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Wind power variations during storms and their impact on balancing generators and carbon emissions in the Australian National Electricity Market

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A B S T R A C T

This paper examines changes in Frequency Control Ancillary Services (FCAS) generator output due to several large wind farm power variations occurring in the Australian National Electricity Market (NEM) during 2012 and 2013. Using data from actual FCAS generator output fluctuations during selected storm events and reconstructed heat rate curves for each FCAS generator, the authors address the research question of what effect such variations have on net carbon emissions from electricity generation, given balancing fossil-fueled FCAS generators will be pushed back into less efficient operating ranges. The study finds that, for all storm events evaluated, net carbon emissions decreased with each large increase in wind power, even though FCAS generator carbon intensity increased in two of the three events. This finding is consistent with the conclusions of other studies that while FCAS generators do move into less efficient operating ranges, the generation of zero carbon emission wind power displaces other fossil fuel generators and more than compensates for this efficiency reduction, creating an overall positive carbon effect. This is a significant finding as it shows that the inclusion of wind farms in the generation mix serving the Australian NEM can lower carbon emissions in both short and long time frames.

1. Introduction

There are literally hundreds of studies of wind power across the world, each analysing different components of the complexity of a variable renewable energy resource and how best to integrate it into a power system. The UK Energy Research Centre (UKERC), in their 2006 review on the impacts of intermittency, studied 212 documents, and included results from 154 of them in their findings [25]. Many of these documents studied the impact of wind power on balancing generators operating on the electrical grid.

When conventional fossil fuel generators are ramped up and down to provide frequency regulation ancillary service balancing the fluctuations in wind power output, there is a reduction in generator efficiency. Inhaber [16] draws a parallel between the drop in efficiency when fossil-fueled generators are cycling (increasing and decreasing their power output) in response to the integration of variable power sources on an electrical grid, and an automobile changing from highway driving to stop and go city driving. In the case of cycling of natural gas turbines the drop in efficiency can be as much as 35–50%, depending on their operating level and the participant's appetite for providing ancillary services.

However, only a few authors to date have examined the efficiency losses of thermal plant offsetting wind power variability and the impact of these losses on the overall carbon emissions from fossil fuel generators on the grid. A number of reports indicate that the use of conventional generators in load regulation leads to minimal emission savings due to the increased cycling of frequency regulation units outweighing emission savings from displaced thermal generators [23, 28]. More recently, studies on cycling of thermal plant providing regulation services have been undertaken in the USA, Spain and Ireland [24,29,30]. Each of these reports agree that whilst there are some efficiency losses by fossil-fueled thermal plant offsetting the wind power variations, overall there is still a carbon emissions saving from incorporating wind energy on a power system. Studies on the world's largest competitive wholesale electricity market, the PJM Interconnection in the USA, found that

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high wind penetration levels of 20% resulted in significant increases in cycling of coal units with associated cycling-related costs and emission penalties, but these emission penalties were small in comparison to the emission savings due to 'displacement of fossil-fueled power by wind power' [21].

In a study of the impact of wind power generation on conventional plant on the National Grid in Ireland, Byrne [9] concludes that plant operate less efficiently and with increasing volatility as wind penetration increases. UKERC [25] attempt to quantify the relationship between thermal plant efficiency and wind penetration, stating that, up to wind penetration levels of 20%, efficiency losses can be between negligible amounts and a reduction in theoretical maximum fuel savings[1] of 7%. Inhaber [16] suggests, based on reports from Denmark, Germany and Estonia, that carbon emissions savings achieved by the introduction of wind power in a grid markedly reduces as wind penetration increases due to the cycling of the fossil-fueled plant that make up the balance of the grid. This is in contrast to Byrne [9] who forecast the increase in wind penetration on the national grid in Ireland from 10% to 30% by 2020 would be accompanied by a corresponding increase in carbon emission savings from 5.4% to 12.9%. Wheatley [27] concurs that reports of wind power emission savings vary widely and attributes this to assessments based on national renewable energy action plans rather than accurate data on emissions and fuel savings. In his own calculations, based on half-hourly generation data from the market operator in the Irish electricity grid during 2011, Wheatley indicates that carbon emission reductions associated with wind power were 0.29 tC02/MWh. These type of savings are lower than figures of 0.43 tC02/MWh stated by Renewable UK (2012) and the minimum of 0.35 tC02/MWh calculated by the UK Institute for Public Policy Research.

Most authors agree that there are many uncertainties in predicting the effect that increasing wind penetration has on carbon emissions reduction. Such uncertainties include the variability of the wind resource, the type of conventional generation displaced by wind power, the type of generation used in the regulation services (e.g. close-cycle gas turbines are more efficient than open-cycle gas turbines) and rate of cycling of regulatory generators. Reliable data is also difficult to obtain: market participants often decline access to hourly production data and hourly fuel use that can be used to calculate reduction in carbon emissions, and a number of authors have called for more studies using actual data rather than model predictions (Gross and UKERC (Organization) 2006).

There has been much discussion recently on the quantity of balancing reserves and how this relates to the integration of renewable energy. Modelling studies in the USA claim that the amount of balancing plant increases with the penetration levels of wind power in large grids [13] and in small islanded systems [11], however, this is in direct contrast to actual results found in Germany and Australia where the level and cost of regulation has actually decreased [14, 18].

The issue of wind integration has become very important in Australia in recent years. National renewable energy targets have resulted in an almost doubling of installed renewable energy from 10,650 MW in 2001 to 19,700 MW in 2012. Wind energy has made up the majority of this increase with annual wind energy generation growing from 200 GW h in 2000/01 to 5800 GW h in 2010/11 [19, 22]. In its Clean Energy Australia Report, the Clean Energy Council (CEC) of Australia reported 9777 GW h of wind energy in 2014 from a total of 71 wind farms with a capacity of 3807 MW [10].

The Australian Energy Market Operator (AEMO) in its role of providing a secure and stable power system has conducted many studies to investigate the impact of the expected increase of wind capacity on the NEM, which in 2013 they forecast to be an additional 8.88 GW by 2020 [5]; i). These include their 2013 report on wind integration, and the hypothetical 100% renewables study conducted in 2012 [4, 5]; which incorporated a wide range of renewable development, not solely wind. Both studies found that from an operational view point large scale wind and even total renewable energy generation were "operationally manageable" [4]; 9). AEMO also commissioned German consultants Energynautics to review reports and experiences world-wide and determine which were relevant in the Australian NEM [2]. The AEMO studies suggested the importance of investigating the impact of high wind power variance (due to e.g. storms) on regulation frequency control ancillary services (FCAS) generators, in terms of the effect on generator efficiency and related changes in carbon emissions.

A literature search for studies examining FCAS carbon emissions attributable to fluctuations in wind power generation, however, located no relevant research specific to Australia. The absence of such studies based on measured empirical data in Australian conditions indicates a significant knowledge gap. This study seeks to address that gap and asks the research question: do large increases in wind power that displace fossil fuel generation still have a net carbon emissions benefit even though thermal generators providing balancing energy reduce their output into possibly lower efficiency zones? It also investigates impact of large wind power fluctuations on the procurement level of balancing plant and its effect on the system time error.

This paper assesses three 1-h storm periods shown to have caused large variations in wind power between 5-min dispatch intervals, and uses 4-s FCAS data recorded from each power station via the Supervisory Control and Data Acquisition (SCADA) system, to track the movement in the regulation generators as a response to the variations in the wind power and load (net). The output of each generator is the total output, including energy and any FCAS dispatch. Carbon emission curves are developed for each of the regulation generators and applied against the 4-s SCADA data. This produces actual GHG emissions, in line with the operating point of the generators, and shows how carbon emissions vary in the short term as wind power in the NEM ramps up. This will be further explained in Section 2.2.

2. Materials and methods

2.1. Generator production data

AEMO publishes data on all scheduled and semi-scheduled market generators down to 4-s intervals. This Ancillary Services Market Causer Pays data is used in the allocation of FCAS charges across the market [6]. The comprehensive file requires two index files, and is stored in 5 min blocks on the AEMO website [7]. For each generator it stores several variables, including the instantaneous power output, the dispatch level,[2] and the amount the generator is contributing to regulation services (Regulation Participation Factor, %). It also stores the frequency and electrical time error on specific nodes across the NEM. The causer pays files were retrieved from AEMO for 1 h of data for each of the three storms selected (12 files of 5 min each).

[1] The theoretical maximum fuel savings occur when every MWh of wind energy produced saves 1 MW h of energy from fossil fuel generators.

[2] The *dispatch level* is defined as "the estimate of the *active power* at the end of the *dispatch interval* specified in a *dispatch instruction*" AEMC [31], 1192.

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