Market-wide impact of renewables on electricity prices in Australia*

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Abstract

This paper estimates the market-wide impact of utility-scale renewables on Australia's National Electricity Market (NEM) wholesale prices from 2009 to 2020. The goal is to understand the medium-run impact of renewable generation, as opposed to the short-run impact of weather-driven changes in renewable output. The focus is, therefore, on the relationship between renewable generation (and its growth) and wholesale prices over a long period of time. In particular, we exploit the half-hourly nature of wholesale price setting in the NEM to uncover the impact of solar and wind daily production on the distribution of prices throughout the day.

In contrast to the merit order effect literature, which focuses on the short-run, contemporaneous impact of renewables, our results suggest that the total daily solar production has a positive, although not always significant, impact on wholesale prices throughout the day during an early development stage of solar generation. For a more recent period, following a substantive increase in utility-scale solar generation, the results are more in line with the merit order effect literature with total daily solar production reducing wholesale prices for most of the day. This impact, however, is of several orders of magnitude lower than that predicted in the literature. We also show that the daily production of wind has a small, negative impact on wholesale prices for most of the day, throughout the entire period of analysis.

JEL Classification: D4, L94,

Keywords: renewables, energy-only markets, prices.

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1 Introduction

This paper estimates the market-wide impact of renewables on Australia's National Electricity Market (NEM) prices. The aim is to better understand the role of markets in the transition to a net zero-emissions electricity sector where non-renewables still play an important role in the provision of firm or dispatchable electricity. In particular, we study the impact of total daily wind and solar generation, as a measure of potential capacity, on wholesale prices throughout the entire day. In a market such as the NEM, where generators submit bids to supply at 5-minute intervals, an increase in the penetration of solar and wind (intermittent) generation will impact bidding strategies of different types of generators, and therefore market prices. For example, gas and coal generators need to take into account the need to ramp up generation to meet peak demand as daylight ends.

The NEM started its operations in December 1998. It is one of the world's longest interconnected power systems, covering five regions: New South Wales, Queensland, South Australia, Tasmania and Victoria. Around 150 large power stations (and approximately 240 plant units in total) participate in the NEM. The transmission network, encompassing around 40 thousand km of high voltage power lines, transports electricity to large energy users and distribution networks. A competitive retail market services approximately 10 million residential, commercial and industrial energy users.[1]

The somewhat unique NEM design includes a wholesale market in the form of an energy-only gross pool, with a spot market where prices and the quantity dispatched by each generator is determined through the interaction of supply and system demand. All electricity is traded in the spot market. A dispatch price is set every five minutes and it is equal to the bid of the marginal generator. Six dispatch prices are averaged every half-hour to determine the spot price for each trading interval for each of the NEM regions. System demand can be met within one region or across regions. Interconnectors deliver energy from lower price regions to higher price regions and, as such, prices across in the regions are connected. When interconnectors are constrained, electricity continues to be transported from a lower price region and sold in a higher price region up to the capacity of the interconnector, but prices are no longer co-determined. [2]

The wholesale market is complemented by a deep forward derivative market that connects the economics of the physical power system to investment and resource adequacy. Generators earn additional revenue from participating in two separate financial markets. In the over the counter (OTC) market, generators sell hedging contracts (swaps or contracts for differences) to large buyers including retailers and other participants. Futures products are also traded on the Australian

[1] See, for example, AEMC (2018), Chapter 2.

[2] Detailed information on the least-cost security-constraint dispatch process followed bythe market operator can be found at https://aemo.com.au/en/energy-systems/electricity/national-electricity-market-nem/system-operations/dispatch-information.

Securities Exchange (ASX), and participants include generators, retailers, speculators, banks and other financial intermediaries. The equivalent to 172 per cent of underlying NEM demand was traded on the ASX in 2017-18. Existing information suggests that OTC trades account for less than 25 per cent of the ASX trading.[3]

The NEM was designed to promote efficient outcomes. In an industry characterised by large sunk costs, effective competition ought to lead to prices that converge to the long-run marginal cost. This way generators would recover their efficient investments (including a return on and of capital). This was to be achieved through prices that reflected the system's short run marginal cost when the system was not constrained (i.e., the marginal cost of the marginal generator), and that would reflect congestion rents when the system was constrained. The uniform-price spot market auction design helps to ensure that prices reflect the relevant opportunity costs.[4] Exposure to the contract market reinforces incentives for generators to bid closer to their costs.[5]

There is considerable evidence that the NEM has performed well, with a very high market price cap (currently at A$15,100/MWh) ensuring that the missing money problem that prevailed in many electricity markets around the world did not manifest itself in the NEM.[6] For example, Simhauser (2019c, p. 1) concludes that:

'A vast oversupply of generation plant was cleared, unit costs plunged, plant availability rates reached world class levels, requisite new investment flowed when required, investment risks were borne by capital markets rather than captive consumers, and reliability of supply – in spite of an energy-only market design – has been maintained with few exceptions . . . '

The NEM's success in promoting allocative and dynamic efficiency, however, has ended for a number of reasons including the uncoordinated exit of a large coal power plant, climate change policy uncertainty and the discontinuity of the carbon price in 2014, with consequential developments in the gas market.[7] Out of market mechanisms, such as renewable certificates and public underwriting of new investment, and more recently direct interventions, has severed the link between NEM prices, investment requirements and system operations.[8] In particular, while the combination of market and out of market mechanisms has been sufficient to support investment in renewable generation, investment in firm, dispatchable electricity has not materialised as a result of market

[3] See Australian Energy Regulator (2018, p. 120).

[4] For an introduction to auction theory, and the properties of uniform-price auctions, see for example Menezes and Monteiro (2008).

[5] Allaz and Vila (1993) have shown that, under certain conditions, forward markets may mitigate market power and improve efficiency.

[6] The missing money problem refers to the fact that imperfections in wholesale energy-only electricity markets, such as market price caps, result in generators not earning net revenues that are sufficient to support investment in a least cost portfolio of generating capacity and to satisfy consumer preferences for reliability. See, for example, Joskow (2007) and Joskow and Tirole (2007).

[7] See, for example, Simshauser (2019a).

[8] See, for example, Simshauser (2019b).

forces – and instead has been largely driven by government intervention. Despite the substantive increase in renewable generation, as discussed in Section 3, wholesale prices in the NEM have increased markedly between 2015-2019, but have decreased subsequently.

The intermittency of renewables (alongside a weak demand response) requires firm, dispatchable technologies (e.g., batteries, pumped hydro or gas) to meet demand at all times. That is, dispatchability is a technology-driven externality, and an important economic question is whether a well-designed market can provide enough incentives for investment in dispatchable electricity. This paper aims to help answer this question by studying the impact of renewables on NEM prices across the entire day. Our goal is to understand the medium-run impact of renewable production, as opposed to short-run weather-driven changes in renewable output.

There is a large literature that shows that an increase in near-zero marginal cost renewable output will result in a reduction in the wholesale price at the time the output is generated. This has been referred to as the merit-order effect.[9] In the case of Australia, using largely the same data as we do for the NEM, Csereklyei, Qu and Ancev (2019) estimate (and provide evidence in favour of) the contemporaneous merit order effect, either using half-hourly data or aggregate daily data. In contrast, we exploit the half-hourly nature of wholesale price setting in the NEM to uncover the medium-run impact of renewables on the distribution of prices throughout the entire day. By focusing on what happens to prices, in the medium-run, throughout the day, we can increase our understanding of the impact that renewables have had on the economics of non-renewable generation.

In our analysis, we control for demand or supply trends that may explain wholesale price changes: on the demand side, we use the half-hourly total production in the NEM; on the supply side, we control for natural gas and coal prices. In addition, we control for what appears to be a significant increase in (utility-scale) solar (and to a lesser extent, wind) capacity from July 2018 (the terms solar and wind production refer to utility-scale unless otherwise stated). Indeed, both capacity as well as renewable production in the NEM increased significantly at that time.

Our results suggest that, until July 2018, daily solar production has a positive, although not always significant, impact on wholesale prices throughout the day. While the contemporaneous merit-order effect literature suggests that solar production may have a negative impact on the wholesale price during the time when solar electricity is generated - and, indeed Csereklyei et al. (2019) find evidence of a merit order effect for solar production in the NEM - our analysis suggests that the longer-term impact of solar-based electricity is more complex, especially during a period where solar generation was still at an early stage of development. Our results are capturing, we believe, some of the system-wide costs of increased solar penetration at that early stage. This includes, for example, the costs of ramping up and down coal and gas generating units, which are

[9] See, for example, the discussion in Sensfuß, Ragwitz and Genoese (2008). For evidence of the merit-order effect in the US, see Woo et al. (2011, 2012, 2013, 2016).

built into the bids by these generators. From July 2018 onwards, following a substantive increase in utility-scale solar generation, the results are more in line with the merit order effect literature with total daily solar production reducing wholesale prices for most of the day. This impact, however, is of several orders of magnitude lower than that predicted in the literature, although this is not entirely surprising given our research question and methodology. Indeed, because we are looking at the impact of total daily solar and wind production on half-hourly wholesale prices across states, the relationship between the two is not as direct as when we look at the (contemporaneous) merit order effect.

We also show that daily wind production has a small, negative impact on wholesale prices for most times of the day - and this is true both before as well as after July 2018. The negative impact of daily generation, however, is again substantially smaller than that predicted in the merit-order effect literature, which focus only on the contemporaneous impact - although this is not entirely surprising given the different research question we are looking at.[10] While the impact of daily wind generation on wholesale prices throughout the day is small, it is still larger than the impact of daily solar generation. This is consistent with optimisation studies that show that the least-cost generation mix favours wind generation over solar - the reason being that the production of solar is highly self-correlated, since it is available during daylight hours.[11] In contrast, wind generation spread across the NEM exhibits less correlation, and therefore is subject to more geographical smoothing.[12]

The paper has the following structure: Section 2 describes the policy environment that underpinned the introduction of renewables in the NEM; Section 3 describes the data used; Section 4 presents our empirical methodology and Section 5 contains our results; and Section 6 concludes.

2 Renewables Policy in Australia

Australia's mandatory renewable standard has been in operation since 2001. Known previously as the Mandatory Renewable Energy Target, the initial aim was to ensure that two per cent of the nation's electricity generation was sourced from renewable sources by 2010. It required all liable retailers to submit Renewable Energy Certificates (RECs) each year to meet progressively higher targets. In 2009, the target was increased to ensure renewable energy made up the equivalent of twenty per cent of Australia's electricity (or 41 000 GWh) by 2020.

In January 2011, the Renewable Energy Target (RET) was divided into two schemes.[13] The Small-scale Renewable Energy Scheme (SRES) created financial incentive for individuals and businesses to install small-scale renewable energy systems such as rooftop solar, water heaters and heat

[10] See, for example, Forrest and MacGill (2013) or Csereklyei et al. (2019).
[11] See, for example, Gilmore et al. (2015).
[12] See, for example, Elliston et al. (2016).
[13] See, for example, http://www.cleanenergyregulator.gov.au/RET/About-the-Renewable-Energy-Target.

pumps. The financial incentives took the form of small-scale technology certificates (STCs), which are issued up-front for a system's expected power generation (based on its installation date and geographical location) until the scheme's expiration in 2030. Large energy users are required to purchase a fixed proportion of STCs and surrender them to meet their obligations under the RET.

The Large-scale Renewable Energy Target (LRET) provided financial incentives to establish and expand renewable power stations such as solar farms, wind farms and hydro-electric power stations. This scheme was to deliver the majority of the 2020 target. The incentives were in the form of large-scale generation certificates (LGCs), which were issued based on the amount of electricity generated. As with STCs, high-energy users are required to buy the LGCs and surrender them to meet their obligations under the LRET. In June 2015, the Large-scale Renewable Energy Target was reduced to 33 000 GWh in 2020 with interim and post-2020 targets adjusted accordingly. While the smaller target was met in September 2019, the scheme will continue to require high-energy users to meet their obligations under the policy until 2030.

The RET underpinned a substantial increase in the penetration of renewables in the NEM. For example, between 2006 and 2018, the shares of renewables in electricity generation grew from 0% to 51% in the small NEM region of South Australia, and to about 8% in the large and more strongly interconnected regions of Queensland, Victoria and New South Wales.[14]

Despite its initial impact on incentivising investment in renewables[15], the RET undermined the economics of the wholesale market, as part of the income of renewable generators is not connected to wholesale prices. This breaks the connection between wholesale prices and short and long-run marginal costs. In particular, wholesale prices no longer provide signals for efficient capacity expansion. The market distortions were compounded by interventions by states and territories through out of market mechanisms or direct intervention to fulfil their own renewable targets or to replacing exiting coal generators. The federal government too made use of out of market mechanisms in the form of underwriting investment in firm energy and through direct investment in pumped hydro.

3 Data description

Solar production in Australia has started relatively recently.[16] Figure 1 shows that the 21st March 2015 marks the first day that solar production was traded in the NEM (energy generated in New

[14] See, for example, Simshauser (2019c), as well as Section 3.

[15] A carbon price, at at \$23 per tonne of CO2e was introduced on 1 July 2012, with the intention of transitioning to an emissions trading scheme (ETS) in July 2015. However, the CPM was repealed by the new Liberal government on 17 July 2014. Section 5 provides an estimate of the cost-pass through of the carbon tax, compares it to other estimates in the literature, and provides a brief review of the literature that assesses its impact on investment in renewables.

[16] We note that rooftop solar generation has grown significantly over the sample period, reaching 8,148 GWh in 2018, with an increase of 1,355 GWh over 2017 levels. (https://reneweconomy.com.au/nem-review-2018-more-renewables-greater-efficiency-less-emissions-16524/).

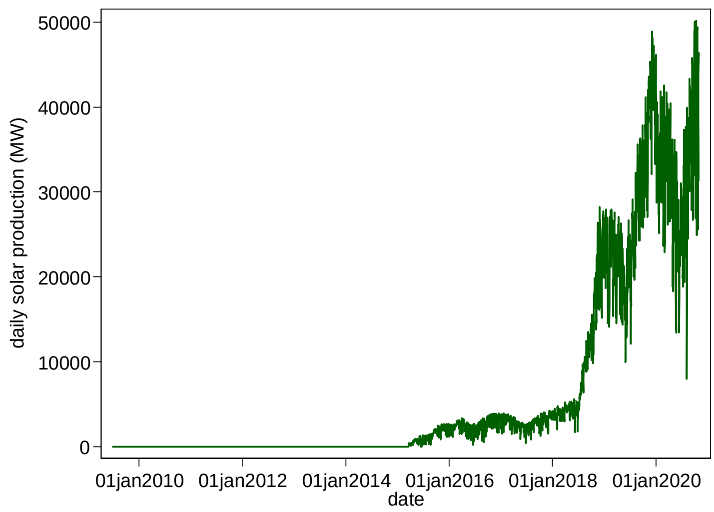

Figure 1: Daily solar generation (all states)

South Wales). From that day onwards, the trading of solar-generated energy in the NEM has increased markedly. This pattern, however, is not common across all states. In particular, Tasmania does not have solar production in our sample period (2009-2020) whilst solar production started in Queensland in 2017 and in South Australia and Victoria in 2018. In addition, we note that from July 2018 solar generation has increased rather significantly. Moreover, if we construct an index whose base (100) is equivalent to the average daily solar production in the first full year (365 days) that solar was generated in each state, Figure 2 shows that solar production has increased in all states, but at a much faster rate in Queensland (which started solar production later than New South Wales).

Wind-based electricity, on the other hand, has been traded in the NEM since the start of our sample period (1 July 2009) and it has grown significantly over time (see Figure 3). But again, significant differences exist across states (see Figure 4). For example, Queensland does not have wind production during most of our sample period. In addition, South Australia and Victoria emerge as the most significant wind-based electricity producers.

Figure 5 shows the average total generation across states for each half-hour in 2009 and 2020. The picture that emerges is that of a decrease in generation, particularly in the morning. Although we compare only the first and last year in our sample period, this trend is not specific to the years we consider. More concretely, for every half-hour slot, a decrease in generation is observed almost every year between 2009 and 2020.

The sharp increase in renewable generation - both solar and wind - has not been felt in a similar way across the daily half-hour slots. Obviously, as Figure 6 shows, solar generation occurs during daylight hours. At midday, solar generation has increased more than seven-fold between 2015 and

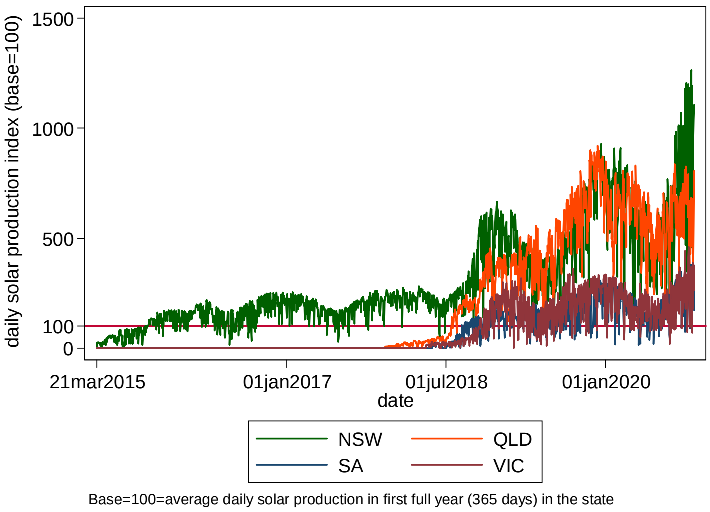

Figure 2: Daily solar generation index in each state

2018 and almost four-fold between 2018 and 2020, whilst wind generation has also increased around five-fold in a much longer time span (from 2009 to 2017). Wind generation exhibits a different pattern during the day, with high generation levels during the afternoon and night. Interestingly, when solar generation is at its maximum level (around midday), wind generation is at its lowest.

With this sharp increase in renewable generation, the overall weight of renewables in total generation is now significant. As Figure 7 shows, at most (during the day) wind generation accounts for just over 11% of total generation in 2020, whilst solar generation accounts for just over 9% - although, as mentioned above, their respective peaks occur at different times of the day. Naturally, these weights are yearly averages for the whole NEM: in our sample period, the maximum weight that wind (solar) had in total generation in a specific half hour was 23.7% (17.7%).[17]

The evolution of electricity prices in the NEM can be seen in Figure 8. First, in all states, there has been a trend towards an increase of electricity prices for almost all half-hours during the day. Second, the pattern of prices during the day has shifted from having a single peak in mid-afternoon (around 16h-17h) towards a double (asymmetric) peak: one small peak early in the morning, around 6h, and another larger peak late in the afternoon, between 17h-19h (depending on each state). It is worth mentioning that a sharp price increase (across all half-hourly slots) was observed between 2016 and 2017 (with a reduction in 2018 and 2019, in most states except Victoria, which generally still left prices above 2016 levels). This was felt across states but to a much more significant extent in Victoria (where prices in 2019 actually increased relative to 2016), whilst in Tasmania the sharp increase was felt one year earlier, between 2015 and 2016.

Due to the nature of the NEM, with physical interconnection taking place between states, it

[17] Naturally, in specific regions, because of their larger relevance in solar or wind production, these weights are larger (and consequently lower in other regions where solar or wind have a lesser role).

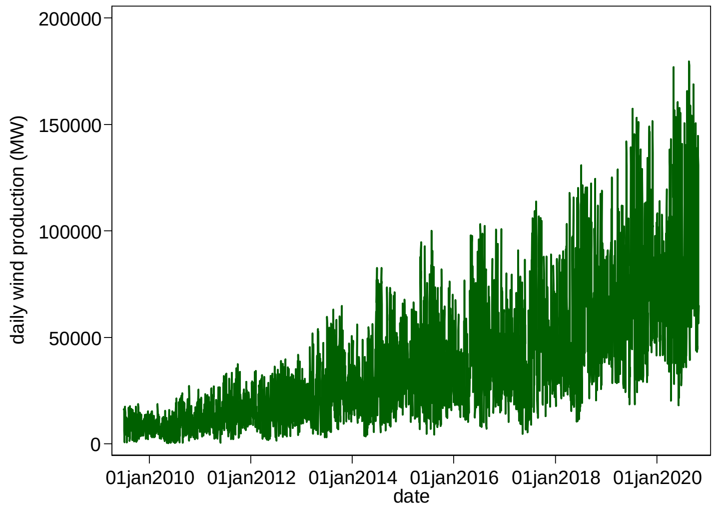

Figure 3: Daily wind generation (across states)

is interesting to note, in Table 1, the correlations in prices between interconnecting states (highlighted in bold). Price correlations are highest between the adjacent regions of Victoria and South Australia, and between New South Wales and Queensland. As discussed earlier, these correlations reflect the imbalance between supply and demand in each state, as well as the interconnector's capacity.

	NSW	QLD	SA	TAS	VIC
NSW	1				
QLD	**0.3126**	1			
SA	0.0668	0.0505	1		
TAS	0.036	0.0405	0.0425	1	
VIC	**0.1933**	0.0519	**0.5433**	**0.0429**	1

Table 1: Price correlations between states

4 Empirical approach

We are interested in finding the extent to which daily solar and wind production affects wholesale prices. As in Bushnell and Novan (2021), we are more interested in understanding the medium-run impact of renewable production, as opposed to short-run weather-driven changes in renewable output. Our focus is, therefore, on the relationship between renewable capacity and production (and its growth) on wholesale prices over a long period of time. Bushnell and Novan (2021) note that seasonal and day-to-day variation in solar and wind production is largely driven by exogenous factors, such as sunlight or wind speeds; therefore, one should not expect renewable production to endogenously fluctuate as a reaction to changes in wholesale prices. Naturally,

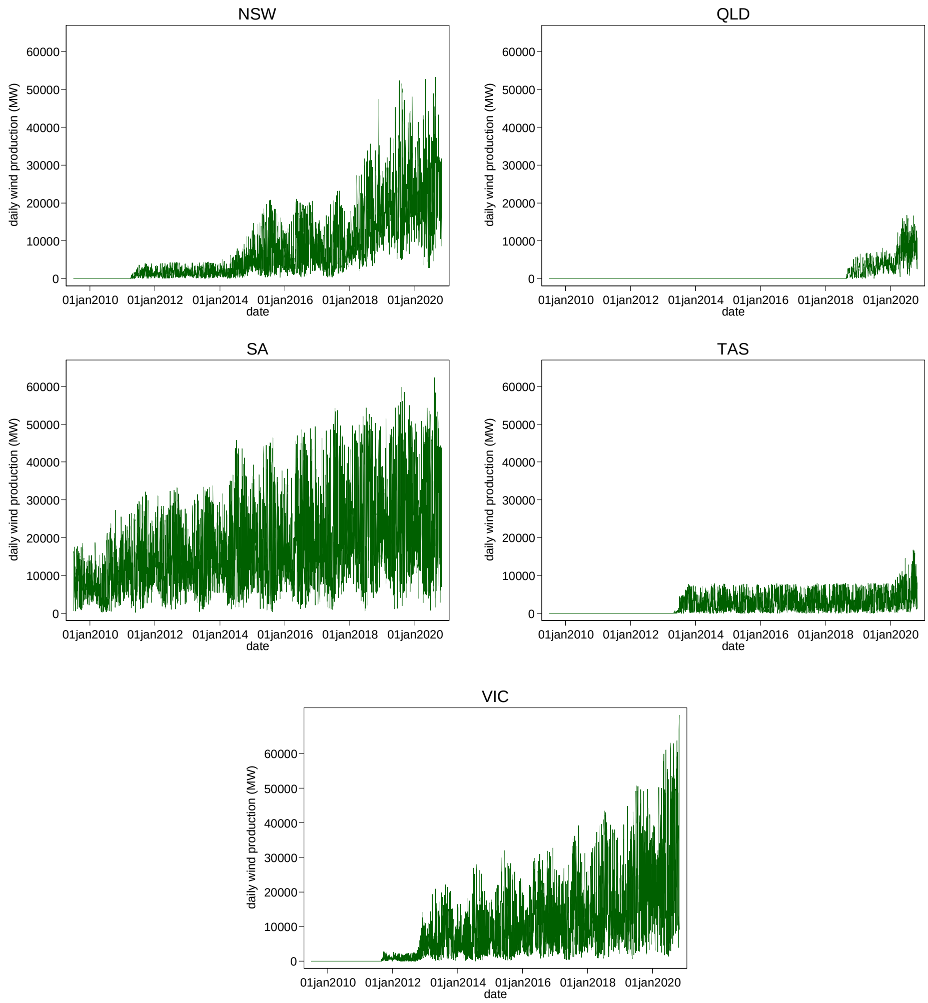

Figure 4: Daily wind generation in each state

seasonal and day-to-day factors, such as demand, must be controlled for in the analysis, as they may explain wholesale prices' fluctuations. By considering a long time horizon with significant growth in renewable capacity and production, we are able to understand how wholesale prices have responded to this.

Also following Bushnell and Novan (2021), we are interested in within-day price responses and not on average daily effects of renewables on wholesale prices. This allows for a more detailed understanding of how renewable production may impact wholesale prices across the day, and importantly the economics of non-renewable generators. As such, we exploit the half-hourly nature of wholesale price setting in the NEM. In doing so, we are able to identify differential impacts of renewable production (solar or wind) for every half-hour of the day and, therefore, to uncover the impact of renewables on the distribution of prices during the day.

Also, as in Bushnell and Novan (2021), we are more interested in price responses that do not

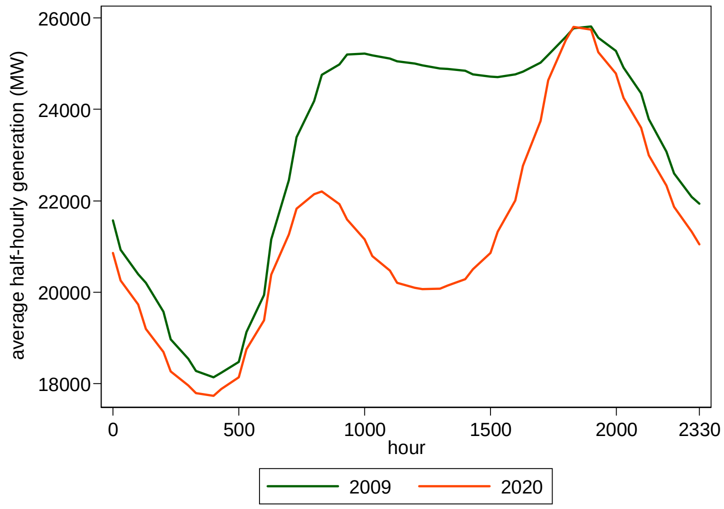

Figure 5: Average half-hourly generation: 2009 vs 2020

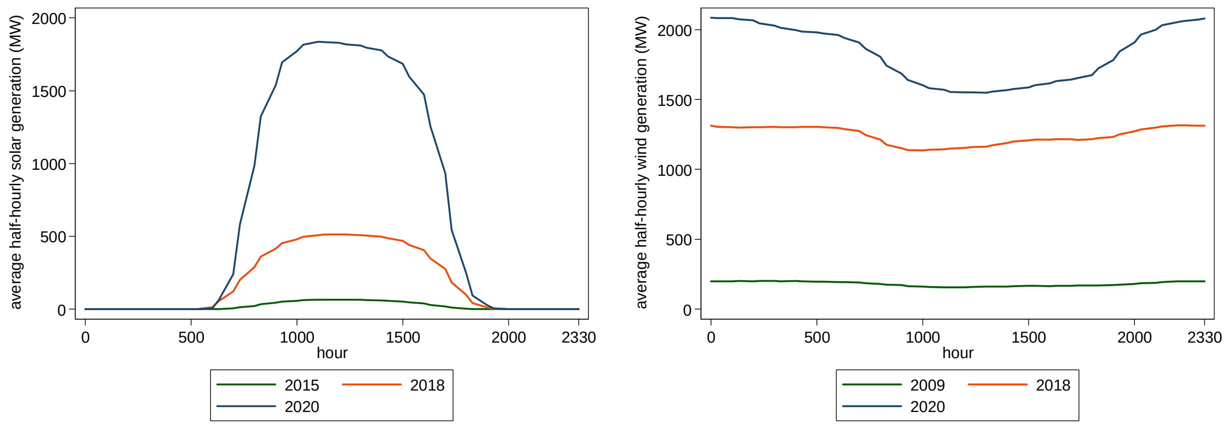

Figure 6: Average half-hourly solar (left) and wind (right) generation

necessarily reflect solely the contemporaneous renewable output levels. In practice, this implies that we are looking for the impact on the distribution of prices (during the day) in days with high solar or wind production vs. days with low solar or wind production. Bushnell and Novan (2021) note that not doing so would overly restrict the analysis: solar production, for example, only occurs during daylight. Using only contemporaneous solar production in the analysis would be tantamount to assuming that solar capacity only impacts wholesale prices during daylight hours - which may not necessarily be true for the reasons discussed in the Introduction (and indeed our results provide support for this). In our analysis, we control for demand or supply trends, as we explain in detail below.

In the NEM, prices are established on a half-hourly basis for each state. For every half hour

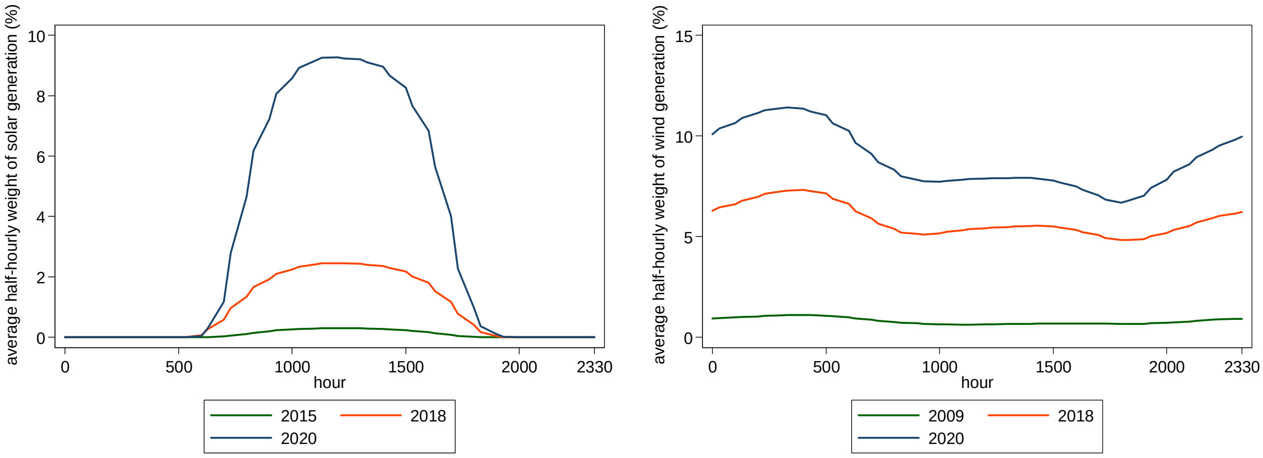

Figure 7: Average half-hourly weight of solar (left) and wind (right) generation

of each day (which we define as 'hh') within the period under analysis (2009-2020), the dataset contains wholesale prices for each state s. That is, we have a panel dataset for each half-hour: for each of the five Australian states, we have a time series of half-hourly prices. In this context, as our baseline regression, we estimate (OLS) the following equation separately for every half-hour of the day (20,695 observations for each half-hour):[18]

$$\begin{aligned} P_{hh,s} \quad = \quad & \alpha_{hh,s} + \beta_{hh}^{July2018}.July2018 + \beta_{hh}^{solar}.Solar_d + \beta_{hh}^{solarXJuly2018}.July2018.Solar_d + \\ & +\beta_{hh}^{wind}.Wind_d + \beta_{hh}^{windXJuly2018}.July2018.Wind_d + \\ & +\beta_{hh}^{ngas}.NaturalGas_{hh} + \beta_{hh}^{coal}.Coal_d + \beta_{hh}^{householdPV}.HouseholdPV_d + \boldsymbol{\gamma}_{hh}.\mathbf{X}_{hh,s} + \varepsilon_{hh} \end{aligned} \tag{1}$$

$Solar_d$ and $Wind_d$ are the total (across states) daily solar and wind-based (respectively) electricity inserted into the NEM in each day d of the sample period. These are the main variables of interest. Solar and wind generation are available for each state on a half-hourly basis. Therefore, these variables were constructed by summing the total solar (wind) production (i) across states, (ii) for every half-hour of day d. Given that a rather significant increase in solar production was observed around 10 July 2018 (see Figure 1), and to a lesser extent an increase in wind production as well, we have created the dummy variable $July2018$ which takes on the value of 1 from this date onwards. We have explored the possibility that this date has an impact on prices which extends beyond a price level shift (through coefficient $\beta_{hh}^{July2018}$). In particular, we also allow for the possibility that this particular date affects the marginal effects of daily solar and wind generation on price levels (through coefficients $\beta_{hh}^{solarXJuly2018}$ and $\beta_{hh}^{windXJuly2018}$). While the choice of 10 July

[18] For the very first day of our sample, we do not have information (across all five states) on the midnight half-hourly slot. Therefore, for this particular slot, the number of observations is 20,690.

2018 to define the dummy variable was driven by the data, we note that the sharp increases in wind and solar generation from 2018 onwards was also noted by the regulator (Australian Energy Regulator, 2021).

The variable $\alpha_{hh,s}$ is a dummy variable for each state and captures possible state-specific (fixed) effects on prices. $Naturalgas$ is the price of natural gas. We have used the Declared Wholesale Gas Market (DWGM) price which is available on an intra-day basis in 5 schedule intervals. We have therefore matched the price of each schedule interval in each day with the respective half-hour/day in our dataset. $Coal$ is the price of coal. As the daily price of coal we used the ICE (Intercontinental Exchange) Newcastle Coal price – the price of thermal coal exported out of the port of Newcastle. It is the price benchmark for seaborne thermal coal in the Asia-Pacific region. The data was sourced from SS&P Capital IQ. Finally, we have also included in our regression the total PV electricity generation by households ($HouseholdPV$). This data is available in half-hourly intervals in each of the five states, and it was obtained from the Australian Energy Market Commission. In line with what we have done regarding solar production, this variable aggregates total household PV generation in each day across all five states.

The vector $\mathbf{X}_{hh,s}$ includes several other explanatory variables: $XD_{hh,s}$ is the excess demand for electricity in half-hour hh in state s, that is, the difference, in that half-hour, between state s's total demand and its own electricity production. This variable essentially captures the 'net needs' for electricity in state s which cannot be met by own production. In practice, a positive value of $XD_{hh,s}$ means that state s in half-hour hh needs to 'import' electricity generated from other states and, therefore, use the interconnectors. Because the latter typically have limited capacity this variable attempts to capture potential price impacts of this interconnection limitation. TG_{hh} is the total electricity production in half-hour hh across all states and captures possible long term trends in demand. CPI is the consumer price index, obtained from the Australian Bureau of Statistics on a quarterly basis (which we matched with the respective half-hour/day in our dataset), which controls for broader long term trends in prices. The variable *carbonprice* is a dummy variable which reflects the introduction, in Australia, of a carbon price of AU$23 per tonne between July 1st 2012 and July 17th 2014. Because this carbon price may feed through to wholesale prices, this dummy variable takes on the value of 1 for this period. The variable $post - Hazelwood$ is a dummy variable which takes on the value of 1 from 31 March 2017 onwards. Hazelwood is a large coal-based plant, whose closure could have had a significant impact in the NEM. We also account for possible weekday or month fixed effects through the use (respectively) of the dummy variables $weekday$ and $month$.

Given the nature of our data and the regression methodology we propose, there may exist correlation across states and across time. Regarding the latter, we report Newey-West standard errors with a 7 days lag in order to correct for serial correlation. Regarding the possible correlation across states, we do not model it explicitly. Instead, we use state-specific fixed effects and a variable

- excess demand - which captures the net electricity needs of a given state vis-a-vis other states. Given that prices for each state are simultaneously determined so as to match supply and demand continuously, taking constraints into account, excess demand is likely a main driver of a possible correlation across states.

As outlined above, we largely follow the econometric approach of Bushnell and Novan (2021). The main differences are: (i) we control not only for natural gas prices, as they do, but also for coal prices, because coal generation is very relevant in Australia; (ii) because of the nature of the NEM, which interconnects five states, we include state fixed effects as well as the excess demand variable to capture possible price effects of interconnection restrictions, whereas Bushnell and Novan (2021) focus only in the CAISO market in California; (iii) in addition to month fixed effects, we also include weekday fixed effects; (iv) we include the consumer price index to account for price trends which are not necessarily related to electricity; (v) we include the carbon price dummy variable, to reflect this specificity of the NEM during the period this carbon price was active; (vi) we do not include, as Bushnell and Novan (2021) a variable to capture hydroelectric potential, because around a third of Australia's hydroelectric capacity is pumped hydro; and (vii) we look into the marginal effects of daily solar and wind production in two different time periods - until 10 July 2018, which we characterise as an early development stage of solar generation, and after that date, corresponding to a more advanced development stage of utility-scale solar generation.

The main coefficients of interest are β_{hh}^{solar}, $\beta_{hh}^{solarXJuly2018}$, β_{hh}^{wind} and $\beta_{hh}^{windXJuly2018}$. These coefficients will provide an indication of the impact of solar and wind production (respectively) on the wholesale price of state s in half-hour hh. Concretely, these coefficients provide an indication (respectively) of the impact on wholesale prices in the NEM associated with an increase of 1 MW in the daily level of solar or wind electricity generation (before and after 10 July 2018).

5 Results

For our baseline regression, Figure 9 and Figure 10 display the 48 estimates (one for each half-hour, as well as the corresponding 95% confidence intervals using Newey-West standard errors) of β_{hh}^{solar} and β_{hh}^{wind} respectively, before and after 10 July 2018.[19] For the case of solar before 10 July 2018, note how most of the estimated coefficients are positive throughout the day, although they are not statistically significant during many day periods, e.g. 8h30-10h30 or 20h-21h30. In order to gauge the magnitude of these effects, consider 12h00: the coefficient estimate is 0.00423, which suggests that an additional 1GW in daily solar generation increases wholesale prices in each state in that half-hour by AU$4.23/MWh. Rather importantly, we find no evidence of a negative impact of solar production on wholesale prices: although some of the coefficient estimates are negative during the

[19] For solar (wind), before 10 July 2018, the coefficient of interest is β_{hh}^{solar} (β_{hh}^{wind}); after 10 July 2018, the coefficient of interest results from the sum of β_{hh}^{solar} and $\beta_{hh}^{solarXJuly2018}$ (β_{hh}^{wind} and $\beta_{hh}^{windXJuly2018}$).

afternoon, they are not statistically significant. This result is only partly consistent with that obtained by Bushnell and Novan (2021): they find a positive coefficient in the early morning (6h-8h) and in the late afternoon (19h-20h), but a negative coefficient during the day (9h-18h), which suggests a merit order-type effect during most of the sunlight hours. By contrast, our results suggest, at best, an insignificant impact on prices during a part of the day (13h00-21h30) and a positive effect for (almost all of) the rest of the day. After 10 July 2018, the results are considerably different: most of the coefficient estimates are either negative and statistically significant (for most half-hour slots between 19h30-4h00 and 7h00-13h00) or statistically insignificant (4h30-6h30 and all but one half-hour slot between 13h30-19h00). Clearly, this is more consistent with the merit-order effect, although it still does not emerge in as visible a way during daylight hours as in Bushnell and Novan (2021).

For the case of wind, the results are different. Before 10 July 2018, for most of the day, the coefficient is negative and statistically significant. The exception is, again, the afternoon: from 14h-21h00, the coefficient is not statistically significant at the 5% significance level. Consider 12h00: the coefficient estimate is -0.00027, which suggests that an additional 1GW in daily wind generation decreases wholesale prices in each state in that half-hour by AU$0.27/MWh. Interestingly, for the case of wind, with the exception of the afternoon, we do find some support for a merit order-type effect. This is also consistent with the results of Bushnell and Novan (2021), who find a negative coefficient for most of the day. In addition, Bushnell and Novan (2021) provide a possible explanation for our findings during the afternoon period: wind production is higher, on average in the early morning and late night hours, which means that an additional 1GW of wind production would most likely materialise in those periods. This could explain why the coefficient is statistically insignificant during the afternoon hours, because this is when wind production is its lowest level (see Figure 6). This is consistent with the diurnal wind patterns at numerous locations, which typically dip during the afternoon. Unlike what we observe for solar production, there are very few changes in the marginal effects of wind production after 10 July 2018 - if anything, the coefficient estimates are slightly more negative than before 10 July 2018.

5.1 Comparison with the merit order effects literature

The focus of our analysis has been on measuring the impact of total daily solar and wind generation on wholesale prices throughout the day, including when there is no solar or wind generation. We argue that this captures the medium-run impact of the increased penetration of solar and wind on market dynamics. It is worth, however, comparing our results with that of the merit order effects literature, which focuses on the impact of solar and wind at the time of generation.

As discussed in the introduction, Csereklyei, Qu and Ancev (2019), using largely the same data as we do for the NEM, estimate the contemporaneous merit order effect.[20] These authors find

[20] Earlier studies include Cludius et al. (2014), Cutler et al.(2011); Forrest and MacGill (2013); McConnell et al.

that an extra GW of wind generation decreases the wholesale price by $11/MWh at the time of generation, while solar decreases by $14/MWh.[21] In contrast, and focusing on the post-July 2018 data, as shown in Figure 9, we find that the impact of an extra GW of total daily solar generation is mostly close to zero throughout the entire day, and results in a decrease of around $2/MWh at 17h00 and an increase of around $2/MWh after the sun sets at 18h30. For wind, the highest impact we estimate is 41cents/MWh at 2:30 am before July 2018, and 50 cents per MWh after July 2018 at 18h30. While these numbers are not directly comparable – the merit order effect measures the impact of an extra 1 GW of solar or wind at a particular half hour and we measure the impact of an extra 1 GW of total daily production, our results suggest that the market-wide impact of solar and wind are more complex and nuanced than simply assuming that the entry of lower marginal cost suppliers will result in lower market prices.

5.2 The impact of other variables of interest

Figure 11 displays the impact on wholesale prices of an increase in the natural gas price (top panel) and in the coal price (bottom panel). Our results are consistent with those of Bushnell and Novan (2021), who find a positive impact of the natural gas price on wholesale prices. In addition, the 'profile' of these impacts is remarkably similar, with higher impacts during the peak hours. This is not a surprising result. Gas plants often set the price in the NEM (19% of the time in Q1 2020) and gas generation is needed to meet demand at peak hours.[22] Thus, a rise in gas prices, and indeed, a rise in gas turbine output, is expected to be associated with rising wholesale electricity prices.

The impact of daily coal prices on wholesale electricity prices, however, is counterintuitive. We find that coal prices have a negative impact on wholesale prices during the day. We conjecture that we may be capturing a strategic effect. Many coal generators are not exposed to coal prices. They either own adjacent coal mines or have long-term contracts with nearby mines. Therefore, when they are called to generate during peak hours, they can shadow price gas generators to ensure that they are dispatched, resulting in them often setting the market price and inducing small reductions in the wholesale price (compared to the prices that would have been set by gas generators).

Figure 12 displays the impact of household PV generation on wholesale market prices. For most of the day, the coefficient estimate is either negative and statistically significant or statistically insignificant. There are only three half-hourly slots for which the estimate is positive and statistically significant: 17h, 17h30 and 19h30. Recall that household PV generation effectively 'subtracts' electricity traded in the market, that is, increases in household PV generation imply (all else equal) that less electricity generation needs to be traded in the market. Therefore, our results suggest that increases in (daily) household PV generation ultimately have either no effect or

(2013); and Simhauser (2018).

[21] Forrest and MacGill (2013) estimate that an extra 1 GW of wind generation at a particular half hour resulted in a price reduction of $8.05/MWh for South Australia and of $2.73/MWh for Victoria in the period of 2009–2011.

[22] See https://aemo.com.au/-/media/files/major-publications/qed/2021/q1-report.pdf?la=en.

a small negative effect on wholesale prices in the NEM. This result is very similar to that obtained for daily solar production after 10 July 2018.

Two other results are worthy of further discussion. First, we obtain estimates of the impact of the carbon price on each half-hourly slot. All the coefficient estimates are statistically significant (at the 1% level) and point towards an average (throughout the day) impact on wholesale prices of $19.5/MW. Second, the coefficient estimates of the Hazelwood coal plant closure are positive and significant during a large part of the day, with the most notable exception being 16h30-19h30, when they are not statistically significant. When significant (at the 5% level), the average coefficient estimate is $20.2/MW, that is, the plant closure led to a lasting increase in wholesale prices during a large part of the day.

5.3 Substitution effects between renewables and non-renewables

We go beyond the estimation of the impact of daily solar and wind generation on prices. We also look into possible substitution patterns between renewables and non-renewables that may help explain the observed price impacts. In order to do so, we reestimate equation (1) using as a dependent variable the half-hourly production of the most important sources of electricity in the NEM with the exception of solar and wind: in the period under analysis, the most relevant energy sources (excluding solar and wind) were black coal (56%), brown coal (25%), natural gas (9%) and hydro (8%). Together these four energy sources account for 98% of energy production excluding solar and wind.

Figure 13 presents the marginal effects of daily solar production on the half-hourly generation of black coal, brown coal, natural gas and hydro. Before 10 July 2018, an increase in daily solar production induces a reduction in natural gas generation (the strongest negative effect) and in brown coal generation (the second strongest negative effect). However, and interestingly, it contributes to an increase of black coal production and hydro. These effects hold pretty much across all hours of the day. This differs from Bushnell and Novan (2021), who find that during daylight hours, solar production effectively substitutes all other main energy sources. In Australia, this ‘substitution effect’ does not emerge - possibly because in this period solar production still has a low weight in total production. After 10 July 2018, we obtain a result that is more consistent with Bushnell and Novan (2021), suggesting that increases in daily solar production effectively substitute other energy sources (except natural gas) for almost all half-hours in the day. Notably, the impact of increases in daily solar production on black coal production is the most negative during daylight hours, suggesting that solar production is effectively ‘substituting’ black coal generation to a larger extent than other energy sources. The exception - natural gas - suggests that after 10 July 2018, solar and natural gas production are complements. This is more visible in the non-daylight hours, suggesting that increases in (daily) solar generation lead to an increase of natural gas production during that period.

However, it is important not to neglect the significance of brown coal plant closures (Northern Power Station, in 2016, and Hazelwood Power Station, in 2017). This led to a reduction in (low marginal cost) brown coal output. In addition, LNG exports commenced in 2015 and natural gas output in the NEM has decreased (McConnell and Sandiford, 2020). The combination of these two factors may explain the results of Figure 13: post-2018, black coal is the main energy source being curtailed when renewable generation starts, in a context of reduced levels of brown coal and natural gas generation.[23]

Figure 14 presents a very different picture for wind generation: either before or after 10 July 2018, wind generation effectively substitutes all other energy sources. During the night, when wind production is highest, the most 'displaced' energy source until 10 July 2018 was brown coal, followed by black coal; by contrast, after 10 July 2018, the most displaced energy source is black coal followed by natural gas. This result is consistent with Bushnell and Novan (2021), who find that when wind production is highest, thermal and net imports are the sources suffering greatest declines.

6 Conclusion

This paper examines the market-wide impact of renewable electricity generation - solar and wind - in Australia. Rather than looking for possible evidence of a contemporaneous merit order effect - a decrease in wholesale prices associated with the introduction of near-zero marginal cost renewable output in the system, which has largely been established in the literature (including in Australia) -, our focus is on the medium-run impact of renewables as measured by total daily generation. Indeed, an intricate relationship exists between the generation of firm dispatchable electricity by non-renewable generators (e.g., gas or coal) and the intermittent total daily production of renewables which is unlikely to be captured by looking solely at contemporaneous effects. In addition, precisely because of this intermittency in renewable production, such a relationship between different sources of generation may be different at different times of the day. Our results shed some light on this issue.

First, daily solar production has a positive (although not always statistically significant) impact on wholesale prices throughout most of the day until July 2018 - a period in which there is low penetration of utility-scale generation. This is in stark contrast with the merit order effect, but our belief is that this result simply reflects the complex relationship that exists between the production of different types of electricity and wholesale prices during that early stage with a lower penetration of solar. Our results may be pointing towards the existence of system-wide costs of increased solar penetration, that is, the increased costs associated with the additional need to ramp up the generation of dispatchable electricity as a result of a reduction in solar generation, and the higher

[23] We thank a referee for this observation.

ratio of capacity to generation associated with renewables. After July 2018, and the substantive increase in solar generation, we obtain evidence that is more consistent with the merit order effect, although (unsurprisingly) the impact of solar on wholesale prices is of several orders of magnitude lower than that predicted in the merit order effects literature, and we still find that an increase in total daily generation leads to an increase in electricity prices at 18h30 after the sun sets.

Another contributing factor to our results could be associated with the impact of large inflexible coal plant closures. As Simshauser (2020) notes, such closures may reverse short run merit order effects. This could help explain the different results obtained for the pre- and post-2018 periods - although, as we argue above, we believe these differences not to depend solely on such plant closures.[24]

Second, throughout our sample period (2009-2020), the impact of daily wind production on wholesale prices is more consistent with the merit order effect literature: it is small but negative for most time of the day. We conjecture that wind generates less system-wide costs because given its geographic dispersion, it is a closer substitute to firm dispatchable electricity across the NEM. As such, because of its near zero-marginal cost, its impact on wholesale prices is negative.

At the moment, our analysis is carried out in a very aggregate way. More concretely, although we account for possible price differences in each of Australia's five regions (both through fixed effects as well as through imbalances between generation and demand in each region), we did not examine possible differential effects of solar and wind generation across regions. Each region has a different mix of solar/wind generation vis-a-vis non-renewable generation and, as such, it may be that the impact of solar and wind in each region is indeed different. This is left for future research.

Moreover, although we have already identified the existence of a subtle and complex relationship between the generation of electricity from different sources, we have yet to explore this relationship in depth. In particular, due to the nature of the NEM, wholesale prices can be used as signals for investment. In the future, we intend to look more closely at the possible impact of our results on different generators' profitability and, consequently, on the investment incentives for each type of electricity generation. In that context, this paper is the first step within a larger research agenda looking into these issues.

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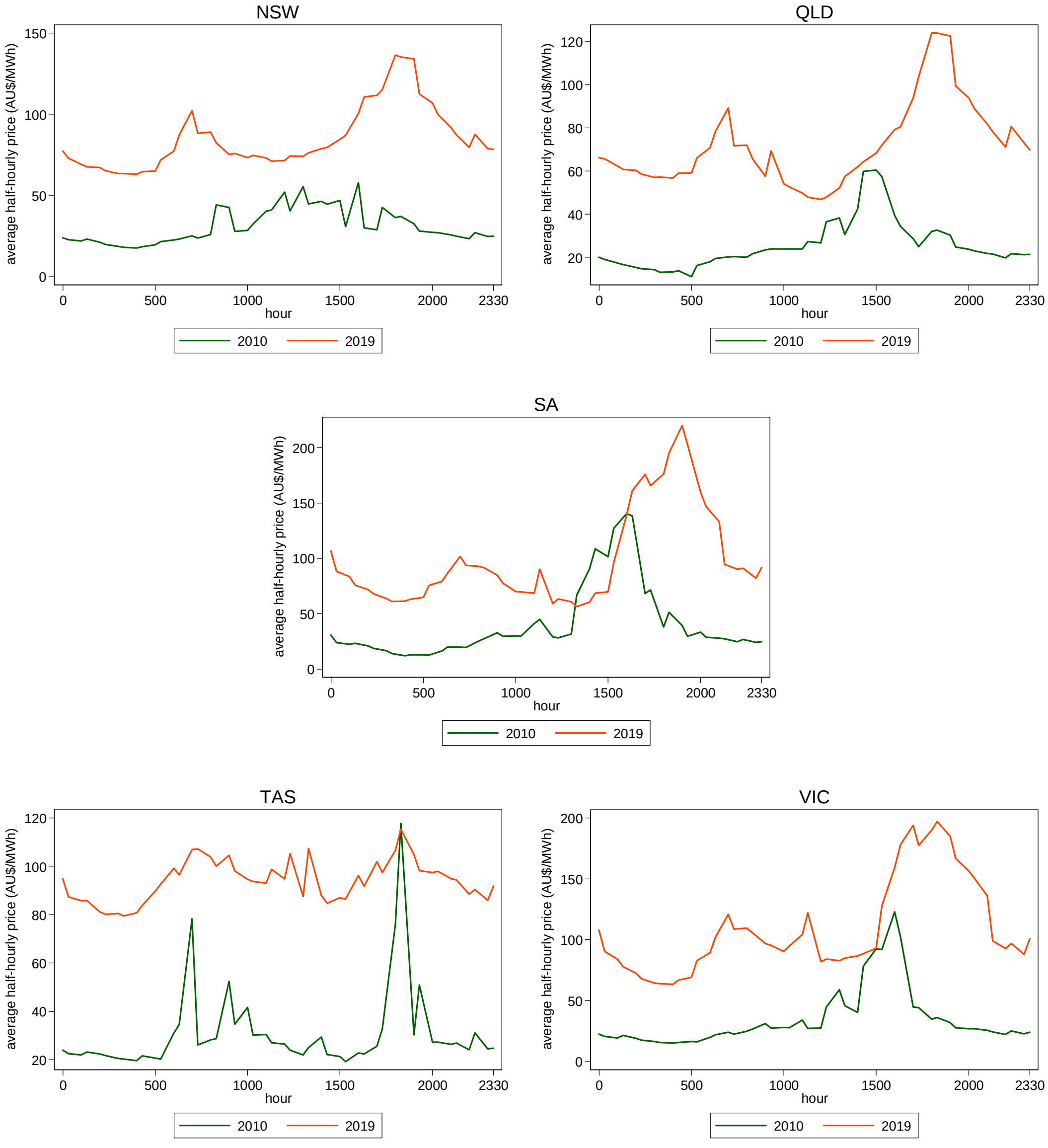

Figure 8: Average half-hourly price in each state: 2010 vs. 2019

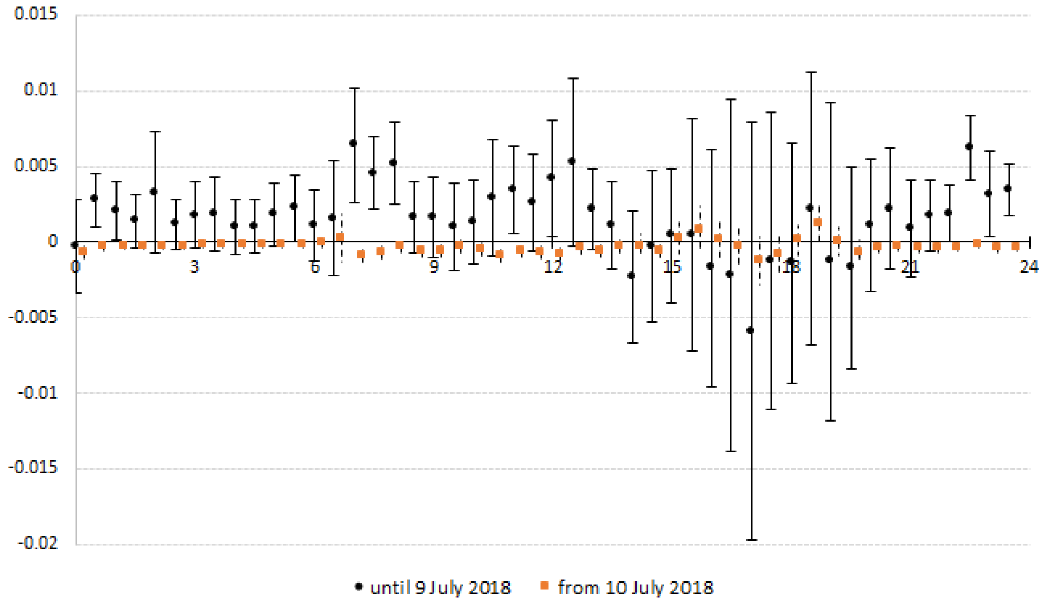

Figure 9: Baseline model: coefficient estimates of β_{hh}^{solar} (before and after 10 July 2018)

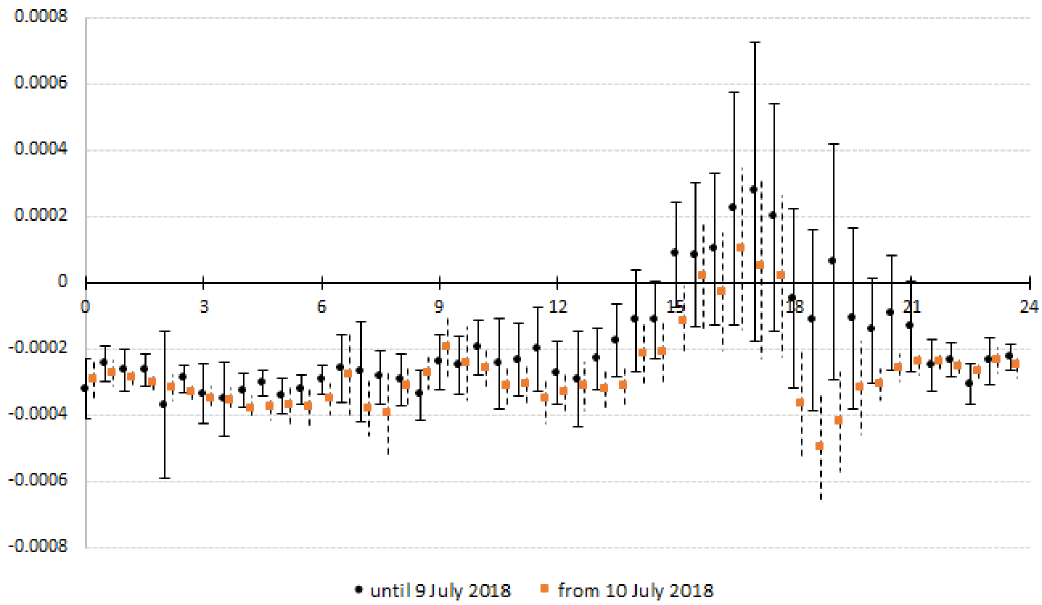

Figure 10: Baseline model: coefficient estimates of β_{hh}^{wind} (before and after 10 July 2018)

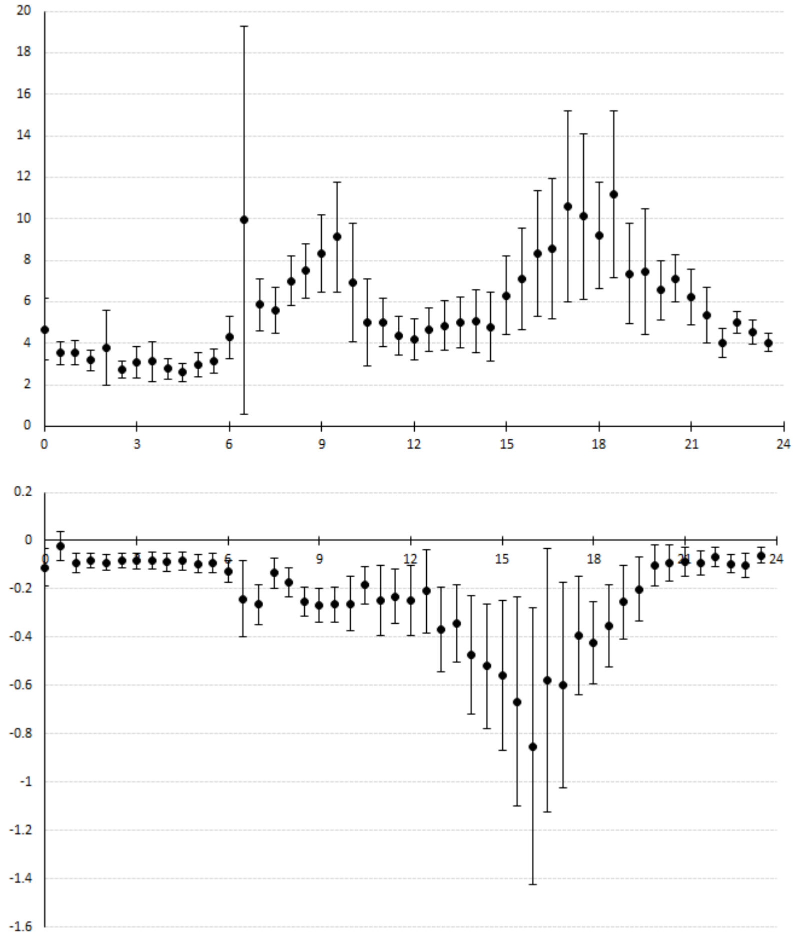

Figure 11: Baseline model: coefficient estimates of $naturalgas_{hh}$ (top) and $coal_d$ (bottom)

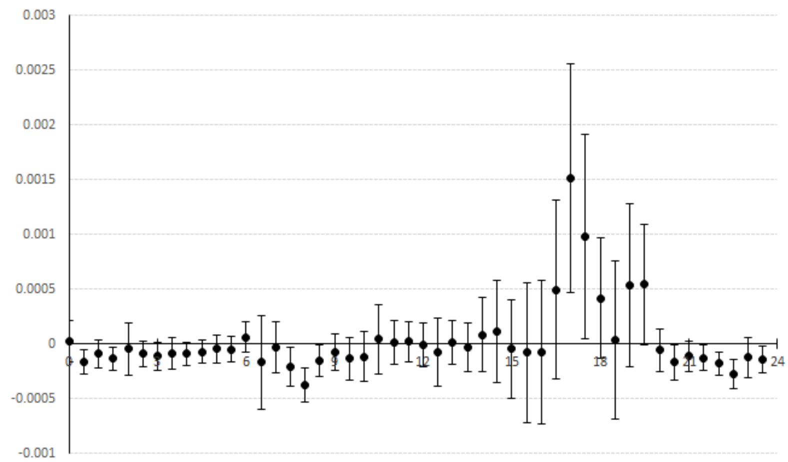

Figure 12: Baseline model: coefficient estimates of $householdPV_{hh}$

Figure 13: Change in output for each energy source per MW of daily solar production: before 10 July 2018 (above) and after 10 July 2018 (below)

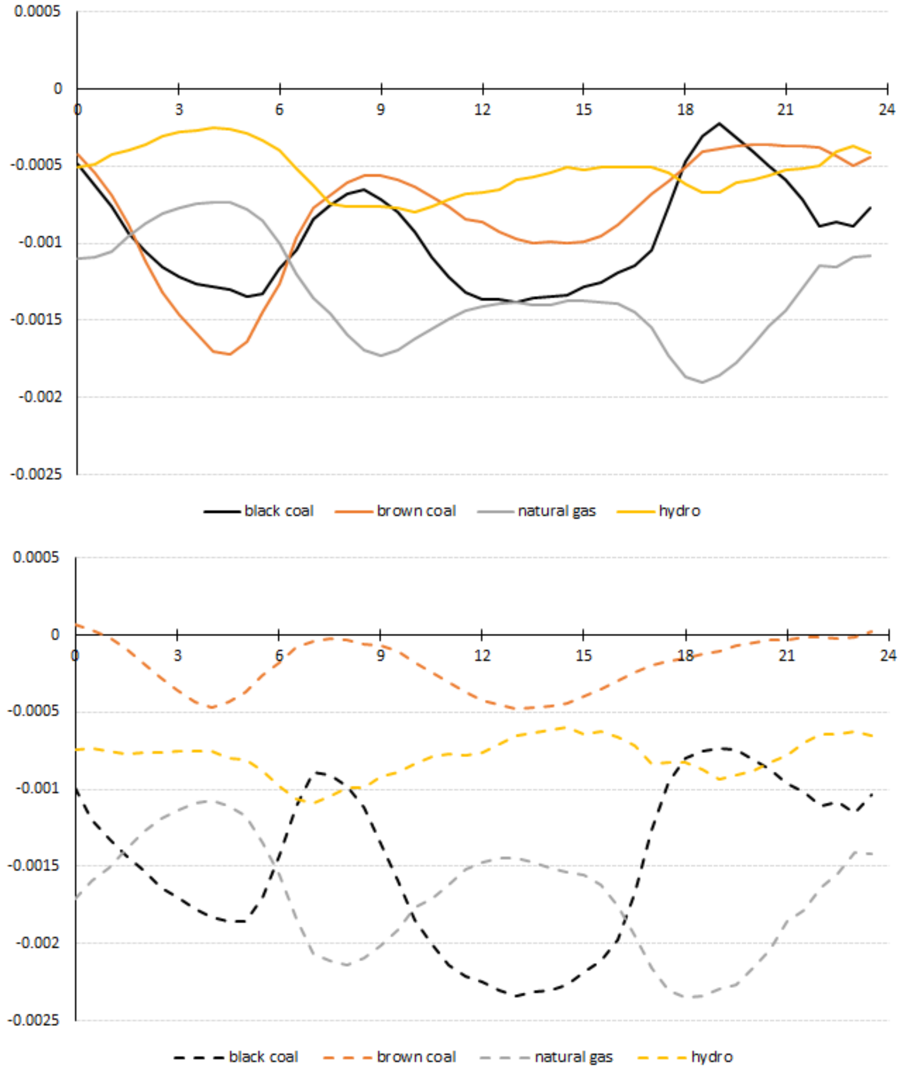

Figure 14: Change in output for each energy source per MW of daily wind production: before 10 July 2018 (above) and after 10 July 2018 (below)