricity generation. Kartha et al. describe this approach as “the most sophisticated and accurate operating margin approach” for establishing CO2 displacement impacts [3] Dispatch models, unlike the PEE and empirical methods, are generally used to investigate possible future effects of changing electricity system conditions,.

The system characteristics and the prevailing external conditions are identical across scenarios, apart from the level of renewable energy generation. By comparing the fuel use and resultant CO2 emissions over the scenarios, the effectiveness of renewable electricity generation in displacing fossil-fuel can be estimated. The models typically arrange the generators into a merit order, from the lowest-cost generator to the highest-cost, and dispatch the least-cost arrangement of generators required to meet demand, subject to a range of constraints (system operation requirements, network constraints, generator capabilities). These models can optimise dispatch for a given period by looking at how system conditions are likely to change over the coming periods.

The challenge in the dispatch method is how well reality is simulated. There are complications when simulating the power system operation with and without wind power. Variability and uncertainty of wind power causes need to procure more reserves and increases the utilization of those reserves and balancing markets. Also cycling of conventional power plants[1] is likely to increase, and this will influence the emissions from the power system. A detailed model can incorporate the impact of any forecasting uncertainty and variability and capture additional efficiency losses due to ramping and start-ups The detailed nature of a dispatch model means it can be labour-intensive to build, and the resulting models can suffer from a lack of transparency. The results are highly sensitive to assumptions such as fossil-fuel prices or generator performance. Without an extensive validated database on generator performance and cost data, and information on system operational rules, these models are difficult to develop and review.

Another challenge is studying future high shares of wind power. Another challenge is studying future high shares of wind power. If large amounts of wind are added the generation mix should also be re-optimized to manage the increased variability and uncertainty from wind energy. However, this case is unlikely to have the ability to function effectively without wind energy (this issue may also apply to some systems in the near future that are adapting, or have adapted, the generation mix for wind energy).

D. *Detailed simulation: Generation expansion models with dispatch models*

The knowledge that wind power will be built is likely to change what other generation will be built – and once built, it will continue influencing the future investment decisions. New investments impacting the marginal emissions can change the emissions considerably. When comparing future scenarios containing a large share of wind power, the generation mix should be optimized to both cases separately in order to get a more realistic estimate on what kind of emission reductions wind power actually allows.

Some studies have had this approach – but mainly published cost data for the future portfolios CO_2 emissions and total costs. To compare the cases to capture CO_2 emission reductions in operation of the systems is again more challenging as also other things than wind power will change in the cases compared.

It is also natural that in future high-renewable systems, when most fossil fuel based sources are replaced, further CO_2 reductions can only be very limited.

III. EXAMPLES OF METHODOLOGY IMPLEMENTATION

A. *Displacement estimation*

Kartha et al. suggest three possible options to estimate marginal fossil-fuel displacement: the operating margin, the build margin or the combined margin approach [3]. Low-cost and must-run generators are assumed to be unaffected by the addition of renewable capacity. The system average of the remainder of the generation portfolio determines the operating margin. The build margin is based on the historical data for the generation – the weighted average of the most recent 20% of plant additions to the portfolio or, if the data is inadequate, using a proxy plant method. Implementation of the proxy plant method in Ireland has tended to assume gas-fired CCGT as the proxy plant. [4], [5] The combined margin approach combines the previous two methods.

SEAI [5] previously estimated the fuel displacement from renewable electricity generation using the operating margin approach. The associated emissions displacement was estimated as 2.42 million tonnes of CO_2. This represents a displacement rate equalling 0.489 tCO_2/MWh [6] of wind-generated electricity in Ireland.

Using a similar approach based on the average CO_2 intensity of the system, EWEA estimated that wind energy avoided 126 million tonnes of CO_2 in 2010 or 0.696 tCO_2/MWh [7]. This figure was increased to 175 million tonnes in 2013 or 0.674 tCO_2/MWh. The average CO_2 intensity of the EU system stem from modelling of the European Commission which used a detailed simulation method similar as the one described in section *D*.

B. *Empirical statistical methodsfor historical data (Econometric methods)*

Kaffine et al. specified a model that took into account hourly wind energy output, hourly load, average hourly temperature, the expansion of wind capacity and the day-of-the-week changes in electricity demand [6]. They found that marginal emissions reduction due to wind energy in the Texas region was 0.523 tCO_2/MWh of wind generation. The paper highlights the sensitivity of the results to the makeup of the generation portfolio in operation over a given period. In a large system, such as the Texas system, plant and interconnector outages are averaged over a large generation portfolio. In a small system like the All-Island system, comprised of the synchronous grids of the Republic of Ireland and Northern Ireland, an outage of a single plant can significantly alter the generation portfolio and affect system flexibility and the fossil-fuel and emissions displacement estimates for a given period.

A similar method has been used for the Republic of Ireland by Wheatley [8]. This model accounts for wind generation and system demand only and how these relate to changes in plant-specific emissions. This excludes possible influencing factors such as the impact of network constraints, and unexpected generator outages. The analysis was for Republic of Ireland electricity generation only and was therefore not a whole system analysis, nor did it consider the effects of interconnector flows.Thus changes in plant emissions have been interpreted as being caused by changes in wind output when other dynamic factors may also be influencing emissions at the same time. The 2011 period examined in the analysis was exceptional due to the reduction in system flexibility. The pumped storage capacity was offline for maintenance and the interconnection capacity was offline. The paper suggests that the marginal displacement due to wind energy in 2011 was 0.28 tCO_2/MWh.

[1] Cycling refers to the operation of electric generating units at varying load levels, including on/off, load following, and minimum load operation, in response to changes in system load requirements.

Amor et al. looked at several years of data in Ontario to establish the impacts of wind generation on electricity price and GHG emissions [9]. The model specification accounts for variations in demand, wind output, baseload generation from hydro and nuclear, and output from marginal generators. The impact of network constraints is also included. The study finds that wind displacement effects are strongly influenced by the level of network constraints. The paper estimates GHG displacement in the range 0.283 to 0.394 t CO2.

Cullen examined the impact of wind in the Texas system between 2005 and 2007 [10]. Wind output, electricity demand, network congestion and changing efficiencies of fossil-fuel generators are included. As the generation output of fossil-fuel generators influences future output, due to the additional costs and inefficacies involved in starting up a generator that has been offline for longer period of time, Cullen includes lagged data for these variables to help explain the generator output. Generator outages and fossil-fuel spot prices are also included as well as controls for generator pricing strategies. The relationship between these variables is expressed as linear and non-linear relationships that can capture some of the more nuanced effects of wind generation of fossil-fuel generator output. The results show that wind tends to displace natural-gas CCGTs but also displace less efficient natural-gas generation from OCGTs. Overall the CO2 reduction is estimated as 0.43 tCO2/MWh.

Forthcoming analysis by di Cosmo and Malaguzzi Valeri examines the displacement impact of wind between 2008 and 2012 in the All-Island system. The estimation relates changes in power-plant emissions to variations in the output of wind generators, fluctuations in demand and changes in other influencing factors. Findings show a displacement effect that varied across individual years due to changing system conditions affecting the generation mix and system flexibility.

An empirical method that includes a full specification of the explanatory factors that contribute to emissions of the electricity grid has the potential to provide some insight into the impact of renewable electricity generation on emissions reduction. Historical data is required for several influencing variables over short-time horizons of several years to better understand the historical period examined. The nature of the relationship between the explanatory variables and emissions can be difficult to identify, with the possibility that the influence of some factors is non-linear and lagged in time.

The empirical models tend to focus on what the past displacement impact of renewable electricity was, with models specified to fit the available data as closely as possible. Models capable of predicting and explaining the impact of the various factors require different specifications that include the influence of network constraints, forecasting uncertainty, demand in preceding periods, must-run generators and the availability and flexibility of plant in the generation portfolio. Amor et al. point out that, due to the complexity of electricity systems, empirical methods are unable to fully explain the reasons for observations and that the strength of empirical models lies in their ability to observe an emissions reduction impact in historical data. [9]

C. *Detailed simulation: Dispatch models*

EirGrid conducted a study in 2007 [11], updating earlier analysis [12], using the dispatch model methodology applied to future renewable electricity deployment scenarios. Four electricity system scenarios were examined: a no-wind reference case and three scenarios with increasing levels of wind-power generation. The impact of additional cycling was examined as part of the analysis. It showed that wind energy displaces between 906 and 974 tCO2/MW of capacity installed. This is equivalent to between 0.260 and 0.502 tCO2/MWh. Denny and O'Malley [13] confirmed the effect of fossil-fuel and CO2 displacement, including the impact of any additional cycling, estimating a CO2 displacement impact of 0.33 – 0.438 tCO2/MWh.

The National Renewable Energy Laboratory (NREL) outlined in a recent report [16] a method to analyse the effect of renewables (wind and solar) on increased thermal plant cycling. Using PLEXOS power market simulation software, a dispatch model was created to simulate scenarios with various levels of renewable penetration in the Western Interconnection of the United States. To carry out the analysis, detailed emission curves for nearly all thermal power plants in the West were obtained from the U.S. Environmental Protection Agency, which tracks and collects these data. These emission curves were directly incorporated into the production simulation model. Emission penalties for start-up and part-load operation were modeled also, with CO2 penalties for part-load operation ranging from 6%-18%, based on type of unit. Ramping emissions were also penalized; however it was found that CO2 ramping impacts are equivalent to less than 3 minutes of full-load operation.

The generation mix was not-reoptimized for the wind energy that was added to the system. The generation assumptions were adopted from the Western Electricity Electricity Council (WECC) transmission planning process, which has representatives from all regions in the West and produces a collaborative model of the generation fleet and transmission network.

The study found that a 24-26%[2] wind and solar energy penetration avoids 29%-34% of the carbon dioxide compared to the base case, depending on the relative mix of wind and solar. This is approximately 0.489 to 0.523 tCO2/MWh of wind/solar generation. The emission reduction rate exceeds the penetration rate because much of the displaced generation is natural gas, which has relatively low carbon emissions rates. In the high wind energy case, more coal was displaced, thus even less CO2 emissions were produced (34% reduction from base case). Thus the study concluded that even when start-up, additional cycling, and other efficiency penalties are incurred, overall CO2 emissions are reduced significantly with the inclusion of high levels of wind and solar energy.

Valentino et al. examine the emissions impact of incorporating wind energy into the electric power system in Illinois [17]. Their findings showed a reduction in CO2 emissions for all levels of wind penetration of between 0.672 tCO2/MWh and 0.847 tCO2/MWh.

[2] The percentage of renewable energy was 33% of the US demand, but when non-US parts of the interconnection were included in the modeling, the penetration rate declined with the increase in demand

For Nordic countries, the electricity system is dominated by hydro power, in addition to coal and gas. Wind power was estimated to reduce CO2 emissions by 0.3-0.7 tCO2/MWh, depending on whether coal or gas powered plants were substituted. The market model used in simulations optimises also the hydro power generation in the Nordic countries [1]. Reservoir hydro can hold the water on windy periods, and even if it is replaced by wind during a single hour, it will be generated at a later stage. This is why wind will replace mostly coal and gas also in Nordic system. However, adding larger amounts of wind power will result in CO2 savings also outside the Nordic countries, like Germany.

SEAI [19] carried out a detailed analysis of the real time operation of the All-Island electricity system in order to estimate the fossil fuel savings from wind generation and other renewable electricity sources in 2012. Wind generation accounted for 15% of electricity consumption on the All-Island system in 2012. The generator dataset underpinning this analysis has been validated by the Commission for Energy Regulation (CER) and is publicly available, as is the PLEXOS modelling software [16]. The dispatch model method used for the analysis incorporates the extensive range of dynamic factors that influence the operation of fossil-fuel generators and are accounted for in the evaluation of overall savings from renewable electricity generation. These factors include ramping effects, cycling effects, contingency reserve, network constraints, wind characteristics, generator availability, and cross-border electricity trade. On the All Island electricity system as a whole in 2012, wind generation is estimated to have displaced 826 ktoe of fossil-fuel and brought about a CO2 emissions reduction of 2.33 million tonnes. 61% of the savings are due to the displacement of natural gas CCGTs with the remaining 39% due to the displacement of coal. The average intensity of net displacement intensity by wind generation was 0.46 tonnes of CO2 per MWh.

D. *Detailed simulation: Generation expansion models with dispatch models*

The All-Island Grid Study examined the impact of five future renewable electricity development scenarios for the 2020 power system in the island of Ireland. The analysis showed CO2 savings due to renewable energy [14]. The emissions reduced from 20 Mt CO2/year (16 % share of renewables) to 15 MtCO2/year (42 % share of renewables), but different portfolios had different CO2 emissions even for the three portfolios for 27 % share of renewables (18-22 Mt CO2/year). It also showed equal emissions reductions in the UK system to those in Ireland associated with wind additions solely in Ireland.

Analysing results from generation planning model simulations where wind power is one investment option shows very high difference in CO2 reductions [20]. Changing the level of wind power investment cost resulted in a change in the amount of invested wind power. All analysed scenarios had low levels of CO2 emissions, since the system was based heavily on wind power and nuclear power. In a scenario where new nuclear power was not allowed, , the increasing amount of wind power had a CO2 reducing impact of 1.20-1.22 tCO2/MWh. This is more than emission from a coal plant and is explained by the dynamic factors in the system: coal power plants were increasingly replaced by natural gas power plants when there was more wind power. Gas power plants had lower capital costs and higher operational costs than coal power plants. They were not as influenced by the lower utilization rate. The generation planning model did not include other cycling costs. In cases with a very low level initial level of CO2 emissions (a scenario where nuclear was allowed), the emissions actually increased when wind power increased (0.01-0.02 tCO2/MWh increase). In these cases more flexibility was needed and it was economic to source it partially from fossil fuel sources. The availability of flexibility measures (smart charging electric vehicles and flexibility in district heating) had also a sizeable impact on the emission reductions. The main conclusion from this paper is that the emission reductions of future systems are highly dynamic and dependent on the assumed system conditions and cost assumptions.

IV. Conclusions and Discussion

Figure 1 shows the range of results from the various studies (PEE, empirical and dispatch) referenced above for displacement of fossil-fuel generation and associated CO2 emissions for the All Island electricity system (shown in green) and for systems in other countries (shown in blue). For the studies pertaining to the All Island system, the overall range of emission displacement intensities, for different periods and under different scenarios, extends from 0.260 tCO2/MWh to 0.502 tCO2/MWh.

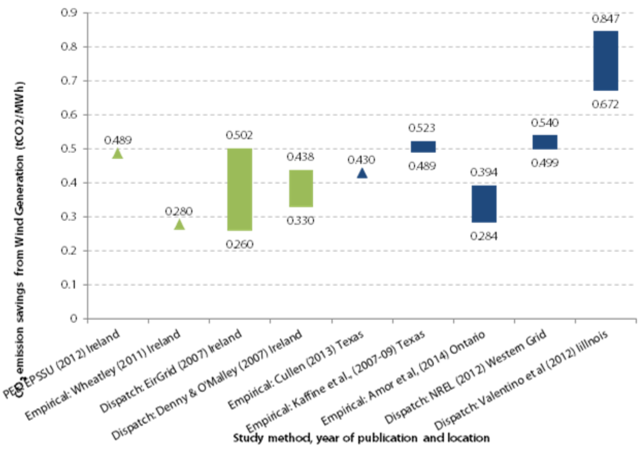

Figure 1. Emission reductions of wind power in Ireland from different methodologies (green), compared to estimates for North America (blue).

The All-Island System and U.S. Western Grid have high proportions of less carbon-intensive gas generation. In contrast, the Illinois system is dominated by more carbon-intensive coal combustion. Renewable energy displacing less carbon gas results in a lower displacement impact than when renewable energy displaces coal – for coal dominated systems 0.489 to 0.847 tCO2/MWh has been estimated. Cycling impacts are shown to have a minor overall impact when compared to the absolute 'bottom line' reduction in CO2 emissions.

Detailed dispatch simulations that capture additional cycling impacts is the most correct approach to estimate the impacts of wind power on CO2 emissions in power system operation. Increased cycling due to wind capacity addition has to be clearly distinguished from the existing level of cycling in the system. Cycling impact has been estimated to be small and will not offset the benefits of wind energy in reducing emissions [16].

Using emission rate data and assumptions on fuels displaced can be first estimate but especially at higher penetrations will not be accurate. Using historical data can give insight to CO2 reductions, however, years are different and capturing impacts due to wind power instead of other changes is challenging. Transmission system congestion may have a fundamental influence upon emissions but this is rarely quantified.

Exchange to neighbouring countries will complicate the analyses. The distinction between political and system boundaries is critical to proper analysis, even when these coincide, interconnector flows may effectively export or import CO2 emissions. Governments are only responsible for abatement within their particular jurisdictions and external effects may go unreported if analysis and reporting is focused solely on national effects.

Systems that have appreciable penetrations of wind to date may not be utilising existing flexible resources and DSM to their full potential, greater CO2 displacement may be possible. Incorporating wind into legacy generating systems may result in a non-optimal flexibility resource in the balance of generating plant. This will be resolved as the generating system evolves but ex-post analysis of a power system with a steadily growing wind penetration (undergoing a wind energy transition) may underrepresent the long term potential for CO2 displacement by wind power

Most of the work so far has concentrated in capturing the impacts operationally, short term. As demonstrated by couple of studies, the impacts can be very different for long term. Newly built wind power, together with other low marginal cost units, will push out the highest marginal cost units during each scheduling period. However, the same wind power will also influence what new generation or electricity demand is worthwhile to develop at a later time. Wind power will supress prices during many hours of the year and decrease the incentive especially for baseload power plants. The CO2 emissions of a system with high amounts of wind power are highly sensitive to the resource mix that results from past investments in generation and DR [20]. Thus, the lifecycle emissions of a wind power plant should consider the impact over the whole operational period of the plant [21].

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