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Abstract

This study assesses the impact of the Australian Carbon Pricing Mechanism (CPM) on electricity prices in the National Electricity Market (NEM). An econometric model is designed to examine the influence of short-run marginal costs, electricity demand and emission intensities on carbon pass-through rates on spot electricity prices. The developed model also allows to capture the non-linear relationship between spot electricity prices and demand that has typically been suggested in the literature. Our sample period from July 2009 to June 2016 allows us to analyse three different sub-periods in order to quantify pass-through effects: the period before the tax (July 2009 – June 2012), the period when the carbon tax was effective (July 2012 – June 2014) as well as a post-tax period after the repeal of the CPM (July 2014 – June 2016). Therefore, it allows a comprehensive evaluation of the effect of carbon pricing on the Australian electricity spot market. Our results demonstrate a high degree of carbon costs pass-through across the considered markets with the increase in electricity prices typically exceeding carbon costs in particular for the markets in New South Wales, Queensland and South Australia. The estimated carbon pass-through rates seem to be inversely related to emission intensities for each of the regions: they were relatively low for Victoria that is characterised by electricity generation from fossil fuels and high emission intensities, while they were the highest for South Australia, a market with the lowest emission intensities and a higher share of renewable energy generation. We also find that for most markets, emission intensities were only reduced by a relatively small margin during the tax period and that electricity prices have never reverted back to their pre-tax levels after the repeal of the tax.

Keywords: Electricity Prices, Carbon Tax; Carbon Pass-Through Rates, Climate Policy

JEL classifications: C22, C51, D22, G18, L94

1. Introduction

On 10 November 2016, Australia ratified the Paris Agreement and the Doha Amendment to the Kyoto Protocol to reinforce its commitment to action on climate change. Under the Paris Agreement, Australia has an emissions reduction target of 26 to 28 per cent below 2005 levels by 2030. This would require the intensity of carbon emissions for the economy to fall by around 65 per cent, and the emissions per capita being halved. It appears that in order to meet these climate commitments, the implementation of a cap and trade scheme for electricity generators could be reconsidered by the Australian government as part of the 2017 Climate Change Review. Hence, this paper investigates the impact of the previous Australian Government's Carbon Pricing Mechanism (CPM) on wholesale electricity prices.

In 2011, the CPM was introduced as a key element of a Climate Change Plan by the then Labor Government in order to reduce greenhouse gas emissions to 5 per cent below 2000 levels by 2020. The CPM's aim was to incentivise Australia's largest emitters to enhance energy efficiency and invest in sustainable energy. Australia's emissions per unit of GDP are around twice that of the OECD (IEA, 2010), mainly due to a high share of electricity generation from fossil fuels. Stationary energy in Australia is the largest source of CO_2, contributing to approximately half of total emissions (Treasury, 2011). Two thirds of stationary energy comes from electricity generation, thus accounting for 35 per cent of all CO_2 emissions in Australia. With regards to the Australian electricity market, the aim of the CPM was to increase the cost of fossil fuel combustions and encourage generators to reduce coal-fired generation and move more towards gas and renewable sources of energy generation.[1] The CPM became effective on 1 July 2012, and during its introductory phase the price of uncapped permits was fixed at $23 per tonne of CO2e for the financial year 2012-2013, while the permit price[2] was planned to increase to $25.40/tCO2e for the financial year 2014-15 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.

[1] Approximately 85% of Australia's electricity consumption is fuelled by coal-fired electricity generation with relatively high emission intensities. Gas-fired plants account for around 8% of electricity generated, while less than 6% of output is from hydroelectric generation (ABARES, 2011).

[2] Due to the fact that there was unlimited availability of permits at a fixed price for firms during the introductory phase, the CPM was commonly dubbed a "carbon tax", which is why this term is used in the present paper.

This study develops a framework to measure carbon cost pass-through rates (CPTRs) on electricity prices by using volume-weighted daily spot prices for four major regional markets in the Australian National Electricity Market (NEM): New South Wales (NSW), Queensland (QLD), Victoria (VIC), and South Australia (SA). We adopt an econometric approach to examine the influence of carbon costs, demand and emission intensities on electricity prices to answer the question to what extent the observed increase in wholesale electricity spot prices during the tax period could be attributed to the cost of carbon. This paper also analyses the impact of the CPM after the repeal of the tax, and investigates how much of the tax saving is passed on to consumers through lower wholesale electricity prices after the tax was repealed.

Following Sijm et al. (2008) and Nazifi (2016), we define the carbon pass-through rate as the ratio of change in the price of electricity to the change in marginal costs due to the carbon tax. Similarly, Nelson et al. (2012) and Huisman and Kilic (2015) define the carbon pass-through rate as the proportion of carbon prices passed through to electricity prices. Clearly, such an analysis is also related to the question of what proportion of the higher costs incurred by consumers in the form of higher electricity prices is attributable to the carbon tax.

A thorough empirical assessment of the impact of the CPM on wholesale electricity spot prices may also help to reveal the effectiveness of the carbon tax in encouraging the substitution of fossil fuel power generation with technologies that are less low-carbon-intensive. Thus, analysing emission intensities and CPTRs also allows us to address the impacts of a carbon price on the key participants in the NEM with regards to their attempts to curb the growth of carbon emissions. A higher rate of CPTR is indicative of consumers bearing a large proportion of the tax, while a lower rate shows that the tax incidence would be internally absorbed to a significant extent by generators, subsequently altering the marginal cost relativities, changing the competitive landscape and potentially further encouraging the use of carbon-efficient technologies.[3]

[3] It is worth mentioning that relative fuel price changes or price signals are only one of a number of elements that could enhance the competitiveness of low-carbon technologies to generate electricity. Any discussion of a technological shift would need to take into consideration many other factors that may influence switching activity, such as the variability in plant efficiency, technical factors, environmental regulations and policies (for instance, the Renewable Energy Target scheme) and other specificities of the power market, to fully investigate this change and the extent to which each of these factors is likely to contribute to this shift (IEA, 2013). The current paper statistically measures the carbon costs pass-through rates to see if the CPM could further incentivise generators to switch to carbon-efficient technologies and thereby assess the CPM's likely effectiveness in terms of its contribution to lowering greenhouse gas emissions. The present analysis applies

There have been numerous studies investigating the impact of the price of European allowances (EUAs) on electricity prices in the European Union (EU).[4] Most of these studies find that carbon prices have a significant impact on electricity markets in the EU, and typically present pass-through rates ranging from 30% up to even more than 100% (see, for example, Gulli and Chernyavska, 2013). Although there appears to be sufficient evidence to conclude that carbon prices affect European electricity prices, there is a lack of empirical studies investigating the impact of the CPM on electricity spot prices in Australia. As pointed out by Nelson et al. (2012), a number of modelling and simulation studies on the potential impacts on electricity prices from the introduction of a carbon tax, and the broader economic impacts related to the introduction of an emission trading scheme, have been conducted before the actual tax was implemented. These studies were undertaken mainly by leading Australian economic modelling firms, using techniques such as linear programming, general equilibrium models or dynamic partial equilibrium analysis. Interestingly, obtained results were rather inconsistent in their estimation of carbon pass-through rates, providing estimates for pass-through rates ranging from 17% (McLennan Magasanik Associates, 2008); 100% (ROAM, 2008); 128% in the Garnaut Review (Garnaut, 2008); and up to more than 393% by Simshauser and Doan (2009).

Recently there have also been a few empirical studies on the pass-through rate of the CPM on wholesale electricity prices in the Australian NEM. For instance, using monthly data on average spot prices in different regions, Nazifi (2016) investigates the interaction between a carbon price signal and wholesale electricity spot prices within the NEM, for the first 15 months of the tax until October 2013. Her findings suggest that carbon costs were indeed fully passed on to wholesale electricity spot prices, resulting in higher electricity prices for

daily observations for the volume-weighted average emission intensity for each state to calculate the costs of the carbon required to generate one MWh of electricity in order to estimate the CPTRs. However, in order to analyse precisely whether this technological shift has occurred, further analysis based on average intensity data is needed. According to existing statistics, after the introduction of the CPM the emission of CO_2 from electricity within the NEM fell (by approximately 7.7%), however, several studies have reported that this reduction can be mainly attributed to factors unrelated to the carbon tax (see, for detailed information, Frontier Economics (2013) and Quarterly Update of Australia's National Greenhouse Gas Inventory (2013)). For example, the shut-down of a substantial amount of brown coal generation in Victoria due to a mine flood has led to a significant reduction in CO_2 emissions in this sector (Frontier Economics, 2013). Furthermore, the Energy Users Association of Australia (EUAA) has reported that no evidence could be found to support the claim that the CPM has lowered emissions in stationary energy to any meaningful extent (EUAA, 2013).

[4] See, for example, Linares et al. (2006); Sijm et al. (2006); Reinaud (2007); Nordic Council of Ministers (2008); Sijm et al. (2008); Kara et al. (2008); Fell (2008); Fezzi and Bunn(2009); Nazifi and Milunovich (2010); Gronwald et al. (2011); Sijm et al. (2012); Jouvet and Solier (2013); Huisman and Kilic (2015) and Kanamura (2016).

consumers and potential windfall profits for some generators. Apergis and Lau (2015) examine the role of climate policy uncertainties in the Australian electricity market and suggest that the NEM can be described as less stable in comparison to other electricity markets around the world. The authors suggest that in the NEM there is also a relatively high degree of market power exercised by generators across regional markets. This might have significant consequences for the effectiveness of carbon dioxide mitigating policies, especially when there is uncertainty as to whether or not the planned environmental policy is put in place for the lifespan of undertaken investments. O'Gorman and Jotzo (2014) investigate the impact of the carbon tax on electricity demand, supply and emissions during the period 1 July 2012 to 30 June 2014, namely the period when the tax was in place. Their findings suggest that during the considered period, electricity demand in the NEM declined by 3.8%, while at the same time the emissions intensity of electricity supply was also reduced by almost 5%. Overall this has led to a reduction in emissions by roughly 8% compared to the two-year period before the carbon price. The authors also suggest that the carbon price markedly changed relative costs between different types of power plants, leading to emissions-intensive generators such as brown coal and black coal reducing their output. They conclude that the carbon tax has worked as expected in terms of its short-term impacts, while its effect on investment in power generation assets has probably been limited, due to political uncertainty about the continuation of the CPM.

Our study contributes to the literature in several dimensions. First, we extend the relatively sparse literature on the impact of the Australian CPM on wholesale spot electricity prices. We measure the actual impact of the CPM on electricity spot prices in Australia by applying an econometric framework and using empirical data that includes data on spot electricity prices, demand, fuel costs and emission intensities from a relatively long sample period. Therefore, in contrast to the few existing studies in Australia that address a similar issue by using simulation analysis (McLennan Magasanik Associates, 2008; ROAM, 2008; Simshauser and Doan, 2009), this paper adopts an empirical approach in order to estimate actual CPTRs in the NEM. Furthermore, this study is conducted in an almost unique environment to examine the impact of both the introduction and the repeal of the carbon tax on wholesale electricity prices due to the facts that, *i*) it considers regional markets where generation is almost entirely based on brown coal, black coal and gas fired power plants (AEMO, 2016); *ii*) there was no significant increase in using renewable energy for most of regional markets between

2009 and 2016 apart from South Australia and Tasmania (AEMO, 2016); and *iii*) there is hardly any demand-side elasticity in Australia since the NEM operates as a gross pool market which means all electricity has to be traded through the exchange (i.e. there are no bilateral contracts).

Another contribution of our analysis is from the development of a framework that examines carbon pass-through rates over a long sample. This includes the period before the carbon tax became effective, the period of its lifetime from July 2012 to June 2014, as well as the period after the tax was repealed from July 2104 to June 2016. While previous studies in the Australian context have been restricted to shorter sample periods, we examine a significantly longer time period of spot prices that allows us to gain additional insights into the impact of the introduction and the repeal of the tax on wholesale electricity prices. To the best of our knowledge, we provide the first study to examine carbon pass-through rates on spot prices taking into account such a long sample period.

Moreover, to improve the estimates of the CPTRs, in our econometric model specification we relax some of the assumptions made by previous studies. Existing studies in Australia are restricted by some assumptions in estimating the CPTRs, which might affect the robustness of the obtained results. For instance, Nazifi (2016) considers a model based on assumptions such as a fixed fuel efficiency rate, no changes in technology, and setting electricity prices by a single technology during the observation period. However, in reality, during even a day, prices can be set by a variety of technologies with different fuel efficiencies depending on a number of factors such as the specific load hour, dynamic interaction between fuel and carbon prices, the outage schedule of the generation, and so on. Due to the assumption of a fixed efficiency rate, changes in power prices cannot be attributed to changes in technology which could result in over/underestimation of CPTRs. Thus, in this paper, to improve the robustness of the model, we take into consideration possible technological changes in the generation of power while we calculate the fuel costs of this generation by using half-hourly electricity demand and short-run marginal costs (SRMC) for each individual power generation instalment in the NEM (detailed discussion can be found in Section 3 and 4). Using data on half-hourly demand for each market, we simulate the dispatch of individual power plants to calculate a proxy for half-hourly fuel costs.

Furthermore, in order to capture the typically nonlinear relationship between electricity demand and spot prices, we also allow for a polynomial relationship between these variables instead of applying a linear model only. As such, this study undertakes one of the first evaluations of the CPM and fills a vital research gap around design issues in environmental markets in Australia.

Overall, our results clearly indicate that the implementation of the CPM had a significant impact on wholesale electricity spot prices in the NEM. The extent of the estimated CPTRs for the considered markets reveal that the incidence of taxation is typically borne by consumers rather than generators. Interestingly, the carbon pass-through rates seem to be inversely related to emission intensities for each of the regions and were relatively low for the market with the highest emission intensity (VIC), while they were the highest for the market with the lowest emission intensities and a higher share of renewable energy generation (SA). Furthermore, our findings show that spot electricity prices have not reverted to their pre-tax levels after the tax was repealed, possibly leading to carbon-induced profit effects (so-called "windfall profits")[5] for some generators.[6] These findings could be crucial for policy-makers to make better-informed regulatory decisions when designing new climate policies to reduce domestic emissions and support international efforts and, more specifically, if a transition to an emission trading scheme will occur in the near future.

The remainder of the paper is organized as follows. In Section 2 we provide a brief overview of the Australian NEM, while Section 3 introduces our applied econometric framework, including the model specification and the applied methodology to empirically assess the actual impact of the carbon tax. In Section 4 we discuss the empirical results. In particular, we focus on the carbon pass-through rates in different regional markets across the NEM during

[5] While the conventional meaning of "windfall profits" refers to just the value of economic rent derived from some fixed asset such as free allowances, in this paper, in the context of a CPM and the power sector, the term "windfall profits" broadly refers to changes in the profits of existing power generators due to carbon-induced changes in power prices, production costs and sales volumes (Chen et al. 2008). For instance, if the power price is set by a coal-fired plant, given that the cost of the carbon is fully passed to the power price (while sales volumes do not change) some generators may benefit from the implementation of the CPM (depending on the fuel generation mix of their installations) as the increase in their revenue may exceed the increase in their costs. Furthermore, the availability of financial assistance to electricity generators under the Industry Assistance Programs (such as the provision of the free allocation of carbon units to eligible generators by the Australian government as discussed above) could increase the potential for windfall gains by generators.

[6] However, it is important to note that in this paper, due to the assumption of a fixed efficiency rate, changes in power prices cannot be attributed to changes in technology which could result in over/underestimation of CPTRs (a detailed discussion on this point can be found in Section 4). The impact of the CPM on possible technological changes in generating electricity is left for future research.

the implementation as well as the repeal of the tax. In Section 5 concludes and provides policy implications based on the obtained findings.

2. The National Electricity Market and Wholesale Electricity Prices

The National Electricity Market (NEM) is the major wholesale electricity spot market in Australia. Established in December 1998, the NEM contains one of the world's longest interconnected power systems incorporating approximately 40,000km of transmission lines and cables. The market operates across six states in eastern Australia and includes the regional markets in New South Wales (NSW), Queensland (QLD), South Australia (SA), Victoria (VIC) and Tasmania (TAS). The market is operated by the Australian Energy Market Operator (AEMO), who ensures the effective infrastructure for efficient transmission of power from generators to primarily local electricity distributors across the NEM network. For the financial year 2014-15, 336 registered generators in the NEM with a total installed capacity of 47641 MWh generated 194 TWh electricity, contributing to an annual turnover of 8.2 billion Australian Dollar (AUD) (AER, 2015).[7]

The NEM is operated as a real-time gross pool market, where generators trade aggregated electricity outputs with retailers to meet forecasted demand through a centrally-coordinated dispatch process. Within an interval of five minutes, generators submit amounts of their electricity supplies at particular prices. The bids of supply are stacked according to an ascending order and the dispatch price is the last bid in the queue that meets the demand at a given period. The settlement period for spot electricity prices in the NEM is every 30 minutes. Therefore, the wholesale electricity spot price is reported by AEMO on a half-hourly basis, which is the average of the six five-minute dispatch prices during the period. It is the reference price used to settle transactions traded in the NEM. Besides the wholesale electricity spot price, retail electricity prices paid by consumers also include additional charges such as network costs, service fees and other retail charges (the additional costs make up approximately 20 per cent of the retail electricity price (AEMO, 2013b)).[8]

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[7] 1 AUD = 0.7474 USD according to the market rate on 1 December 2016.

[8] In recent years, the national average residential retail electricity price has risen by approximately 78 per cent (AEMC, 2013). However, it would not be appropriate to attribute this increase in prices merely to the implementation of the CPM. Australian retail prices are affected (in addition to wholesale electricity prices) by a number of factors such as network costs (including transmission and distribution costs), capital costs,

The level of wholesale electricity spot prices can be very volatile. In fact the Australia spot electricity market is one of the most volatile markets in the world (Higgs and Worthington, 2008; Mayer and Trück, 2015). There are a number of factors explaining this large extent of variation. First, the demand for electricity consumption changes within short periods of time. However, switching off generators to adjust electricity supply during the off-peak period is quite costly. As a result, some generators might offer negative price to ensure their supply remain in bid schedule. The boundary of minimum spot price is set at -1,000 *AUD/MWh* (AEMO, 2013c). On the other hand, events such as weather-related incidents or a reduction in capacity due to the maintenance of major power stations can significantly drive up electricity price levels for short periods of time. Furthermore, equipment failure or network congestion could also strongly push electricity spot prices towards their market cap. The upper limit of wholesale electricity spot price in the NEM is capped at 13,800 *AUD/MWh* for FY 2015-16 (AEMC, 2016).

3. Statistical Modelling Approach

This section discusses the statistical modelling approach applied in this paper to measure the magnitude of carbon costs pass-through on the Australian electricity wholesale market. In order to analyse empirically the impact of the carbon price on Australian spot electricity prices, we develop an OLS regression model based on the studies by Chen et al. (2008), Sijm et al. (2008) and Nazifi (2016). Our model uses wholesale spot electricity prices for the four major regional markets (NSW, QLD, SA and VIC) across the NEM and is estimated for each market separately. The dataset is constructed on a daily basis from 1 July 2009 to 30 June 2016. Recall that the carbon tax became effective on 1 July 2012, with an intended introductory phase until 30 June 2015, during which the price of uncapped permits was fixed: first at 23 AUD/tCO2e, then from 1 July 2013 at 24.15 AUD/tCO2e, and from 1 July 2014 at 25.40 AUD/tCO2e. However, after the election of a new government, the carbon tax was repealed by the Australian Senate on 17 July 2014 (with effectiveness from June 30, 2014). Thus, based

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electricity demand, regulation of network businesses, and environmental policies. Any analysis on retail prices would need to take into account these factors and the extent to which each of these major drivers will actually translate in to retail prices. Currently, network costs make up approximately 52 per cent of the national average retail electricity prices, and increases in network costs have significantly contributed to higher retail prices (AEMC, 2013). However, the assessment of the carbon costs pass-through rate in this analysis is based on modelling the wholesale electricity spot prices due to availability of daily data, while the impact of the CPM on the retail electricity market is left for future research.

on the introduction and the later abolishment of the tax in our estimation we take into account three sub-periods:

1. the time period when the tax was not yet implemented (from 1 July 2009 to 30 June 2012);
2. the time period referring to the years when the carbon tax was imposed (from 1 July 2012 to 30 June 2014); and
3. the period after the tax was abolished (from 1 July 2014 to 30 June 2016).

To investigate the impact of the CPM on the NEM, this study assumes that changes in wholesale spot electricity prices can be predominately attributed to changes in fuel costs, demand for electricity, and the price of carbon. Hence, we assume that other factors and generation costs affecting power prices, such as changes in capital prices, operational and maintenance costs, market power or required return on capital are unchanged over the sample period.

Based on the abovementioned assumptions, the econometric specification to empirically assess the carbon cost pass-through rate is defined as follows:

$$P_t^e - P_t^f = \alpha + b_1 d_{tax} C_t + b_2 d_{post} + \gamma_1 D_t + \gamma_2 D_t^2 + \gamma_3 D_t^3 + \varepsilon_t \quad (1)$$

where the left-hand side of the equation refers to the spread between volume-weighted wholesale electricity spot prices (P_t^e) and the fuel costs of power generation (P_t^f). Since AEMO reports the average wholesale spot price based on the dispatch prices in intervals of 30 minutes, there are 48 spot prices during a day. Hence, we derive volume-weighted average spot electricity prices as:

$$P_t^e = \sum_1^{48} \frac{D_i}{\sum_1^{48} Di} \times P_i \quad (2)$$

where P_i denotes the half-hourly observations for electricity spot prices, and D_i represents the associated electricity demand.

According to existing studies, in particular extreme spot electricity prices tend to be profoundly event-driven (Ethier and Mount, 1998; Grotto and Karolyi, 2004, Karakatsani and Bunn, 2004; Higgs and Worthington, 2008; Christensen et al., 2012; Clements et al., 2015; Mayer and Trück, 2015; Ignatieva and Trück, 2016). Hence there may be a significant number of events that are demand-related, weather-related, or equipment-failure-related that lead to extreme prices in the spot market. We find that all regional markets across the NEM exhibit a significant number of price spikes, where spot prices frequently exceed 100 $AUD/MWh, 200 $AUD/MWh, or even 300 $AUD/MWh (detailed information can be found in Section 4). Typically these extreme price events would not be related to the existence of a CPM, but are a result of the above-mentioned events. However, due to their extreme nature, price spikes could have a significant impact on our estimates for CPTRs, resulting either in an over- or underestimation of actual pass-through (depending on whether relatively more spikes are observed in a market during the pre-tax, the tax or post-tax period). Thus, to eliminate the noise created by these abrupt jumps in electricity prices, this study employs a mechanism to filter out extreme observations in the spot electricity prices[9] following the recursive seasonal model (*RM*) originally suggested by Janczura et al. (2013).

Despite the occurrence of price spikes, electricity prices typically tend to return to their long-term levels after an easing of the market condition. The aim of the price filtering mechanism is to reduce price spikes through a continuous value replacement process, which helps to reduce the bias in the estimation. Prior to this filtering, a predetermined absolute price level is set as a threshold, so that all price observations above this threshold can be identified as outliers. In the next step, an OLS regression is carried out, so that the outliers can be replaced by the fitted values. The iterative process continues until all outliers are reduced to the price level below the threshold. Hence, the regression analysis in equation (1) is conducted by using both uncapped and capped volume-weighted electricity prices at either (i)100 $AUD/MWh; (ii) 200 $AUD/MWh; or (iii) 300 $AUD/MWh to exclude noises from price spikes to attain better fitting results.

As discussed above, following Sijm et al. (2008), Chen et al. (2008), and Nazifi (2016), our model assumes that fuel costs are fully and directly passed on to electricity prices. In this paper, fuel costs are calculated based on half-hourly electricity demand and short-run marginal costs (SRMC) for each individual power generation instalment in the NEM based on data provided by ACIL Tasman (2009), ACIL Allen Consulting (2014) and CO2CRC Limited

[9] In addition to the baseline regression with capped prices, we also conduct regressions with uncapped prices. The detailed results are reported in Table A.3. As evidenced, the results are similar in statistical significance, however, the CPTR for SA is the lowest at around 1.60.

(2016).[10] The SRMC is defined as being the additional cost incurred in the production of an additional MWh on average over the course of the year. Using this definition, the SRMC for each station varies as the cost for an increment of output depends on whether the plant is operating and the level of output at which it is operating. Therefore, the SRMC is formed based on the average marginal thermal efficiency, the average marginal fuel cost, the average marginal variable operating and maintenance costs, and the average marginal emission factors incurred for a station over the year (more detailed discussion can be found in ACIL Tasman, 2009).

Using data on half-hourly demand for each market, we simulate the dispatch of individual power plants to calculate a proxy for half-hourly fuel costs. At first, generators are sorted in accordance with their individual SRMCs in ascending order.[11] The cumulative demand in the wholesale electricity market is then used to calculate capacity-weighted fuel costs based on the SRMCs for each generator in the production queue to meet the accumulative electricity demand. We then calculate volume-weighted average daily fuel costs based on half-hourly demand and fuel cost figures. The calculated fuel costs for electricity generation are then subtracted from the volume-weighted wholesale electricity prices to generate the 'spread' as represented on the left-hand side of Equation (1).

The intercept α represents some stable and fixed components of the spread, such as the fixed-cost elements. As noted, the carbon pricing mechanism became effective on 1 July 2012 (Clean Energy Act, 2011), therefore, to statistically evaluate the potential impact of the carbon tax, a dummy variable d_{tax} is created, which is equal to 1 from 1 July 2012 to 30 June 2014, and 0 otherwise. C_t denotes the cost of the carbon permits required to cover emissions from generating a MWh of electricity, which is calculated by using the official carbon tax rate (AUD / tCO_2-e) multiplied by the region's emission intensity (tCO_2-e/MWh) on a particular day. Following Sijm et al. (2008), the b_1 coefficient can be interpreted as the carbon pass-through

[10] These reports provide professional analyses and forecasts on generation costs in the NEM. The report forecasts short-run marginal cost (SRMC) for each individual power generation operating in the NEM.

[11] Generators can be ranked in ascending order of their short-run marginal costs, known as the merit order. So generators with the lowest marginal costs are the first ones to meet demand, and plants with the highest marginal costs are among the last to be brought on line to meet demand. Since the carbon cost per MWh of generation is typically different for each generation technology, the merit order of power generation technologies may shift with the introduction of a carbon price. Thus, for the carbon-tax period, we considered SRMC inclusive of the additional costs of carbon for the merit order, i.e. the ranking of generators from the cheapest to the most expensive. MENTION CLOSURE OF GENERATORS HERE!

rate (CPTR; the degree to which carbon costs incurred by generators translate to the general increase in wholesale electricity prices). Thus, if the estimated b_1 equals unity, carbon costs are fully passed in to electricity prices at a rate of 100%. If the resulting estimate of b_1 is less than unity, then there is less than complete pass-through of the carbon costs, indicating that some portion of the carbon costs are absorbed by the generators. When b_1 is greater than unity, the implication is that there is more than a complete pass-through, and the incidence of taxation would apparently be borne by consumers.

As discussed earlier, the regression model also considers the time period after the carbon tax was abolished. Thus, we incorporate another dummy variable, d_{post} to explore whether spot electricity prices have reverted back to their pre-tax levels. This variable is equal to 1 from July 2014 to 30 June 2016, and 0 otherwise.

Spot electricity prices are strongly affected by demand. As suggested by previous studies (Kanamura and Ohashi, 2007; Karakatsani and Bunn, 2004; Nogales et al., 2002), this paper applies a polynomial relationship (up to order three) between demand and wholesale spot electricity prices due to the increasing relationship in a non-linear fashion between prices and demand for the electricity market[12], rather than a simple linear model (see Section 4 for further discussion). The γ coefficients estimate the impacts of demand on the spot electricity prices. Finally, the impact of all non-stable components in the fuel spread is captured by the error term (ε_t) in Equation (1).

4 Empirical Analysis

4.1 Data and Preliminary Analysis

This study employs data from various sources to analyse the pass-through rate of carbon costs on Australian wholesale electricity markets. We consider spot electricity prices from July 1, 2009 to June 30, 2016 for the four major states in the NEM, namely, NSW, QLD, SA and VIC. We further divide the sample period into three sub-periods: the period before the CPM

[12] It is worth mentioning that this paper assumes that the demand–price relationship is constant and therefore there is no significant change in the number of climate events during the investigated period. In order to check the robustness of the model, this paper specifies another model that considers a linear relationship between electricity prices and volumes without the squared and cubic demand terms. The results are similar (for further details, see Table A.5).

became effective (July 1, 2009 – June 30, 2012), the period where the carbon tax was in place (July 1, 2012 – June 30, 2014) and the time period after the carbon tax was repealed (July 1, 2014 – June 30, 2016). In order to estimate the magnitude of changes in electricity prices that can be attributed to the pass-through cost of carbon, half-hourly observations for electricity spot prices and demand for the four regional markets were collected from AEMO. These half-hourly observations are then used to calculate volume-weighted daily average spot electricity prices as outlined in equation (2).

Table 1 provides descriptive statistics of daily volume-weighted prices for the entire sample period as well as for the three sub-periods. The price series for each state are also displayed in Figure 1. Note that for the purpose of illustration, prices were capped at 300 *AUD/MWh*, while negative prices are also not displayed.[13] For all markets daily spot prices are characterised by the typical features of spot electricity prices and exhibit high standard deviation and extreme kurtosis. Due to the excess skewness, the distribution of spot electricity prices is skewed to the right and for all markets the median price is significantly lower than the mean price. Overall, prices were the lowest in VIC, where the average daily spot price for our sample period is 41.06 *AUD/MWh*, followed by NSW with an average spot price of 45.30 *AUD/MWh*, QLD with 49.48 *AUD/MWh*, while prices were typically the highest in SA where the average spot price is 53.61 *AUD/MWh*. Note that this order also reflects the predominant type of generation for each state, with VIC having the highest emission intensity due to a high share of relatively cheap lignite and coal, followed by NSW and QLD, i.e. states that are also dominated by coal-fired power plants. At the same time SA typically has a much higher share of gas and renewable energy in its generation mix, resulting in significantly lower emission intensities but higher price levels.

[13] In Australian electricity market, 300 *AUD/MWh* is a commonly accepted price mark to identify price spikes. There is a number of electricity derivatives, for example so-called cap options, using the $300 *AUD/MWh* level as a threshold, signifying its market-wide recognition as a threshold for extreme price spikes. https://www.asxenergy.com.au/newsroom/industry_news/new-daily-settlement-prices-f

Table 1: Descriptive statistics of volume-weighted spot electricity prices for the sample period July 1, 2009 – June 30,2016 as well as for the period before the carbon tax (01/07/2009 - 30/06/2012), the carbon tax period (01/07/2012 - 30/06/2014) and the post-tax period (01/07/2014 - 30/06/2016).

Market	Obs	Mean	Median	SD	Max	Min	Skewness	Kurtosis	Price>100	Price>200	Price>300
Entire Sample Period (01/07/2009 - 01/07/2016)											
NSW	2558	45.30	35.59	68.94	1591.20	17.42	16.37	319.54	2.31%	0.86%	0.63%
QLD	2558	49.48	34.58	84.82	2264.89	-15.25	15.67	330.06	5.20%	1.41%	0.94%
SA	2558	53.61	37.57	111.94	2992.58	-82.77	16.87	355.14	6.33%	1.56%	0.78%
VIC	2558	41.06	33.32	54.21	1480.02	-2.58	17.90	414.66	1.76%	0.63%	0.39%
Pre Carbon Tax Period (01/07/2009 - 30/06/2012)											
NSW	1096	39.58	27.24	101.53	1591.2	17.42	11.97	160.65	2.46%	1.73%	1.28%
QLD	1096	32.73	25.46	64.49	1239.73	-15.25	13.69	211.67	1.73%	0.73%	0.64%
SA	1096	43.97	27.78	160.38	2992.58	-82.77	13.24	198.56	2.28%	1.28%	1.09%
VIC	1096	31.87	26.02	69.22	1480.02	-2.58	17.46	341.84	1.00%	0.64%	0.55%
Carbon Tax Period (01/07/2012 - 30/06/2014)											
NSW	730	54.24	52.11	13.23	356.69	44.38	16.94	376.91	0.55%	0.14%	0.14%
QLD	730	64.27	54.25	46.97	678.24	1.39	8.40	92.08	7.12%	1.64%	0.68%
SA	730	68.25	55.48	57.7	996.27	33.23	9.21	120.12	8.49%	1.78%	0.96%
VIC	730	55.90	49.90	43.75	929.12	37.25	14.40	254.38	2.05%	0.96%	0.41%
Post Carbon Tax Period (01/07/2014 - 30/06/2016)											
NSW	732	44.95	37.27	29.69	569.76	19.71	9.01	139.67	2.55%	0.18%	0.14%
QLD	732	59.82	37.31	126.46	2264.89	5.18	13.26	207.54	5.66%	1.46%	1.64%
SA	732	53.43	40.96	40.29	343.96	-4.00	2.84	13.71	6.84%	1.19%	0.14%
VIC	732	40.02	34.07	29.11	545.74	10.80	8.80	132.97	1.73%	0.18%	0.14%

Figure 1: Daily volume-weighted spot electricity prices from 1 July 2009 to 30 June 2016 for NSW (upper panel), QLD (second panel), SA (third panel) and VIC (bottom panel). Note that for the purpose of illustrating the price shift as a result of the carbon tax, prices were capped at 300 AUD/MWh. The carbon tax was effective from 1 July 2012 to 30 June 2014.

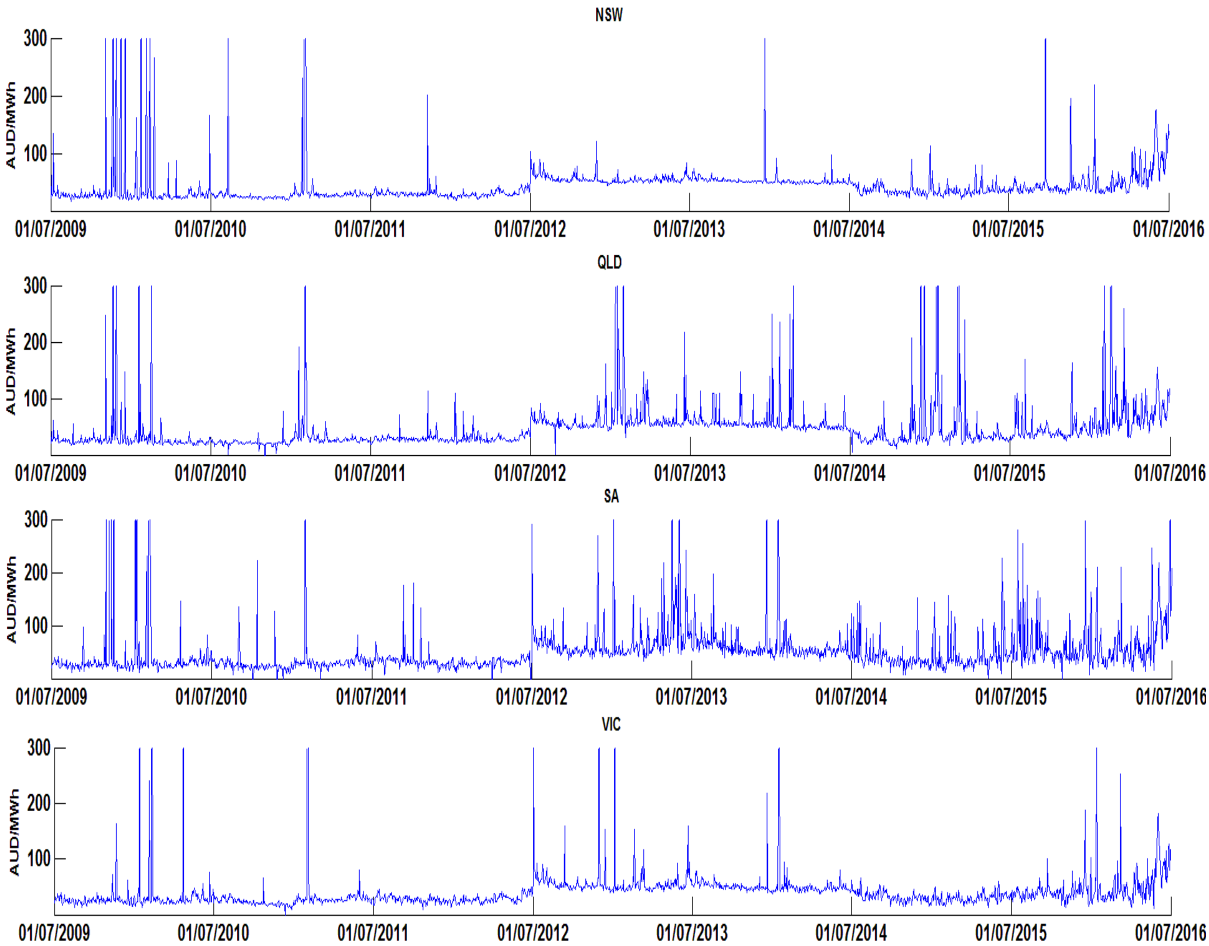
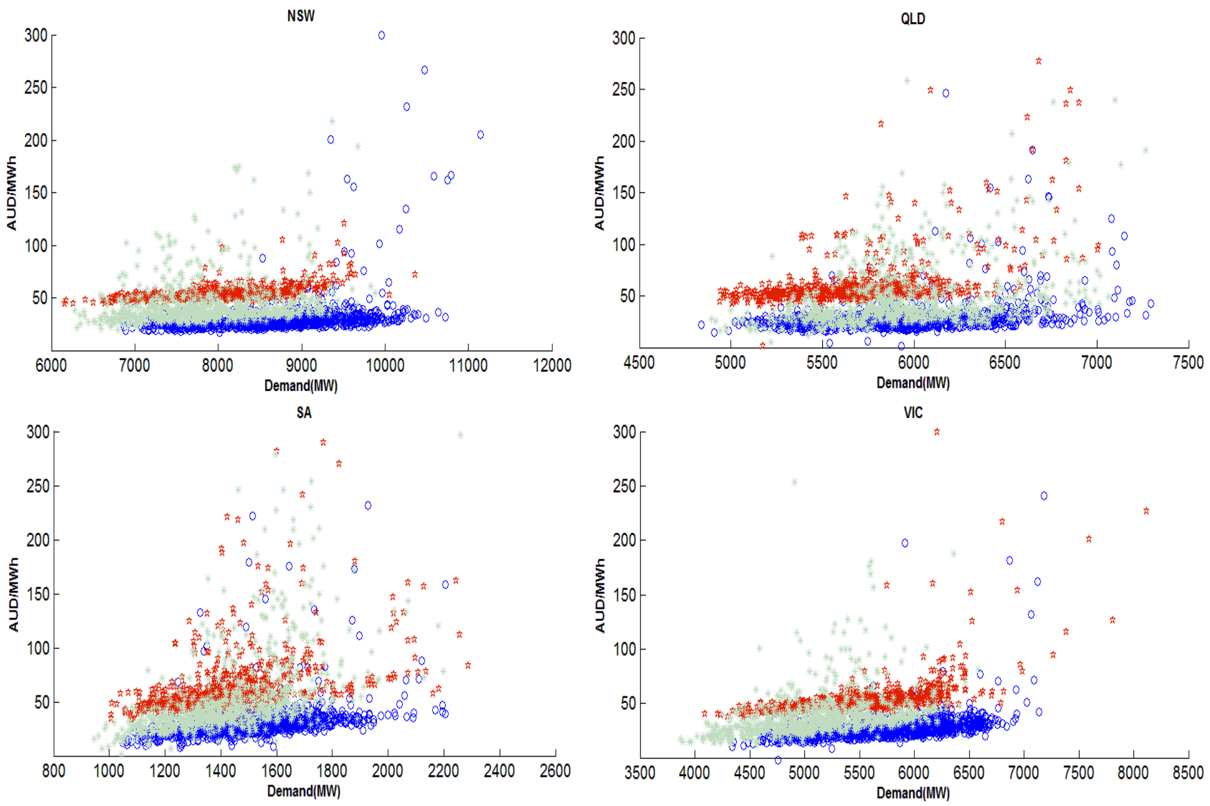


Table 1 and Figure 1 also illustrate the significant variation in spot electricity prices through time. For example, while the average daily spot price in South Australia for the sample period is 53.61 *AUD/MWh,* the daily maximum price in SA reaches 2992.58 *AUD/MWh*, and the observed minimum price is -82.77 *AUD/MWh*.[14] As a result, the standard deviation for daily volume-weighted spot prices in SA is 111.94. Similar observations with regards to an extreme price range and high standard deviations can also be made for the other markets. At the same time, we find that all markets exhibited a significant number of price spikes, with spot prices

[14] Due to significant ramp-up costs for coal-fired power plants, in order to avoid a temporary shut-down of these plants, generators sometimes are willing to accept very low or even negative prices (typically when demand is low) for a certain period of time to keep the generation plants operating.

frequently exceeding 100 *AUD/MWh*, 200 *AUD/MWh* or even 300 *AUD/MWh*. As pointed out in Table 1, 0.63% of prices in NSW exceeded a threshold of 300 *AUD/MWh*, while the respective numbers for QLD, SA and VIC are 0.94%, 0.78% and 0.39%.

Figure 2: Relationship between daily electricity demand and volume-weighted spot electricity prices from 01/07/2009 to 30/06/2016 for NSW (upper left panel), QLD (upper right panel), SA (lower left panel) and VIC (lower right panel). Note that for the purpose of illustration prices were capped at 300 AUD/MWh. We further distinguish between prices for the three sub-periods: prices for the pre-tax period (01/07/2009-30/06/2012) have blue circles as markers, the carbon tax period (01/07/2012-30/06/2014) has red pentagrams and the post-tax period (01/07/2014-30/06/2016) grey asterisks.



The data also demonstrates the strong impact of the CPM on spot electricity prices in the NEM. Between July 2012 and July 2014, when the carbon price was in place, there was a significant shift in wholesale electricity markets that can also be seen in Figure 2. During the tax period, average electricity price levels increased by 14.66 *AUD/MWh* in NSW, 31.54 *AUD/MWh* in QLD, 24.28 *AUD/MWh* in SA and 24.03 *AUD/MWh* in VIC. Interestingly, despite the abolishment of the CPM in July 2014, spot electricity prices did not revert back to their pre-tax levels from this point onwards. Average spot electricity prices have remained at relatively high levels between 40.02 *AUD/MWh* (in VIC) up to almost 60 *AUD/MWh* in SA.[15]

Figure 2 provides a scatter-plot of the volume-weighted daily prices against the demand on the respective day. As noted earlier, the figure illustrates an increasing relationship in a non-linear fashion between prices and demand for all markets. These findings also encourage us to rather apply a model with a polynomial relationship (up to order three) between demand and spot price – see equation (1) – instead of simply estimating a linear model. The figure also illustrates the three distinct price layers for the three sub-periods in each state. While the non-linear and increasing relationship between price and demand seems to hold throughout all sub-periods, spot prices are clearly on a higher average level during the carbon tax period. We also observe that price levels during the post-tax period were still relatively high in comparison to the period prior to the implementation of the carbon tax. Overall, as illustrated in Figure 1 and 2, for the considered sample period, spot electricity prices were at their lowest level in the period before the carbon tax. This also provides us with a motivation to empirically examine the behaviour of spot electricity prices after the repeal of the carbon in July 2014.

Daily emission intensities measured in tons of CO_2 equivalent per MWh electricity generated (tCO_2-e/MWh) are also sourced from AEMO. Figure 3 provides a plot of the time series of daily emission intensities in each state for the sample period. The figure shows quite substantial fluctuations of emission intensities on a day-by-day basis through time. These are typically a result of the level of electricity demand as well as the generation mix used for providing electricity on a specific day. As expected, we also find significant differences in emission intensities between the four markets: average emission intensities were clearly the highest in VIC throughout the sample period (1.21 *tCO_2-e/MWh*), followed by NSW (0.93 *tCO_2-e/MWh*) and QLD (0.84 *tCO_2-e/MWh*). These three markets are dominated by coal-fired generation of electricity. On the other hand, emission intensities were significantly lower in SA (0.56 *tCO_2-e/MWh*), where a substantial share of electricity generation is obtained through renewable

[15] In Figure 2, we also note that there seems to be a trend of decreasing demand for electricity throughout the sample period. The layers representing the price-demand relationship in each sub-period seem to shift more to the left for the second and third sub-period, indicating a lower demand for the considered markets. For instance, in the upper-left panel of Figure 2, in comparison to the layer in blue (price-demand relationship for the pre-tax period), the grey layer (price-demand relationship for the post-tax period) is located to its left. Table A1 in the Appendix also confirms these results, illustrating that for NSW, SA and VIC the average demand for electricity decreased from the period prior to the carbon tax to the post-tax period.

energy sources. To illustrate long-term changes in average emission intensities for these markets, we also added a moving average over 120 days for each region. As pointed out by O'Gorman and Jotzo (2014), there was a reduction for emission intensities in most states during the effectiveness of carbon tax that also can be observed in the time series plot.

Figure 3: Emission intensities from 1 July 2009 to 30 June 2016 for NSW (upper panel), QLD (second panel), SA (third panel) and VIC (bottom panel) with a moving average of 120 days (red line).

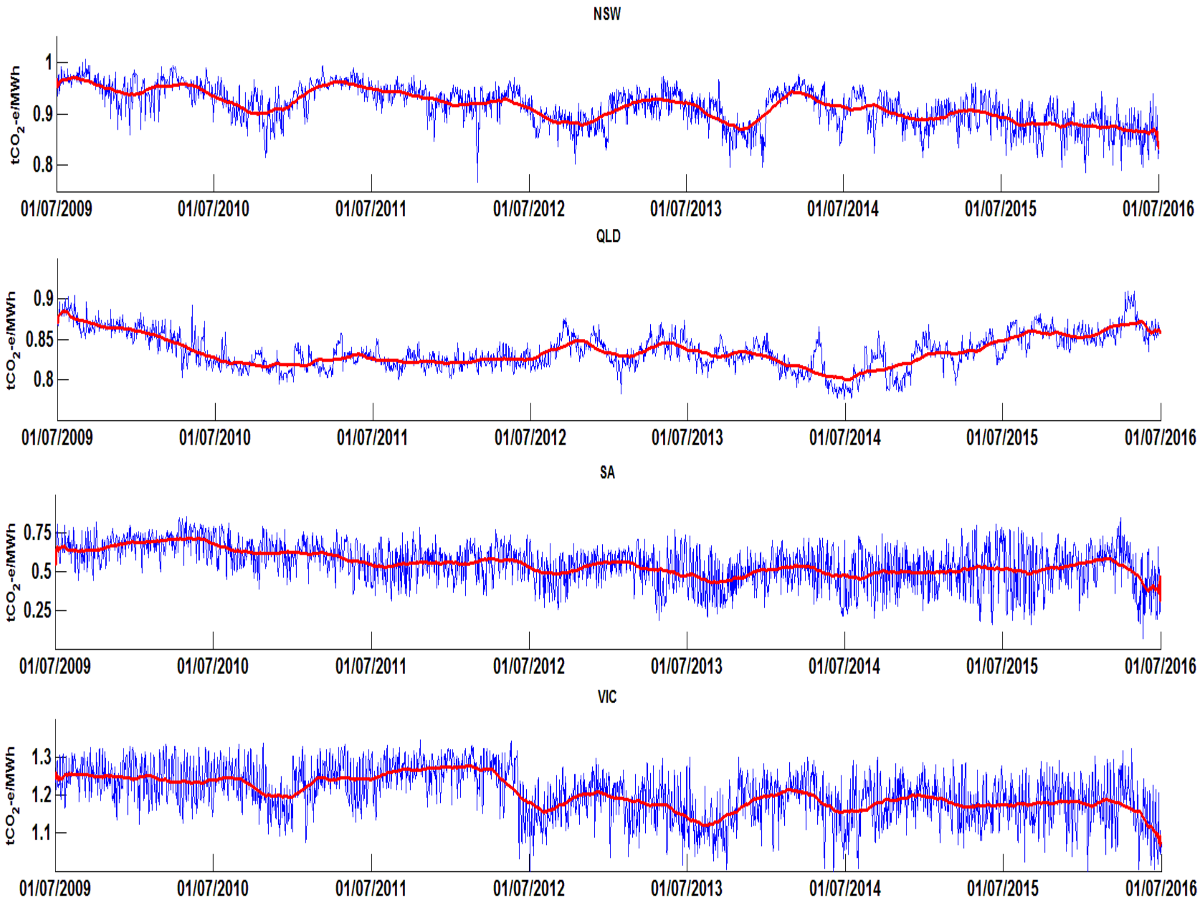


Table 2 provides more detailed information regarding emission intensities for the entire period as well as for the three sub-periods. We find that in comparison to the period prior to the carbon tax, the average emission intensities for all states decreased when the tax was effective. The most significant decrease can be observed for the markets in SA and VIC, where emission intensities were reduced from 0.62 tCO_2*-e/MWh* to 0.50 tCO_2*-e/MWh* (SA) and from 1.24 tCO_2*-e/MWh* to 1.17 tCO_2*-e/MWh* (VIC). Emission intensities in NSW also indicated a slight reduction from 0.94 tCO_2*-e/MWh* to 0.91 tCO_2*-e/MWh*, while for QLD they remained almost at the same level of approximately 0.83 tCO_2*-e/MWh*. Overall, we observe a reduction in emission intensities of approximately 18.6% for SA, 5.5% for VIC, and 3.4% for NSW. For the post-tax period, we find that emission intensities reverted back almost to their pre-tax levels in NSW and to an even higher level of 0.86 *tCO_2-e/MWh* in QLD. For VIC we observe a slight increase in emission intensities after the tax was abolished, however, with 1.19 *tCO_2-e/MWh* emission intensities were still lower than during the pre-tax period. For SA, as a result of the continuous increase in renewable energy generation, emission intensities remained at a relatively low level of 0.51 *tCO_2-e/MWh* also after repeal of the tax. For example, there was an increased dispatch of Natural Gas Combined-Cycle (NGCC) and Gas Thermal plants located in the Greater Adelaide nodal region in SA, after imposing the carbon tax (AEMO, 2013d, Wild et al., 2014) that could explain the reduction of the average emission intensities in SA. Moreover, the closure of Northern Power Station and Playford B plant in SA can be considered as attributor factors lowering emission intensities. [16]The reduction of the average emission intensity in VIC could be attributed to the closure of a few coal-fired plants (e.g. Energy Brix and Anglesea) in recent years in this state.

Table 2: Average Emission Intensity on Australian Wholesale Electricity Market for the entire sample period 01/07/2009 to 01/07/2016 as well as for the period before the carbon tax (01/07/2009 - 30/06/2012), the carbon tax period (01/07/2012 - 30/06/2014) and the post-tax period (01/07/2014 - 30/06/2016).

	Entire Period	**Pre Carbon Tax Period**	**Carbon Tax Period**	**Post Carbon Tax Period**
NSW	0.9145	0.9377	0.9048	0.8895
	(0.0379)	(0.0299)	(0.0338)	(0.0318)
QLD	0.8354	0.8342	0.8300	0.8424
	(0.0225)	(0.0216)	(0.0192)	(0.0252)
SA	0.5536	0.6181	0.5028	0.5078
	(0.1337)	(0.1035)	(0.1183)	(0.1471)
VIC	1.2043	1.2436	1.1746	1.175
	(0.0670)	(0.0533)	(0.0614)	(0.0603)

Standard error in parentheses, Data Source: AEMO (2016)

[16] Results for conducted paired t-tests are provided in the Appendix in Table A2. Our results illustrate that emission intensities in all states were significantly lower during the period when the CPM was effective in comparison to the pre-tax period. While intensities in NSW were even significantly lower after abolishment of the CPM in comparison to the tax period, they increased significantly in QLD. We further find that emission intensities during the post-tax period were significantly lower than before introduction of the CPM for all states except QLD.

4.2. Carbon Pass-Through Rates

In a next step, we calculate carbon pass-through rates for NSW, QLD, SA and VIC, following the econometric specification defined in equation (1). The model is estimated for each regional market separately, using ordinary least squares (OLS). A summary of the OLS regression results is provided in Table 3. Our findings demonstrate that for all states estimated carbon cost pass-through rates (CPTR) Θ are statistically significant at the 1% level. Thus, our results strongly confirm significant carbon pass-through rates on spot electricity prices in the NEM. Naturally, a key question is also the magnitude of the observed pass-through rates: we find that the rates show significant variation across the considered regional markets. For the four states considered in this study, SA indicated the highest CPTR of 290%, followed by QLD, where the estimated rate of carbon costs pass-through was 186%. While more than 130% of carbon costs were passed from electricity generators to buyers in the wholesale market in NSW, this ratio was only 97% in VIC. According to economic theory, the marginal costs of production should increase in line with the carbon costs. Under the assumption of perfect competitive market, the CPTR is expected to be approximately 100%, when a fixed demand with zero price elasticity and perfect elastic supply (i.e. a flat line) is assumed (Sijm et al., 2008). In this case, the marginal revenue increase due to the carbon costs pass-through should match the incremental cost increase induced by the carbon pricing mechanism. However, our results indicate substantially higher CPTRs for three of the considered states, implying that carbon costs were passed to wholesale electricity spot prices to a significantly higher degree in NSW, QLD and SA.

Hence, our results might provide some indication of potential windfall profits for generators in the NEM. They also illustrate that a relatively small reductions in carbon intensities for markets like NSW (3.4%), QLD (0.5%) and VIC (5.5%) were accompanied by substantial price increases in wholesale electricity prices indicated by carbon pass-through rates between 97% (VIC) and 186% (QLD). For SA a significant reduction in carbon emissions (18.6%) could be observed, while calculated carbon pass-through rates were even higher, reaching almost 300% according to our analysis. Thus, despite having lower emission intensity levels in comparison to other states, SA and QLD experienced much higher CPTR.

Our results also reveal that spot electricity prices remained at surprisingly high levels after the repeal of the tax. Note that an estimate close to zero for the post-tax dummy variable Υ_{PT}

would indicate that wholesale electricity prices reverted back to their levels prior to the introduction of the CPM. However, as observed in the third column of Table 3, estimates for Υ_{PT} for all states are significantly higher than zero. The highest Υ_{PT} of 20.02 *AUD/MWh* appears in QLD, followed by NSW, where the electricity price level after the repeal of the carbon tax indicates prices to be approximately 19.85 *AUD/MWh* higher than for the pre-carbon period. Price levels in VIC and SA in the post-tax period are still 19.70 *AUD/MWh* and 19.24 *AUD/MWh* higher than prior to the CPM implementation. Results from alternative model settings also deliver higher estimates for Υ_{PT} (Table A.3, Table A.4 and Table A.5). This shows that generators might still be benefiting from the increased electricity price level two years after the repeal of carbon tax as windfall profit.

We attribute the large extent of carbon costs pass-through to spot electricity prices to a number of reasons: first, the purpose of establishing a CPM is to motivate emission reduction throughout Australia, in order to mitigate the long-term effects of climatic change. According to the modelling results from Treasury Department (2011), imposing a carbon price could lead to a reduction of average emission intensities in the Australian electricity sector by 77 per cent until 2050. An emission reduction in the power sector is expected to occur mainly through switching from coal-fired electricity generation to lower-emission generation alternatives such as natural gas or renewable energy. However, the transition is dependent on a number of factors such as fuel costs, energy prices and the availability of renewable energy generation. During the effectiveness of the CPM, possible changes in the merit order might have also caused increasing electricity generation costs. Due to the effect of carbon pricing, less carbon-intensive energy such as gas was preferred because of its economic attractiveness to the generators. For instance, there was an increased dispatch of relatively more expensive Natural Gas Combined-Cycle (NGCC) and Gas Thermal plants located in the Greater Adelaide nodal region during the peak period in SA, after imposing the carbon tax (AEMO, 2013d, Wild et al., 2014). The rising costs of generating electricity by gas and NGCC were directly passed on to wholesale electricity prices, leading to a higher CPTR for SA. Furthermore, due to the seasonal shutdown of Northern Power Station, SA imported a relatively high volume of electricity from Victoria. This also resulted in much higher electricity prices over the period of investigation (AEMO, 2013b). While similar arguments could also be made for the QLD market, the reason of its increasing electricity prices could be partly attributed to demand-driven price spikes. For instance, the heat waves in January 2013 caused a series of price spikes during that period. Looking back to Figure 2, we observe more frequent occurrence of extreme prices during the carbon tax period and post-tax period, despite an overall decrease in the demand for electricity in these two periods (Table A.1). As a consequence, the rising price could have influenced the estimation of CPTR.

Table 3: Carbon pass-through rates and results for the applied regression model (1) with a price filter of 300 AUD/MWh (volume-weighted).

	Intercept	ϴ	Υ_{PT}	D	D^2	D^3	R^2	R^2-Adj
NSW	-1737.43***	1.31***	19.85***	65.23***	-0.81***	0.0034***	35.63%	35.50%
	(-5.79)	(30.54)	(8.04)	(5.91)	(-6.03)	(6.18)		
QLD	-2328.41*	1.86***	20.02***	121.94**	-2.14**	0.0126**	35.36%	35.24%
	(-1.93)	(19.78)	(7.10)	(1.98)	(-2.04)	(2.13)		
SA	-423.58***	2.90***	19.24***	76.95***	-4.80***	0.1042***	34.42%	34.29%
	(-4.71)	(12.34)	(6.80)	(4.25)	(-4.02)	(4.06)		
VIC	-1266.83***	0.97***	19.70***	70.01***	-1.28***	0.0079***	44.51%	44.40%
	(-9.34)	(24.97)	(7.66)	(9.70)	(-9.98)	(10.32)	(-9.34)	(24.97)

ϴ denotes estimated carbon pass-through rate, ϒPT denotes post carbon tax period dummy coefficient and D denotes coefficient for demand.
Standard error in parentheses
*** denotes statistical significance at the 1% level
** denotes statistical significance at the 5% level
* denotes statistical significance at the 10% level

4.3 Robustness Checks

This section compares our baseline regression results with outcomes from other specifications of the model for the purpose of robustness checks. Besides the baseline regression with volume-weighted electricity prices capped at 300 *AUD/MWh*, we conducted regressions with (i) volume-weighted electricity prices capped at 100 *AUD/MWh*, (ii) volume-weighted electricity prices capped at 200 *AUD/MWh*, (iii) volume-weighted electricity prices with no price cap. Furthermore, we also undertake regressions with simple average daily electricity prices instead of using volume-weighted prices. Regressions without squared and cubic demand terms are also implemented based on volume-weighted prices. These include regressions with prices filters of (iv) 100 *AUD/MWh*, (v) 200 *AUD/MWh* and (vi) 300 *AUD/MWh*. The detailed results for this analysis are reported in Table A.3 A.4 and A.5 in the Appendix.

Overall, a comparison of the additional regression results shows that the estimation of CPTRs for the considered markets is relatively robust. While there is no significant difference for estimated pass-through rates for NSW and VIC across the different models, CPTRs for QLD and SA typically become lower when the threshold for the price filter is reduced. The lowest CPTRs for QLD are obtained for data with a price filter of 100 *AUD/MWh*. A glance at Table 1 suggests that over 5% of spot electricity prices for QLD over the investigation period are greater than 100 *AUD/MWh*. Moreover, the proportion increased to more than 7% during the carbon tax period. As certain factors influencing electricity prices are not included in the regression framework, filtering outliers above 100 *AUD/MWh* might exclude incident-driven price spikes, in order to reduce the possibility of biased estimates for the CPTRs. Furthermore, filtering with a price cap of 300 *AUD/MWh* delivers the highest estimates for CPTRs for SA when volume-weighted prices in combination with a linear model are applied. A comparison of regression results for SA illustrates that the estimated CPTRs decrease when the parameters for nonlinear demand terms increase. This suggests that demand-driven price movements push up the CPTR estimation for SA. Interestingly, for the highest price filter of 300 *AUD/MWh* , the degree of carbon costs pass-through rates in SA is the lowest, while the explanatory power of the model is the highest in comparison to other model specifications.

However, overall the conducted robustness checks strongly confirm our findings on the significance and magnitude of carbon pass-through rates in the NEM. They also confirm the significantly higher price levels observed after the abolishment of the tax in comparison to pre-tax periods in all markets.

4.4 Comparison with other studies

As a major issue affecting the Australian electricity sector, carbon pricing caused concerns over its potential impact on electricity markets. Existing studies mainly applied theoretical and simulation methodologies, which delivered mixed results due to different model assumptions. Simulations conducted by Australian Treasury Department (2011) showed that average wholesale electricity prices could go up by approximately 18 *AUD/MWh* over the first five years after imposing carbon tax. After simulating with agent-based model, Wild et al. (2014) concluded that carbon cost is not completely passed through to consumers. The estimated CPTR in the Garnaut Report (2008) using a multi-area probabilistic dispatch algorithm was around 128 per cent. Nelson et al. (2010b) forecasted an average emission intensity for Australian electricity generation around 0.94. Emission intensities predicted by Tasman, A. C. I. L. (2011) indicated a CPTR ranging from 0.63 to 0.91 in NSW, QLD, SA and VIC from 2012 to 2014. CPTR estimated by other consulting papers ranged from 0.17 to 3.93 (McLennan Magasanik Associates, 2006; Simshauser and Doan, 2009). The significant variation in forecasting results demonstrate inconsistent *ad hoc* market expectations regarding the degree of carbon costs pass-through in the Australian electricity market.

Further studies reveal the actual rate of carbon costs pass-through in electricity prices after the CPM became effective one July 1, 2012. On the first day of the implementation of a carbon price, volume-weighted average pool prices in the NEM increased by roughly 23 *AUD/MWh* for NSW, QLD and VIC, which was approximately 100% (Frontier Economics, 2012). O'Gorman and Jotzo (2014) found that carbon pricing lead to 59 per cent increase in average spot electricity prices one year after the introduction of carbon price. Using a dataset constructed on a monthly basis from July 2010 to October 2013, Nazifi (2016) statistically measures the actual impact of CPM on electricity spot prices in the NEM. In comparison to the results of current work, her findings show relatively lower carbon pass-through rate (still greater than one) across all states. As our dataset covers the complete carbon pricing period, the actual CPTRs calibrated in this study are higher than what has been suggested in previous studies.[17] Overall, conclusions from this study are overall consistent with earlier work that typically concludes that consumers are bearing the costs of carbon rather than generators.

In addition to higher electricity price level during carbon pricing discovered by previous studies, our study found that electricity prices did not revert back to their level before the effectiveness of the CPM. Nazifi (2016) shows some evidence for potential windfall profits

[17] Australia's CPM was effective from July 2012 to July 2014. The dataset in this study covers the period 2 year prior to the CPM effectiveness, the whole carbon pricing period and 2-year period after the carbon tax repeal until end of June 2016.

for electricity generators during the CPM period: the estimated CPTRs demonstrate that carbon costs were not internally absorbed by generators. Firms in the electricity sector potentially benefited from the CPM implementation due to increased price levels, which is confirmed by the high extent of CPTRs found in our study. However, the revenue generated through high carbon costs pass-through did not boost a shift to cleaner generation technology. As indicated by AEMO (2013b), as a consequence of policy uncertainties, investment in power generation assets has rather been limited due to expectations about a discontinuation of the CPM. Therefore, gas-fired generation did not replace coal-fired generation at significant levels after the introduction of the CPM. Furthermore, despite the repeal of carbon tax in July 2014, household savings on electricity bills are significantly lower than the average estimated by the government (Alviss Consulting, 2014). Results from this study illustrate that electricity price levels in the post-carbon tax period for all states are still approximately 20 *AUD/MWh* higher than for the pre-tax period. The higher wholesale electricity price levels after the repeal of the tax might also reflect some stickiness of prices and that the price reduction effect attributable to the tax repeal was not fully passed on. Thus, generators might still be profiting from higher price levels induced by the CPM after its abolishment. As the aim of the CPM was to economically encourage emissions abatement and adoption of low-pollution technologies, the above observations cast some doubts on the effectiveness of the CPM policy.

In comparison to Australia, the magnitudes of carbon pass-through rates under the EU-ETS are typically lower. However, due to differences in countries, data, methodologies as well as different definitions of pass-through rates, reported results for the EU show some significant variation. After investigating EUAs and electricity prices, Reinaud (2007) finds a complete pass-through of EUA costs to electricity prices. Fell et al. (2010) examined the relationship between electricity, fuel and carbon prices in Germany, France, Netherlands and Spain. Their findings show that carbon costs are fully passed through to electricity futures prices in most countries and are typically above 100%. Besides Aatola et al. (2013) finds that a carbon price has a positive impact on electricity prices depending on the marginal production plants. Interestingly, Zachmann and von Hirschhausen (2008) discovered a stronger impact of carbon costs pass-through when wholesale electricity prices are increasing. While Sijm et al. (2006) show that degrees of carbon costs pass-through in electricity prices are between 60 per cent and 100 per cent in Germany and Netherlands, Jouvet et al. (2013) conclude that there is no empirical evidence of cost pass-through over the second phase of the EU-ETS. Due to the free permit allocation system, the pass-through is generally viewed as a windfall profit to the electricity industry in Europe. Looking back to the estimated CPTRs in Australian electricity market (Table 3), the windfall profit due to carbon pricing range from 34 per cent to 173 per cent for NSW, QLD and VIC. Overall, according to the diverse empirical results, there is no clear evidence for a different mechanism of carbon costs pass-through rates between the EU-ETS and the Australian CPM.

5. Summary and Conclusions

In July 2012, the Australian government introduced a price on carbon to constrain GHG emissions. This study empirically estimates the actual pass-through rate of carbon costs on to wholesale electricity spot prices across the NEM. A regression model is constructed to examine the temporal links between volume-weighted wholesale electricity spot price, carbon costs, fuel costs for electricity generation and electricity demand over the period July 1, 2009 to June 30, 2016. Due to the observed nonlinear relationship between electricity prices and demand, squared- and cubic-formed demand terms are also incorporated into the regression model. Furthermore, as the CPM was repealed after its two-year implementation in July 2014, we also investigate whether Australian spot electricity prices have returned to their pre-tax levels after the abolishment of the tax. In comparison to existing studies, the major contribution of our work is a comprehensive examination of the effects of the CPM on electricity spot markets during and after the implementation of a carbon tax.

Our results clearly confirm a substantial increase of electricity prices during the carbon tax. Further, we find that the magnitude of carbon costs pass-through vary across different regions in the NEM. While approximately 100% of carbon costs were passed onto wholesale electricity prices in VIC, CPTRs in NSW, QLD and SA are 131%, 186% and 290% respectively. For some markets, due to the additional costs of electricity generation from lignite and coal, less carbon-intensive generation from gas or renewable energy was slightly increased. However, the rising costs of generating electricity from gas, NGCC or renewables were typically directly transferred to electricity prices, which caused a higher CPTR in SA and QLD. Moreover, higher electricity prices due to seasonal shutdown of regional power stations and demand-driven price spikes also contribute to a greater extent of carbon costs pass-through. Based on the empirical results from this analysis, it can be concluded that carbon costs would be unlikely to be internally absorbed by generators. In contrast, our results could be interpreted as firms taking advantage of increasing electricity price levels during the implementation of the CPM to generate windfall profits.

Our findings also illustrate the effect of the CPM on spot electricity prices and emission intensities in the NEM. During the effectiveness of the CPM, there was a significant level shift for wholesale electricity prices across the NEM. However, despite the abolishment of the CPM in July 2014, spot electricity prices did not revert back to their pre-tax levels from this point onwards. Spot electricity price in all states remained still approximately 20 *AUD/MWh* higher than during the pre-carbon tax period. With regards to emission intensities of electricity generation, we find s slight decrease in emission intensities for all states. Interestingly, for the post-tax period emission intensities seemed to remain at lower levels for NSW and VIC, while they showed a tendency to increase again for the states of QLD and SA. However, for SA due to the overall increase in renewable energy generation, emission intensities remained at the lowest level across all states. We also conduct various additional tests with alternative model specifications that confirm the robustness of the obtained results.

With regards to the success of the tax in changing generator behaviour, our results suggest that the impact of the CPM on investment into 'greener' generation assets has been rather limited. Although there was an overall reduction in emission intensities during the carbon tax period, one could argue that a minor reduction of intensities by 3.4% for NSW, less than 1% for QLD, and 5.5% for VIC resulted in a far more substantial increase in spot electricity prices. Further, it seems like the CPM rather resulted mainly in short-term and minor changes in generation behavior, since it was not considered to remain in place over relevant investment horizons. Therefore, based on our study, a key implication for environmental policy makers is that any future mechanism for carbon pricing in Australia should be accompanied by a stable and long-term policy framework. Otherwise, it is rather doubtful that carbon pricing mechanism have its full effect and lead to long-term changes in generator behaviour.

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Table A.1: Average demand for electricity in major Australian states among carbon tax period (01/07/2009 - 30/06/2012), carbon tax period (01/07/2012 - 30/06/2014) and post carbon tax period (01/07/2014 - 01/07/2016)

	Pre Carbon Tax Period	Carbon Tax Period	Pre Carbon Tax Period
NSW	8972.96	7991.59	7862.00
	(22.22)	(24.39)	(25.99)
QLD	5918.42	5730.43	5949.04
	(12.53)	(13.62)	(15.72)
SA	1517.35	1435.52	1427.85
	(6.23)	(8.09)	(15.72)
VIC	5778.50	5526.00	5150.39
	(15.78)	(20.67)	(19.21)

Standard error in parentheses
*** denotes statistical significance at the 1% level
** denotes statistical significance at the 5% level
* denotes statistical significance at the 10% level

Table A.2: Differences in average emission intensities on Australian wholesale electricity market among carbon tax period (01/07/2009 - 30/06/2012), carbon tax period (01/07/2012 - 30/06/2014) and post carbon tax period (01/07/2014 - 01/07/2016) and paired t-test results

	Pre Carbon Tax Period Vs. Carbon Tax Period	**Carbon Tax Period Vs. Post Carbon Tax Period**	**Pre Carbon Tax Period Vs. Post Carbon Tax Period**
NSW	0.0329***	0.0153***	0.0482***
	(21.85)	(8.88)	(32.88)
QLD	0.0042***	-0.0124***	-0.0082***
	(4.29)	(-10.61)	(-7.42)
SA	0.1153***	-0.0050	0.1103***
	(22.01)	(-0.72)	(18.79)
VIC	0.0690***	-0.0004	0.0686***
	(25.46)	(-0.15)	(25.53)

Null hypothesis of paired t-test assumed identical average emission intensities between two periods under comparison.
t-test statistics in parentheses
*** denotes statistical significance at the 1% level
** denotes statistical significance at the 5% level
* denotes statistical significance at the 10% level

Table A.3: Regression Results with Price Filter of 100 AUD/MWh, Price Filter of 200 AUD/MWh and No Price Filter (Volume-weighted)

	Intercept	Θ	Υ_{PT}	D	D^2	D^3	R^2	R^2-Adj
Regression Results with Price Filter of 100 AUD/MWh								
NSW	-235.86*	1.28***	17.08***	8.73*	-0.11**	0.0004**	54.11%	54.02%
	(-1.82)	(29.13)	(9.25)	(1.92)	(-2.02)	(2.21)		
QLD	-1571.23***	1.62***	15.78***	79.76***	-1.35***	0.0077***	49.93%	49.84%
	(-2.94)	(29.89)	(7.27)	(2.96)	(-2.99)	(3.06)		
SA	-197.61***	2.51***	12.46***	32.65***	-1.84***	0.0369***	46.20%	46.09%
	(-5.51)	(21.23)	(7.40)	(4.86)	(-4.48)	(4.56)		
VIC	-569.93***	0.93***	16.49***	30.35***	-0.53***	0.0032***	61.48%	61.41%
	(-7.31)	(27.19)	(9.23)	(7.54)	(-7.75)	(8.27)		
Regression Results with Price Filter of 200 AUD/MWh								
NSW	-1380.11***	1.31***	20.02***	51.39***	-0.63***	0.0026***	40.24%	40.13%
	(-4.32)	(27.44)	(7.14)	(4.40)	(-4.48)	(4.59)		
QLD	-1546.71*	1.75***	18.91***	80.46*	-1.40*	0.0083*	39.60%	39.49%
	(-1.69)	(23.43)	(6.98)	(1.73)	(-1.80)	(1.90)		
SA	-161.81***	2.79***	17.58***	22.95**	-1.12*	0.0213	33.60%	33.47%
	(-3.08)	(14.24)	(6.91)	(2.25)	(-1.73)	(1.64)		
VIC	-1106.32***	0.96***	19.26***	60.62***	-1.10***	0.0067***	48.71%	48.61%
	(-9.43)	(27.22)	(7.33)	(10.09)	(-10.72)	(11.53)		
Regression Results with No Price Filter								
NSW	-11706.7***	1.29***	19.57***	437.96***	-5.43***	0.0223***	34.19%	34.06%
	(-3.76)	(16.94)	(6.96)	(3.80)	(-3.84)	(3.89)		
QLD	-15494.87**	2.00***	25.37***	813.77**	-14.22**	0.0828**	16.97%	16.81%
	(-2.12)	(11.10)	(4.30)	(2.15)	(-2.19)	(2.24)		
SA	-4270.72***	1.60***	12.63***	880.81***	-59.73***	1.3344***	45.98%	45.88%
	(-3.02)	(2.91)	(2.95)	(3.07)	(-3.13)	(3.22)		
VIC	-3659.35**	0.92***	19.94***	208.91**	-3.94**	0.0248**	23.28%	23.13%
	(-2.37)	(10.21)	(7.51)	(2.38)	(-2.39)	(2.42)		

Θ denotes estimated carbon pass-through rate, Υ_{PT} denotes post carbon tax period dummy coefficient and D denotes coefficient for demand.
Standard error in parentheses
*** denotes statistical significance at the 1% level
** denotes statistical significance at the 5% level
* denotes statistical significance at the 10% level

Table A.4: Regression Results with Price Filter of 100 AUD/MWh, Price Filter of 200 AUD/MWh and Price Filter of 300 AUD/MWh (Non-volume-weighted)

	Intercept	ϴ	Υ_{PT}	D	D^2	D^3	R^2	R^2-Adj
Regression Results with Price Filter of 100 AUD/MWh								
NSW	-284.42**	1.28***	16.53***	10.57**	-0.13**	0.0005***	56.51%	56.43%
	(-2.32)	(29.37)	(9.13)	(2.45)	(-2.57)	(2.79)		
QLD	-1663.11***	1.61***	15.55***	84.21***	-1.42***	0.008***	50.72%	50.62%
	(-3.13)	(30.6)	(7.23)	(3.15)	(-3.17)	(3.24)		
SA	-182.96***	2.48***	12.74***	29.34***	-1.61***	0.0319***	44.24%	44.13%
	(-5.14)	(22.86)	(7.98)	(4.39)	(-3.94)	(3.91)		
VIC	-571.64***	0.93***	15.67***	30.53***	-0.53***	0.0032***	63.03%	62.96%
	(-7.26)	(27.2)	(9.05)	(7.50)	(-7.70)	(8.20)		
Regression Results with Price Filter of 200 AUD/MWh								
NSW	-1462.91***	1.30***	18.90***	54.56***	-0.67***	0.0028***	43.25%	43.14%
	(-5.33)	(29.37)	(7.38)	(5.42)	(-5.50)	(5.60)		
QLD	-1695*	1.75***	18.39***	87.67*	-1.52*	0.0089**	41.11%	40.99%
	(-1.80)	(22.42)	(6.98)	(1.83)	(-1.89)	(1.97)		
SA	-98.23*	2.75***	16.02***	9.91	-0.23	0.0013	33.98%	33.85%
	(-1.85)	(14.26)	(6.39)	(0.95)	(-0.35)	(0.10)		
VIC	-1067.47***	0.95***	18.3***	58.58***	-1.06***	0.0065***	48.67%	48.57%
	(-8.89)	(27.04)	(7.21)	(9.33)	(-9.67)	(10.08)		
Regression Results with Price Filter of 300 AUD/MWh								
NSW	-1958.42***	1.31***	18.82***	73.5***	-0.91***	0.0038***	35.75%	35.62%
	(-4.27)	(28.62)	(8.56)	(4.34)	(-4.41)	(4.51)		
QLD	-1922.66*	1.84***	19.2***	101.31*	-1.79*	0.0106**	35.61%	35.48%
	(-1.74)	(20.06)	(7.17)	(1.79)	(-1.86)	(1.96)		
SA	-357.16***	2.85***	17.84***	63.18***	-3.86***	0.0827***	32.98%	32.85%
	(-4.21)	(13.29)	(6.48)	(3.70)	(-3.43)	(3.44)		
VIC	-1075.13***	0.97***	18.56***	59.26***	-1.08***	0.0066***	45.58%	45.47%
	(-8.5)	(25.89)	(7.92)	(8.78)	(-8.99)	(9.27)		

ϴ denotes estimated carbon pass-through rate, Υ_{PT} denotes post carbon tax period dummy coefficient and D denotes coefficient for demand.
Standard error in parentheses
*** denotes statistical significance at the 1% level
** denotes statistical significance at the 5% level
* denotes statistical significance at the 10% level

Table A.5: Regression Results with Price Filter of 100 AUD/MWh, Price Filter of 200 AUD/MWh and Price Filter of 300 AUD/MWh without Squared and Cubic Demand Terms (volume-weighted)

	Intercept	Ɵ	Υ_{PT}	D	R^2	R^2-Adj
Regression Results with Price Filter of 100 AUD/MWh						
NSW	-19.09***	1.28***	16.61***	0.37***	56.23%	56.17%
	(-3.20)	(27.55)	(8.36)	(5.33)		
QLD	-44.06***	1.61***	15.46***	1.01***	50.03%	49.97%
	(-6.57)	(29.37)	(6.87)	(8.84)		
SA	-41.82***	2.49***	12.55***	2.86***	43.82%	43.75%
	(-10.08)	(21.23)	(7.48)	(10.62)		
VIC	-31.24***	0.94***	15.72***	0.95***	61.15%	61.10%
	(-8.09)	(28.07)	(8.83)	(14.18)		
Regression Results with Price Filter of 200 AUD/MWh						
NSW	-38.14***	1.31***	19.38***	0.60***	37.34%	37.27%
	(-4.16)	(27.70)	(6.93)	(5.51)		
QLD	-81.11***	1.76***	18.35***	1.64***	39.81%	39.74%
	(-7.42)	(22.09)	(6.88)	(8.77)		
SA	-54.6***	2.74***	15.79***	3.75***	34.08%	34.01%
	(-8.71)	(13.63)	(6.11)	(9.04)		
VIC	-47.70***	0.98***	18.94***	1.24***	43.02%	42.96%
	(-6.54)	(27.02)	(7.14)	(9.68)		
Regression Results with Price Filter of 300 AUD/MWh						
NSW	-50.78***	1.33***	19.59***	0.76***	26.54%	26.45%
	(-4.50)	(27.13)	(8.01)	(5.57)		
QLD	-107.28***	1.86***	19.2***	2.09***	33.63%	33.55%
	(-6.81)	(19.55)	(7.19)	(7.78)		
SA	-67.33***	2.9.***	17.88***	4.61***	31.39%	31.31%
	(-8.03)	(12.97)	(6.32)	(8.32)		
VIC	-51.41***	1.00***	19.29***	1.31***	39.92%	39.84%
	(-6.82)	(25.76)	(7.74)	(9.85)		

Ɵ denotes estimated carbon pass-through rate, Υ_{PT} denotes post carbon tax period dummy coefficient and D denotes coefficient for demand.
Standard error in parentheses
*** denotes statistical significance at the 1% level
** denotes statistical significance at the 5% level
* denotes statistical significance at the 10% level