Economic and investment models for future grids: Final Report Project 3

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Economic and investment models for future grids: Final Report Project 3

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Deliverable 6:

CSIRO Future Grid Flagship Cluster

Project 3: Economic and investment models for future grids.

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1. Introduction

This final Future Grid Cluster Project 3 report provides the deployment of key modelling results and the identification of strategic priorities for stakeholders. The purpose of the University of Queensland's project has been to create "Economic and Investment Models for the Future Grid" and the primary objectives are as follows:

- Provide broad understanding of how the electricity sector will need to change in a carbon constrained world. This transition to a lower emissions intensive technology base will require significant structural and regulatory reform to the energy markets.
- Development of quantitative methods to analyse how price levels and volatility on the wholesale electricity market are affected by changes to the transmission network structure and technology deployment.
- Implement modelling platforms which can inform stakeholders in the energy market of how changing network structure and electricity generation technology effects electricity prices.
- Develop market simulation platforms for natural gas to gain a better understanding of how changing the fuel and technology mixes will affect the power delivery process.
- Develop a scenario planning tool set for future electricity market modelling.

This deliverable 6 reports the final analysis and results for the Future Grid project for the University of Queensland (UQ). It is also intended to highlight the progress made on the following topics:

- Modelling the National Electricity Market under fuel price uncertainty and the shift from coal to gas as the primary fuel source in the generation fleet.
    - The tools developed to model the east coast gas market are discussed in the previous deliverable report [1].
    - The planning and scenario development is discussed in brief below (section 2) and in [2-4].
- Modelling the rise Renewable Energy with a proactive consumer base ("Prosumer") and the effects on the electricity market
    - The details of proactive consumers affect electricity markets and the development of modelling techniques to accommodate this new consumer class are detailed more fully in [5, 2, 6, 4, 7].

This report summarises the work carried out by the Project 3 team and a separate report details the work of Future Grid Cluster and its interconnections and progress by other projects. The work carried out by this team is also summarized by several working papers available on the Energy Economics and Management Group website[1]. Details of how this and other projects within the cluster have co-contributed to addressing the transition to a carbon constrained future is detailed in its final summary document[2].

[1] http://eemg.uq.edu.au/working-papers
[2] http://www.futuregrid.org.au/FGC_summary.pdf

2. Future Grid Cluster Scenario Modelling

The CSIRO funded "Future Grid Cluster" has examined the possible investment and policy models required to power Australia into the Future. The key challenges identified for transitioning Australia's electricity sector to a low carbon economy, will shape the way the consumers and energy generators will evolve. These current and emerging challenges in the electricity sector have formed the modelling methodology and the scenarios explored by this project. Our role is to inform key decision makers of these challenges and creating tools for policy development.

2.1 Scenario Overview

This section of the final report represents an overview of the scenarios and the principles that underlie the Future Grid Cluster projects and how they to take into account a broader range of: policy/regulatory; economic/market and technological influences. Initially we will solidify the base scenarios (as developed initially by the Future Grid Forum, see **Figure *1*** below) and expand upon the key points of interest and the sensitivities which are developed by the project.

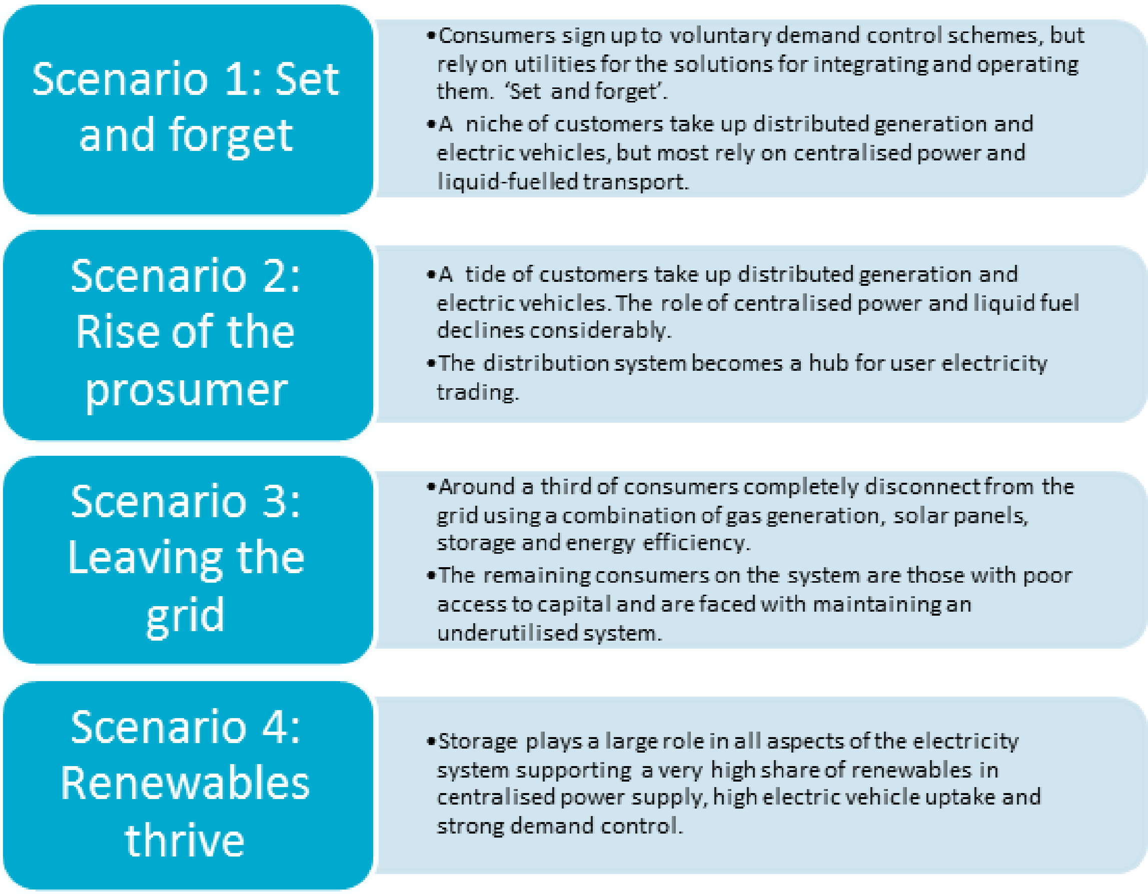

Figure 1: Future Grid Forum core scenarios [8]

2.1.1 Scenario 1: "Set and Forget"

The central tenant of this scenario is based on a consumer who wishes to remain fairly passive in their demand management. Residential households especially, have been seen to take a significant period of time to switch retail providers in several newly liberalised electricity markets [9]. Conversely, as was observed following the 2008 liberalisation of the Texas electricity market, commercial and industrial consumers are far more likely to switch providers [10].

With the implementation of retail price deregulation and smart meter uptake the electricity sector evolves to a semi-controlled, utility/centrally managed approach. Furthermore, the low uptake of distributed generation (DG), electric vehicles (EV) throughout the NEM the development of a well-planned electricity generation fleet is paramount. The growth in energy efficiency technological deployment is considered to grow on a fairly conservative path, with only subtle changes to consumer behaviour and the gradual replacement of capital stock.

2.1.2 Scenario 2: "Rise of the prosumer"

The changing face of the electricity grid as a multi-level network of "Prosumers" will actively participate in managing demand via DG and storage is considered a significant step change [11-13]. DG and active demand management will enable consumers to generate onsite and be integrated into the electricity market via their Distribution Network Service Provider (DNSP) [14, 15]. The use of electric vehicles [16, 17] and their potential battery storage capabilities is also a substantial step towards removing the need for liquid combustible fuels for small car transportation. The complexity of integration of the electricity market and a super-meshed network of devices and consumer types substantially increase emissions reduction potential of the stationary and transportation sectors.

Commercial and industrial consumers are also benefited by the new super-meshed network and onsite (co-)generation with storage. The distribution network will become a hub for electricity user trading which facilitates large commercial sites with the ability to export capacity with the local DNSP. Demand management and grid support provided by these consumer types is also encouraged by the integration of Demand Side Management (DSM) contracts with the DNSP and market operator [5, 2].

2.1.3 Scenario 3: "Leaving the Grid"

As a consequence of rising prices in the Australian electricity sector, consumers have faced increasing incentives to disconnect from the network [2, 8, 10]. The magnitude of change realised by this shift in consumer disengagement results in a surge in solar installations with battery backup and onsite gas generation. While the utilisation of the gas network may increase, the electricity distribution network system undergoes a dramatic underutilisation [10]. Furthermore, with the declining use of the distribution services, the standing charge is dramatically increased making it more difficult for non-owner occupiers to access electricity.

The dramatic consequences of uncontrolled charging of electric vehicles on the NEM [15], are also highly probable given the rate of disconnection by consumers and the lack of control facilitated by the DNSP. The broad scale uncertainty within Australia's energy policy and regulatory landscape are amplified by consumer behavioural changes [18, 7].

2.1.4 Scenario 4: "Renewable Thrive"

The technological integration of renewable energy into the electricity system is facilitated by positivist attitudes to policy and lower capital costs. The penetration of DG and centralised renewable energy options is further engaged by consumer response with the electricity network and the access to capital. Similarly to the rise of the prosumer, the uptake of renewables by residential, commercial and industrial consumers is actively managed and embraced by the DNSP's. Furthermore, the penetration of renewable energy technology options at the utility scale is also assisted by the integration of storage into the NEM. The eventual adoption of a 100% renewables target by 2050 is also a driving factor in reducing carbon emissions from the stationary energy sector. [8, 10].

2.1.5 Key Scenario Influences

Project 3 re-engages the CSIRO's Future Grid Forum (CFGF) scenario set from first principles and this reformulation will allow for this project to take into account a broader range of: policy/regulatory; economic/market and technological influences. These three key system influencer categories are inextricably linked and therefore need to be modelled. Furthermore, these drivers are the cornerstone to scenario development and quite like a chain of influencers which will result in a transparent elucidation of the modelling assumptions.

Firstly, the key influencers were categorised into ten scenario kernel elements that are considered relatively independent of each other. We then generate a set of "Reduced Scenarios" that can be used for discussion, scenario selection and external communication purposes. Secondly, scenarios are represented via all of their explicit sub-components which reflect the "micro" inputs that in turn generate the parameter suite that could be modelled explicitly. The four key influencer categories and their inter-relationships will now be described as follows:

1) Policy (and regulatory) decisions

- Actions in the policy and regulation space which are under the control of Australian policymakers and stakeholders
- Policy actions are orthogonal to states of the world
- Can depend on outcomes of states of the world
- Policy and regulatory decisions can be classified into either supply- or demand-side focused.

2) States of the World

- Forces or influences that are outside Australia's control are described by the following three categories:
  a. *Supply-side forces*: These include changes in the parameters of key supply side technologies: Such as technology costs and costs of fuel feed-stocks
  b. *Demand-side forces*, that are further divided into two sub-categories, those being:
     - Structural and behavioural, and
     - Technological development related
  c. *International Forces*: Includes the state of international markets and the policy decisions of other countries.

3) Sensitivities

Many policy and states of the world need to be modelled as having two or three outcomes. Some are binary (yes/no) and some are sensitivities with several states. We chose to limit sensitivities to three levels, that is, low, medium, and high (or slow, medium, and fast in the case of rate based parameters, such as technological learning). This limitation is imposed in order to limit the extent of the combinatorial explosion that arises when combining all the different possible outcomes.

4) Linkages

There are also interactions between the various forces and their sensitivities. In particular, it is important to note that there can be linkages within and between forces in the following two categories:

- States of the world
- Policy.

2.1.6 Scenario Kernels

In order to facilitate the communication of Project 3's modelling results for scenarios that are relevant to policy and investment decisions, we need to work at an appropriate level of detail. Since the Future Grid Cluster is only concerned with the impacts of policies and external forces on large-scale infrastructure investments and wholesale market behaviour, the kernel scenarios will be handled at this level. The structure for developing the Project 3 scenarios is shown below as follows:

Table 1: Representation of Scenario Kernel Elements

Kernel Element			States of the World		
Supply Side			Low/Slow	Medium	High/Fast
Technology costs and selection	Fossil Technology costs	1			
	Renewable/Zero emission Technology costs reduction	2			
Fossil Fuel Costs		3			
Climate policy	Carbon Pricing	4			
	Renewable Energy Target	5			
Electricity Demand			Decline	BAU	High
Energy Growth (GWh)		6			
Demand profile changes			Decrease	Status Quo	Increase
	Load Factor Change	7			
			-> Day	Status Quo	-> Night
	Day to Night Load peak shift	8			
Policy Support for renewable generation			Yes	No	
Transmission Super projects		9			
Scale Efficient Network Extensions		10			

The above table sets out the ten kernel elements grouped into three major categories: supply-side, demand-side, and policy support. It should be noted that there are eight elements with three sensitivities and a further two which have two sensitivities. This leads to a total of 26,244 possible combinations which are not easily manageable for without a methodology such as ours.

2.2 Scenario Correspondence between CFGF and the Project 3 CFGC

The CFGF has taken a similar and somewhat related approach to developing its own scenario suite but has traversed a slight different path via its need to use detailed modelling levers. This has translated into a modelling and simulation input based approach. Furthermore, the scope and scale of the CFGF had the additional requirement of examining distribution system investment due to expansion, asset replacement and end-user pricing impacts and for the potential for changing elasticities in demand.

The CFGF scenarios have been constructed via three differentiators:

- Centralised generation versus distributed generation
- Significance of peak demand growth and the flattening (skewness) of the load profile
- Deployment of large scale renewable energy generation projects.

These differentiators are represented within this projects' scenario modelling framework, while also incorporating the relationships between the scenario Kernels (as illustrated in **Table 2**). Furthermore, the CFGF scenario drivers are shown in **Table 3** below.

Below in **Table 2**, the relationship between this projects methodology of using supply- and demand-side based drivers, and the CFGF scenarios is shown. Given that there are a variety of ways that drivers can be classified, we have used a mapping matrix as a guide to translating between the two slightly different approaches. As we have reported previously [19, 4], for example, we break the growth of distributed generation (DG) impacts into three components which then become drivers for the modelling scenarios: energy efficiency; and load profile changes of two kinds, load factor changes; and shifts of the peak to different times of the day. While this matrix is not exhaustive, experience is needed to transform the input data into inputs using our framework. We have achieved this in Project 3 by setting up the assumptions database. Also note that the CFGF's energy efficiency driver also maps to the same three drivers in our framework as it can influence all of the above to varying degrees.

The CSIRO Future Grid Scenarios have to be transformed and unbundled to suit communication between the diverse modelling frameworks/tools that are used by the different projects in the Cluster. It should be further noted that without an *explicit* specification of how the CSIRO scenarios are related to specific scenario settings/switches it will become increasingly difficult to ensure that each project in the Cluster are using the same scenario parameters assumptions, inputs or drivers.

The key differences between the framework presented here and the previous deliverable to the Future Grid Forum's representation of the scenarios is that we identify the:

1. **Distinction between supply- and demand-side drivers**.
    - No explicit delineation between supply- and demand-side drivers
        - Future Grid Cluster is focussed on transmission level models and effects.
        - Project 3 will not be explicitly modelling the costs and impacts of various battery storage scenarios or retail tariff innovations.
            - Project 1 will be examining these aspects of the Distribution system.
        - These will be modelled for by including them as externalities through using the different load growth and load shape scenarios sourced from the CSIRO FGF.
2. **Differentiation between controllable and uncontrollable drivers**.
    - FGF scenarios have no explicit distinction made between controllable and uncontrollable drivers.
    - Examples such as:
        - Carbon pricing policies and developments of new customer pricing frameworks or;
        - States of the World and include variables such as natural gas prices or technology costs.

The reduced scenario representation is an extremely useful tool in order to communicate results and to identify and map the CFGF scenarios to the FGC scenarios controllable and uncontrollable drivers. In **Table 4** we have detailed these linkages and demonstrate how all scenarios (CFGF and FGC) are classified according to both the supply- and demand-side and according to the controllability of these by Australian policy makers.

Table 2: Project 3 and CSIRO Future Grid Forum Scenarios

CSIRO Future Grid Forum Scenarios / **Project 3 Scenarios**			*DG Share*	*EV Uptake*	*Demand Response (Storage)*	*Demand Response HVAC)*	*Demand Response industrial)*	*Disconnections*	*GHG reduction commitment*	*Technology Costs*	*Energy Efficiency*	*Network*	*Gas prices*	*Customer Pricing Framework*	*Large Scale Renewables*
Kernels															
Supply Side		**Kernel Element**													
Technology costs and selection	Fossil Technology costs	1								**X**					
	Renewable/Zero emission Technology costs reduction	*2*								**X**					
Fossil Fuel Costs		*3*											**X**		
Climate policy	Carbon Pricing	*4*							**X**						
	Renewable Energy Target	*5*							**X**						**X**
Demand Side															
Energy Growth (GWh)		*6*	**X**	**X**				**X**			**X**	**X**		**X**	
Demand profile changes	Load Factor Change	*7*	**X**	**X**	**X**	**X**	**X**	**X**			**X**			**X**	
	Day to Night demand peak shift	*8*	**X**	**X**	**X**	**X**	**X**				**X**			**X**	
Policy Support for renewable generation															
Transmission Super projects		*9*													
Scale Efficient Network Extensions		*10*													

Table 3: CFGF Scenarios and drivers[3]

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
DG share	Low	High	High	High
EV uptake	Modest Managed charge profile	Medium-high Managed charge profile	Medium-high Absent charge profile	High Managed charge profile
Demand response (storage)	Equivalent to Resi. 1kW for 5 hours 0-20% 2015-2030 but centrally located in suburb	Resi. 1kW for 5 hours 0-20% 2015-2030 In individual homes	Used off-grid. 5kW batteries plus 2.2kW diesel back-up	Resi. 1kW for 5 hours 0-20% 2015-2030 In individual homes
Demand response (HVAC)	Both resi. and comm. managed	Both resi. and comm. managed	Unmanaged, remaining customers can't afford upfront costs	Both resi. and comm. managed
Demand response (Industrial)	Managed	Managed	Unmanaged, remaining customers can't afford actions	Managed
Disconnections	RAPS only	RAPS only	All existing and new DG owners by 2020	RAPS only
GHG reduction commitment	Moderate carbon price	Moderate carbon price	Moderate carbon price	Moderate carbon price plus extended RET to 100%
Technology costs	AETA projections for CG, CSIRO for DG, storage, large scale solar PV	AETA projections for CG, CSIRO for DG, storage, large scale solar PV	AETA projections for CG, CSIRO for DG, storage, large scale solar PV	Accelerated based on stronger global abatement commitment
Energy efficiency	AEMO moderate growth case based on current price pressures	AEMO moderate growth case based on current price pressures	Low energy consumption due to relatively higher costs for those left on grid	Low energy consumption based on expected higher prices due to lower emissions
Network	Modest expansion. Load factor maintained	Flat. Significant decline in load factor	Flat. Significant decline in load factor	Load factor declining. Expansion to connect renewables
Gas price assumption	AETA medium	AETA low supporting gas on-site generation	AETA low supporting gas on-site generation	AETA medium
Customer pricing framework	Cost reflective supporting engagement	Cost reflective supporting engagement	Non-cost reflective encouraging disconnection	Cost reflective supporting engagement
Large scale renewables	Substantial but some technologies limited by cost of back-up	Substantial but some technologies limited by cost of back-up	Substantial but some technologies limited by cost of back-up	Very high supported by storage and lower costs

[3] CSIRO Future Grid Forum – "Modeling The Future Grid Forum Scenarios", Table 3, page 18.

Table 4: CSIRO Future Grid Forum and the Cluster Project 3 Scenario drivers

		Controllable Drivers	Uncontrollable Drivers
Cluster Project 3	Supply Side	Climate policy Carbon Pricing Renewable Energy Target Transmission Super projects / Super grids Scale Efficient Network Extensions	Technology costs (Affected by overseas policies) Fossil Fuel Costs (Affected by overseas policies)
	Demand Side	Energy Efficiency	Electricity Demand Energy Growth (Annual Energy) Demand Profile Change (Inc. Peak Demand growth/decline)
CSIRO FGF	Supply Side	GHG reduction commitment Large scale renewables	Technology Costs Gas price assumptions
	Demand Side	Network (Investment/price regulation) Customer Pricing Framework Reform (CSIRO FGF) EV Uptake (With managed charging) Demand Response (HVAC) Demand Response (industrial)	Energy Efficiency Disconnections DG Share Demand Response (Storage)

3. Electricity Market Modelling

3.1 Overview of Assumptions

Establishing a set of scenarios which examines the possible future given a set of prior assumptions is a difficult exercise [20-22]. The most common starting point for any investigation using the "Scenario Analysis" methodology [23, 24], is to create a summary of known factors and develop possible sensitivities.

Also as previously discussed in Project 3's last deliverable a counter-factual that may or may not represent our future expected states, but is used as a reference state for comparison [25]. Counterfactual scenarios and have been very useful in creating a reference case against which other scenarios can be compared [2, 4, 26, 24, 27, 28]. The assumptions used to develop this Counter Factual scenario are presented in Deliverables 2a through 4/5 [29, 5, 30, 6, 31, 19, 4, 32], and were originally developed for a similar exercise by this project team [33, 2]. A detailed mapping of each of the scenario framework is presented in Deliverable 3 [4], with a sensitivities and driving factors.

The modelling framework that this project is explored in depth in the prior deliverables [3, 6, 4]. The use of Plexos to model the Australian National Electricity Market has been successfully implemented to examine a range of issues such as: Distributed Generation (DG) [34, 11, 35, 36, 12, 37, 13]; Plugin-Hybrid Electric Vehicles (PHEV's) [15-17]; demand side management [38-42]; assess the effects of climate change [43, 29]; validate the benefits of the intelligent grid [44-46, 31, 47-54]; evaluate Australia's integration with international gas markets [55-57, 32, 58-60]; and evaluating the uptake of renewable generation [47, 61, 62, 7]. Furthermore, this report also uses a specialised natural gas modelling suite developed specifically for Australia's eastern gas market [55, 56]. Establishing the ability of Australia's electricity sector as a competitive and resilient system is also paramount to its longevity and success, with this report contributing to that discussion [63-65]. Technological costs and their full specifications have been discussed extensively in the previous deliverables [30, 6], with Levelised Cost of Energy (LCOE) methodologies derived from [66-70, 61, 71]. Input data for technology specification was derived from AETA [72, 73], AEMO [74-80], IEA [81-85] and EIA [86].

3.2 Electricity Production under Uncertainty

The greatest uncertainties in the NEM in 2016 are policy and regulatory. The implications of a shift in carbon and renewable energy policies will have a dramatic effect on Australia's energy landscape [7]. Furthermore, consumer responsiveness mechanisms such as reduced demand and disconnection are a likely factor in evaluating the future for the NEM. These policies and outcomes are highly sensitive to electricity prices and potential technological advancement [76, 87]. Our first task is to examine the key uncertainties which this project has explored in its modelling of the NEM.

3.2.1 Fuel Price Projections

Coal

While the internationalisation of coal from Australia has yet to make an appreciable impact on domestic black coal prices, Hunter Valley coal producers may make the decision to export their coal in the future. We have diverged from the CFGF and assumed a medium coal price forecast. We will use the medium black and brown coal forecasts from the recent 2014 AEMO NTNDP [78] as its initial benchmark price (see **Figure 2**). The possibility of competition between coal exports and power production will be left for future research.

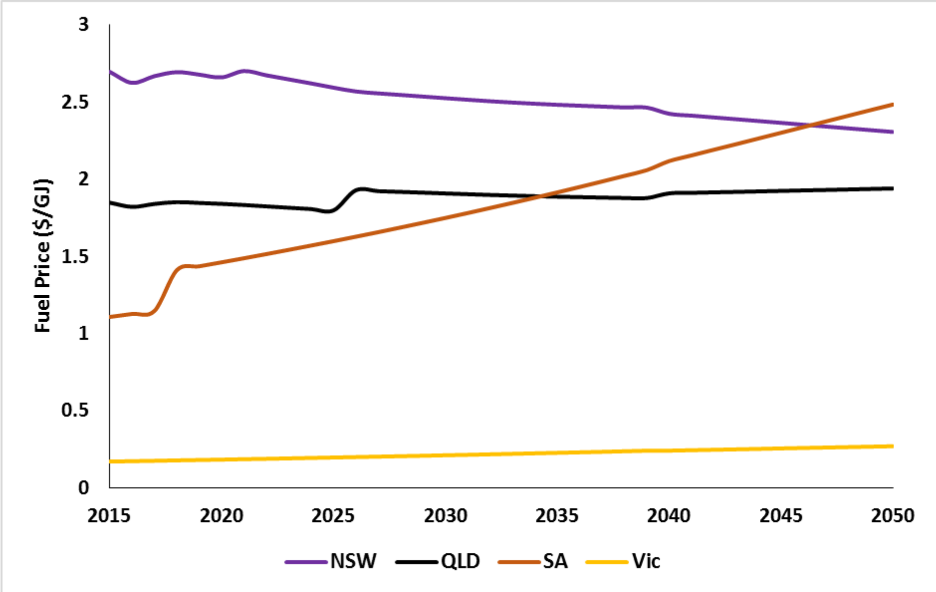

Figure 2: Projected Coal Prices (Medium Forecast) [88-90, 76, 78-80, 91, 92, 72, 73].

Natural Gas Prices

As previously outlined in Project 3 deliverables, this project has developed an integrated gas modelling framework and the price forecast which we have detailed below is the medium case scenario (see **Figure 3**). Furthermore, the gas forecast presented in earlier reports diverges with the expectations of forward prices present by the CFGC [8] by at least 30-50% and those presented in [93-95], due not only to the methodological differences but also with respect to the assumed international market conditions. It should be noted that since that our initial modelling, natural gas prices have been suppressed by Saudi Arabian oil production increases which have flowed onto the Japanese market and consequentially, Australian natural gas markets due to their linkage with oil [96].

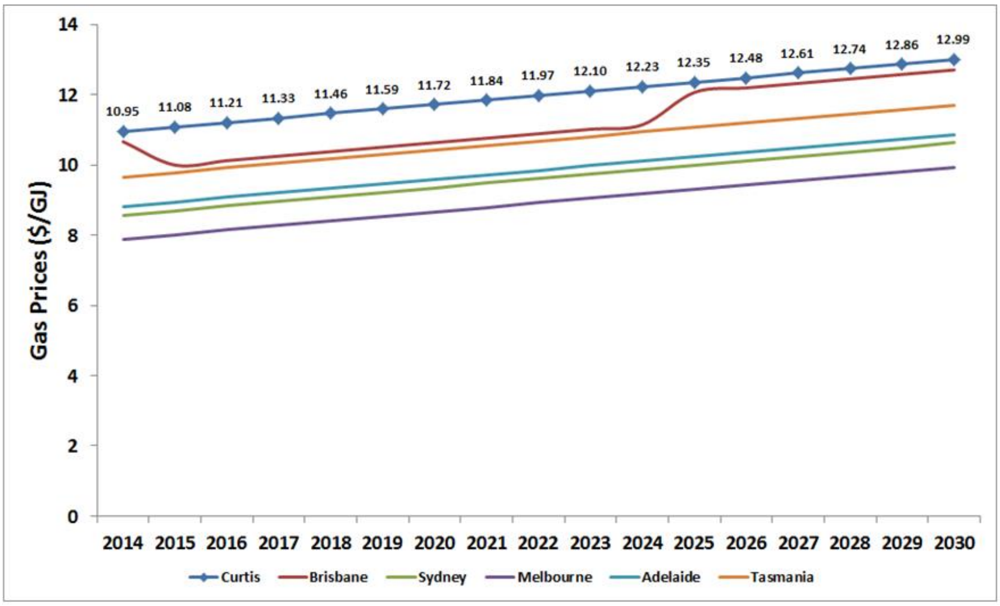

Figure 3: Natural Gas Spot Prices Base Case Scenario

3.3 Electricity Generation and Spot Market behaviour

The spot market wholesale electricity price is highly contingent on a number of modelling assumptions and overarching policy settings. The main drivers of spot price are: new generation technology costs; carbon and renewable energy certificate prices and above all else, fuel prices. These factors interact in a variety of ways in electricity market behaviour and the primary focus of this report is to examine a few of the major outcomes from this modelling. We will continue to adopt the assumption for this work that the implementation of a carbon pricing mechanism to reduce the effects of stationary energy on sector has on the environment will be implemented. Furthermore, we will report here the results which represent continued support for the deployment of renewable energy under the adapted Renewable Energy Target of 33TWh/year. For each of the scenarios we have replicated the intent of the original CSIRO Future Grid Forum scenarios package and the methodology and scenario development for this cluster project have previously been explored at length (see [19, 4]). However, we will explore here two major sensitivities and case studies which diverge from these CFGF scenarios to give some further clarity on current and prevailing energy market conditions which will require further thought by policy makers in the future.

The gas price sensitivities which have been modelled for the entire planning horizon (2016-2040) are most of interest to Australian policy makers. The low gas price sensitivity case (Scenario 1) shows that while depressed LNG prices may result in low cost domestic gas supplies and it is unlikely to facilitate the uptake of renewable generation (see **Figure 4** below). The wholesale market behaviour of natural gas generators and their coal fired counter-parts results in unexpected consequences in the whole of market model [32] (see case study below in section 3.3.1).

The uncertainty associated with natural gas prices and future energy policy in the low sensitivity is indicated by low and non-volatile electricity prices which are indicative of market stagnation. The reliability of a long run fuel price forecast which quite clearly explores the long term burner tip equivalent floor price [97] is questionable. Furthermore, the likelihood that this somewhat, short term trend of low natural gas prices due to the international oil price linkages would continue beyond the next few years is very unlikely. However, the usefulness of this sensitivity is not lost by this project team. The low price sensitivity could be viewed as a "what if" we did rely on this low price as a basis for generation investment. This priory, has indeed occurred several times in the past [88] and has led us to the pre-internationalisation of natural gas price situation of gas being a viable transitionary fuel [2].

Scenario 1 with medium gas price sensitivity, we can observe the most likely outcome for the market from the assumptions associated with "Set and Forget" scenario. The shift towards a gas fired intermediate solution for the reduction of emissions in the electricity sector is unlikely to facilitate long term stability in wholesale electricity prices. Given the internationalisation of gas in the NEM, wholesale gas prices will continue to ebb and flow with our major LNG consumers. This cyclical price behaviour of natural gas only amplifies the uncertainties faced in making investment decisions in electricity generation.

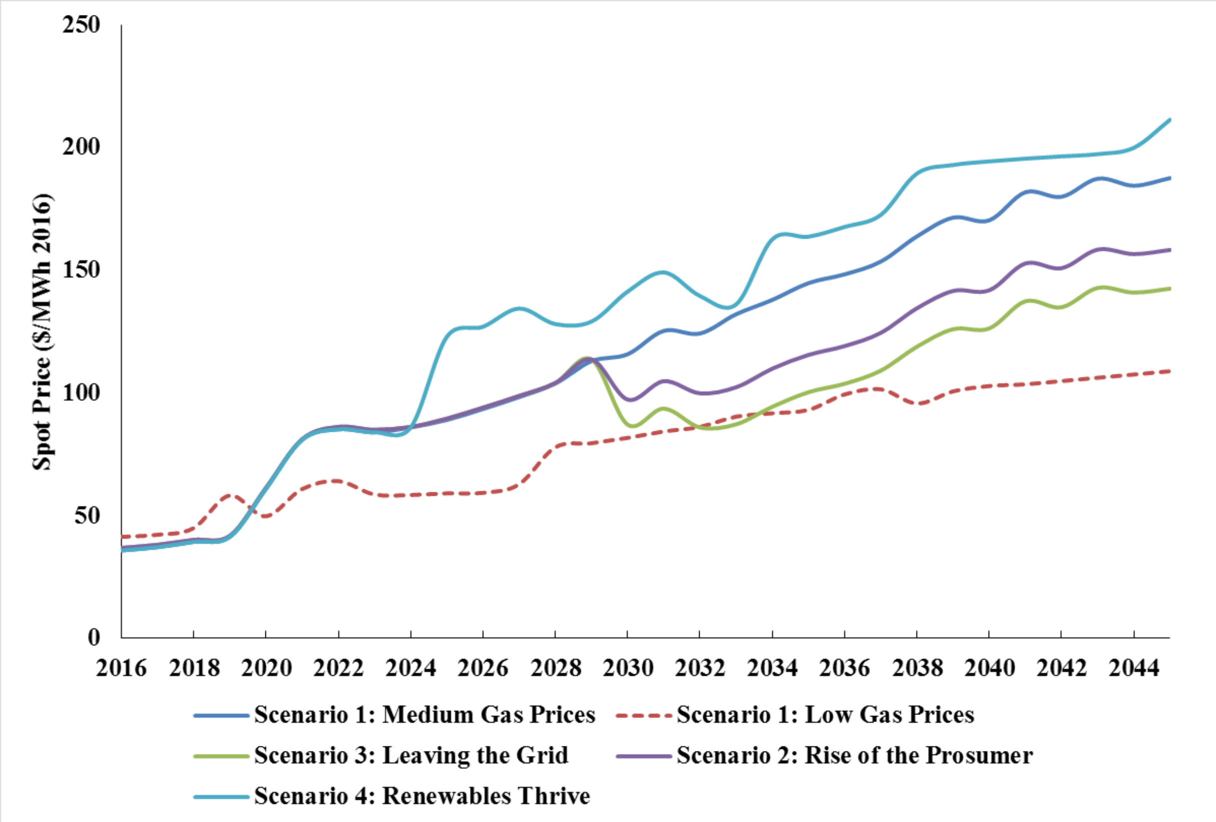

Figure 4: Future Grid Scenario Price Results Comparison

Following the outcomes presented in the previous reports (Deliverable 4 and 5) the project created a proof of concept analytical framework in order to analyse the CFGF modelling and Project 3 capabilities. Furthermore, following this modelling exercise with the input assumptions from the CFGF, updated analysis has come to hand [19, 4], that as shown previously [1] replicate the methodology of [8]. Thus via our scenario formulations presented previously in [19, 4] we can further the work of CSIRO with two case studies. These two cases model the electricity spot market in much greater detail [11, 7, 32]. Firstly the greatest departure from the CSIRO modelling is that full half hourly dispatch is used to examine electricity market behaviour. The doubling in resolution and finer grained detail of all input assumptions results in: higher rates of spot market volatility (and thus higher average prices); generation portfolio behavioural patterns which more closely represent market outcomes. However, it should be noted that the computational requirements for simulating long planning horizons at half hourly (or 5 minute) intervals are currently not available to this project. While **Figure 4** represents a marginal departure from the outcomes of the CFGF, the assumptions and generation investment pathways are almost identical.

We shall now explore two key case studies which represent Scenarios 1 and Scenario 2 which, when used in tandem are largely the current policy settings and the largely ideal outcomes for Australia's National Electricity Market. While Scenarios 3 and 4 represent the possible worst case outcomes of in-action on behalf of policy makers, the integration of a Scenario 2 as the "Renewables Thrive" grid connected high consumer participation (prosumer flavoured) paradigm is one that deserves further investigation in this context.

3.3.1 Case Study 1: Shift of Coal to Gas (Scenario 1)

To better understand the use of gas as a transitionary fuel source, we have examined more closely the potential impacts that this might have on the "Set and Forget" for the CFGF analysis. This case study represents a more thorough analysis of 2035 as a key planning point in the planning horizon from a domestic and international perspective [32] . Furthermore, it is our intention here to highlight the possible adverse effects that reliance on (Very)-low priced natural gas might have on the NEM.

It is assumed that existing plant is retired based on its technical lifespan with the remaining plant participating in the market in 2035. Investment in wind power is based on reaching the country's 2020 target of 20% of generation from renewable sources which would result in deployment of 12GW of wind power by 2020. Deployment of new plant in the NEM is calculated based on demand, fuel and capital cost projections by the Australian Energy Market Operator (AEMO). Other than the use of a forecast Carbon Price, no portfolio optimization is undertaken. Significantly, domestic gas prices are forecast to increase to ~$8/GJ by 2035 as a result of the investment in liquefied natural gas (LNG) facilities to gain access to lucrative international markets compared to an estimated weighted average price of ~$2/GJ for coal in 2035.

Three case studies sensitivities were considered: a no Carbon Price scenario (Scenario 1A); a Carbon Price as projected by the Australian Treasury to be $159 by 2035 if the concentration of CO_2 in the atmosphere is to be limited to 450 parts per million (Scenario 1B); and a Carbon Price as projected by the Australian Treasury likely to be $74 by 2035 (Scenario 1C).

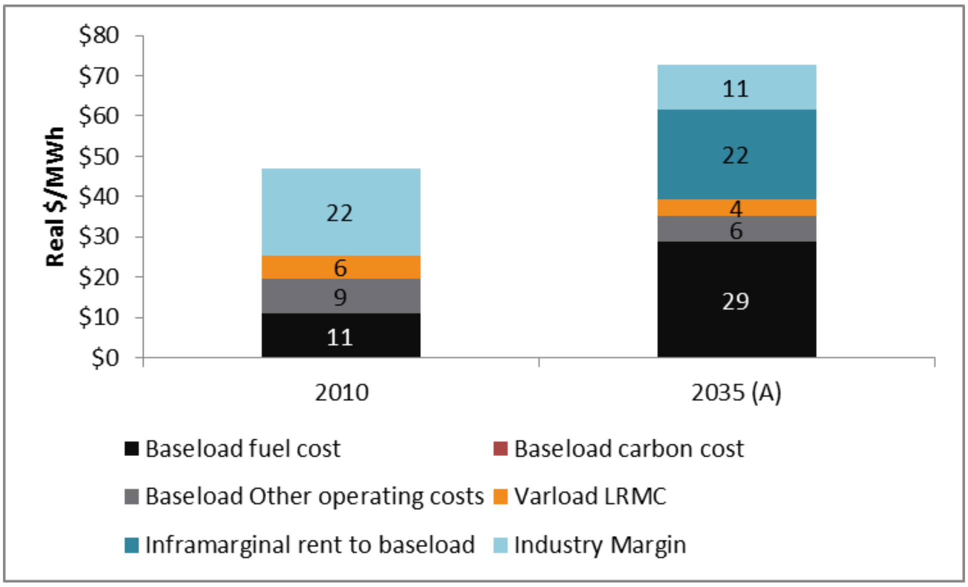

Figure 5: Breakdown of components of Spot price after a shift to gas with no carbon price

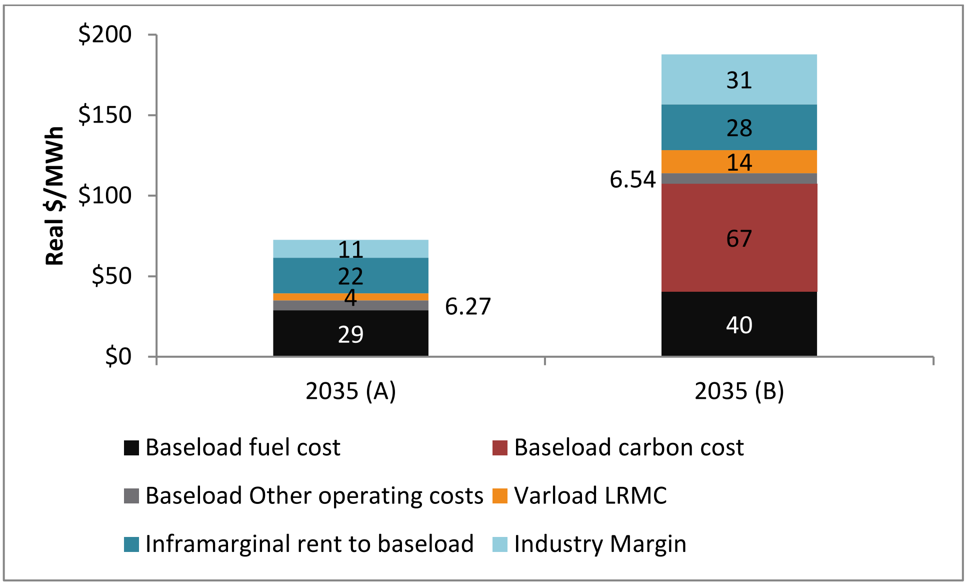

Figure 6: Breakdown of components of Spot price with a high carbon price

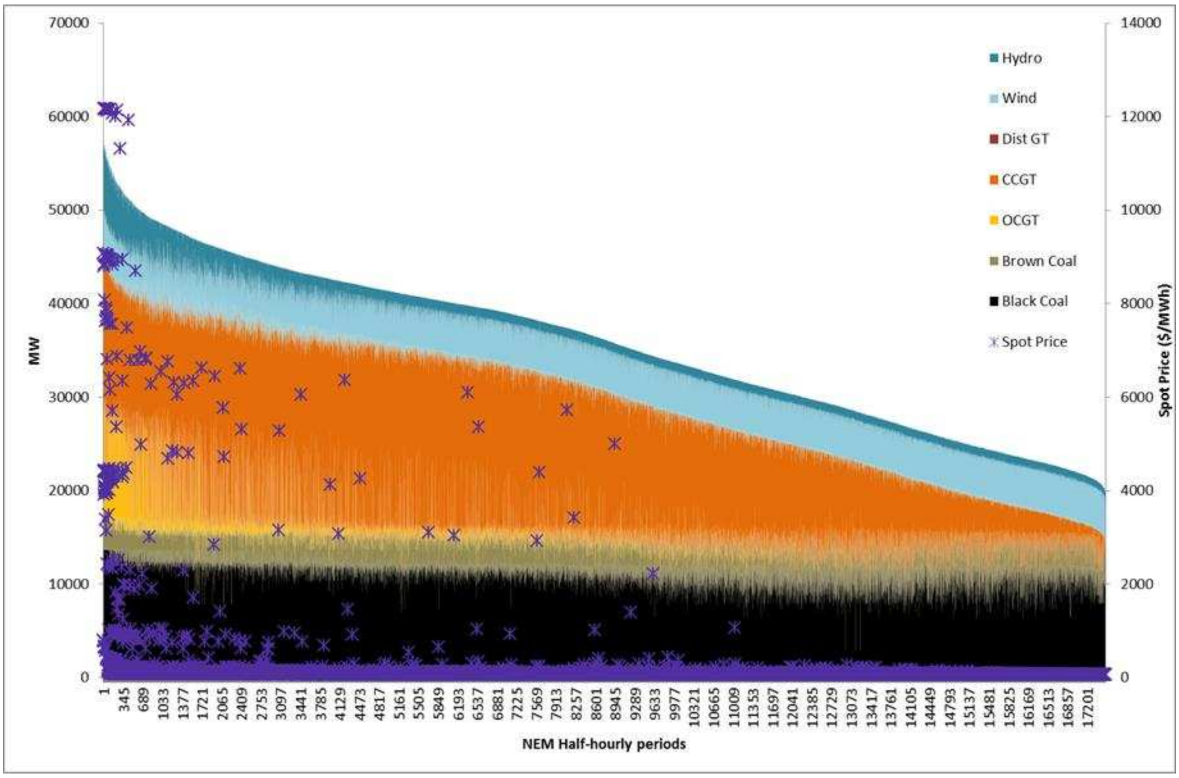

Figure 7: Load duration curve with Spot price for 2035 Scenario 1C

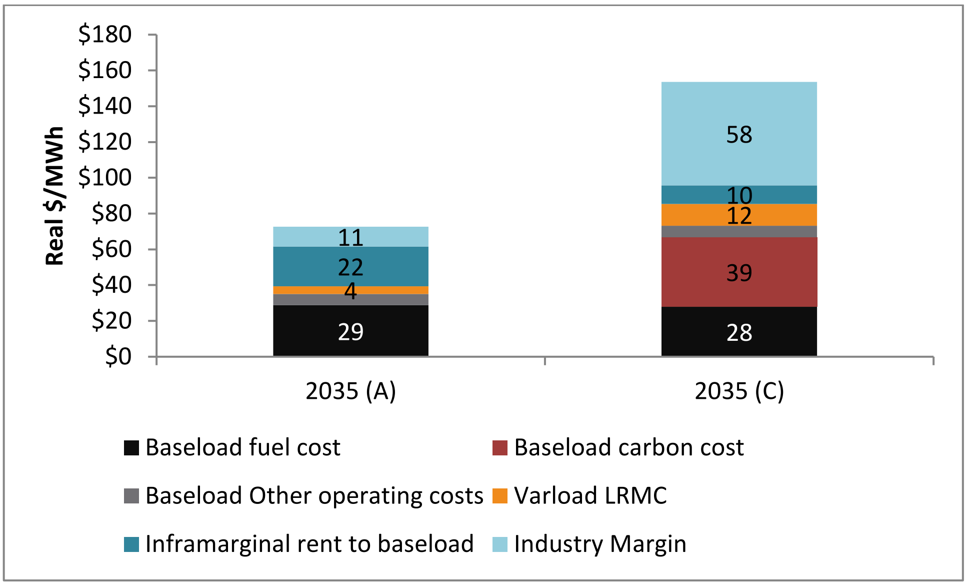

Figure 8: Breakdown of components of Spot price with a mid-range carbon price

The modelling predicts that 7TWh would shift from coal to gas generation as a result of the Carbon Price. This requires only small adjustments to investment to meet demand compared to Scenario 1A. Carbon cost would add $13.5 billion to the generation cost bill, so there would be an expectation for a pass-through of around $43/MWh. While attempting to cover these costs, the model predicts that generators will bid such that the weighted average Spot price increases from $73/MWh without a Carbon Price to $154/MWh, an increase of $81/MWh.

If we look to the costs associated with increased gas-fired generation, we find that gas increases costs by $2/MWh and the Carbon Price increases costs by $43.38/MWh. This fuel and CO_2 cost explains the $45/MWh wholesale price increase which confirms that the costs are passed on in full, but there is still a gap of$36/MWh to the average price as bid.

When we examine infra-marginal rents accrued it is shown that the marginal baseload generator is a combined cycle gas-fired generator with a SRMC of $110/MWh as opposed to the average SRMC for coal fired generators of $81.75/MWh. This gap of $28.25/MWh is applied to 114,438GWh of coal-fired baseload generation, providing a windfall gain of $3.2 billion to coal-fired generators. This equates to $10.35/MWh for infra-marginal rents which falls short of the increase in weighted average Spot price.

On further analysis of the demand and price bids, Scenario 1C showed considerable evidence of volatility. Historical actual annual standard deviation in Spot price from 2000 to 2010 ranged between $81.63 and $194.27/MWh (the highest annual average Spot price was in 2007 when Queensland generators were constrained by water shortages) on annual mean Spot prices of between $24.72 and $65.50/MWh. When modelling the market response in 2035, Scenario 1A showed an annual standard deviation in Spot price of $17.69 on annual mean Spot price of $78.10/MWh. However, modelling for Scenario 1C shows an annual standard deviation on Spot price of $642.73. This volatility is clustered around 8 distinct events where prices surged for between 13 and 18 hours, in different groups of states. We assume that PLEXOS calculated that one or more generators would fail to bid where margins were too low, resulting in a reduction in supply and significant volatility which would drive up Spot price and baseload margins. We tested this assumption by removing the Spot prices for the 8 distinct events and replacing them with pricing for the same day and time from a week after each event. This adjustment caused the standard deviation to drop to $138.14 on a mean Spot of $90.04. However, a weighted average Spot price of $90 would result in baseload gas-fired generators operating at a gross loss (i.e. LRMC greater than Revenue) and coal-fired generators would be operating at no margin at all (i.e. LRMC equal to Revenue).

3.3.1.1 *Discussion of Case Study 1 results*

We therefore conclude that generators are compelled to introduce volatility into bidding behaviour on the wholesale electricity market when profits are too low to sustain baseload generator margin. Historically, infra-marginal rent has allowed generators to pay fixed costs and earn profit. Reasonable profit- levels helps to underpin market stability. Where infra-marginal rent is too low to cover fixed costs, there is an inherent incentive for generators to find a way to drive prices up to make a profit. Figure 4 provides detail of the contribution of costs to Spot price under a mid-range carbon price. As with Scenario 1A, there is no evidence that wind power has a material impact on the average Spot price.

Table 5: Summary of weighted average Spot price components

Cost component	Scenario 1A (No Carbon price) ($/MWh)	Scenario 1B ($159 Carbon price) ($/MWh)	Scenario 1C ($74 Carbon price) ($/MWh)
Baseload fuel cost	28.75	40.44	27.97
Baseload carbon cost	0.00	67.05	38.75
Baseload other costs	6.27	6.54	6.49
Varload LRMC	4.39	14.32	12.17
Inframarginal rent	22.14	28.47	10.35
Industry margin	11.04	30.97	57.87
Weighted avg Spot	**72.59**	**187.78**	**153.61**

So, whilst the increased costs associated with gas and Carbon Price is passed through in full, generators need to engage in strategic behaviour to operate at acceptable margins. Emissions decrease from 174 mtpaCO_2 in Scenario 1A to 167 mtpaCO2 in Scenario 1C, indicating a very small improvement in abatement as a result of the shift to a Carbon Price. This would suggest that even the introduction of a mid-range Carbon Price and substantially higher electricity wholesale prices would not achieve the desired abatement goal.

Whatever drives bidding behaviour, consumers are likely to face a substantial electricity price increase as a result of a significant shift to gas-fired generation. This suggests that the energy sector should remain cautious in promoting a technology that employs gas as a ‘transitional' fuel for power generation.

3.3.2 Case Study 2: Renewables Thrive with Prosumer Tendencies (Scenario 2A: Consumer Action)

The dominant industry view is that gas is a transition fuel which allows Australia to reduce its emissions from power generation at an affordable price [98, 7]. In general, many groups share the view that renewable energy is too expensive and unreliable to be a major component of the energy generated to meet demand. These views have been predicated on different drivers; for instance the low power densities of renewable sources of energy are considered to be insufficient for current consumption habits [99]; and the technical limitations of the current electric power system make it prohibitively expensive if not impossible to overcome the issues of intermittency, variability and flexibility associated with specifically wind and photovoltaic power [100]. At the other end of the spectrum, groups are promoting very aggressive renewable energy deployment to meet carbon emission targets to allow Australia to meet its commitment of an 80% reduction in emissions by 2050 [101].

We consider 2 further cases, where Scenario 1A (Medium gas sensitivity), which reflects the dominant industry view, and a Consumer Action Scenario (2A) which predicts that renewable energy will be deployed as a result of public support and the industry will be influenced by a global roll out of new technologies that are emerging as a result of developments in Europe, Japan and China.

In light of the significant lack of bipartisan support for the Carbon Price legislation and the aggressive infrastructure switch required to serve energy from only renewable energy sources, our Consumer Action scenario recognizes the significant resistance within Parliament, Government and the industry to substantial upheaval in the generator fleet and the delivery of power. The scenario accepts the need for continued dispatch from the existing fleet whilst it is efficient and cost effective to do so, replacing retired generators and meeting new demand with renewable and distributed generation as a transition rather than a revolution. Bearing in mind the quantum of sunk costs in existing infrastructure and what Smil refers to as the inertial reliance on existing technology [99], a scenario that is predicated on a complete replacement of the existing fleet by 2035 would require such an upheaval that, in our opinion, it is unlikely to be realistic. For this reason, to make a pragmatic comparison, we assume that the fleet will either be augmented by gas-fired generation as in Scenario 1A, or by renewable and distributed generation, as in the Consumer Action scenario.

Generation from renewable sources of energy reduces the power system's exposure to global fuel price volatility and therefore provides certainty with respect to energy and power prices. With a focus on diversifying fuel sources toward renewable energy, this scenario effectively mitigates against the global energy forces that will predominate in the future. As Australian peak demand has increased dramatically to address the hottest days of the year, generating power from rooftop solar for use when summer demand peaks, will directly reduce the need to bolster network capacity for just a few hours' of peak demand a year. A reduction in investment in the distribution network will reduce the potential for sharply increasing retail electricity prices because of network infrastructure requirements. When it comes to reducing emissions, renewable forms of generation offer the most significant reduction in emissions. This will better enable Australia to act effectively on climate change and ensure that a public requirement for action on climate change is respected. Power from renewable energy comes at a high capital cost, but this has to be balanced against the reduced cost of fuel many decades after installation. Whilst the capital cost of this scenario is a barrier to renewing the generator fleet, it should not be forgotten that the generator behaviour predicated in the model indicates that wholesale prices will be lower than prices for Scenario 1.

A substantial shift to renewable forms of generation shows that this scenario actively addresses a public expectation to transition to more sustainable forms of power. With European deployment of renewable and distributed generation and Asian development of affordable production of renewable and distributed technologies, the CA scenario recognizes that there are technology changes underway globally that need to be addressed rather than deflected. Australia made a commitment to open participation in a global economy in the 1990s, the transformation of its power system should reflect that openness and willingness to embrace technological advancement and a transition to greater levels of sustainable development.

When we compare the two scenarios Scenario 1A (as our BAU) and Scenario 2A (as a Consumer Action Prosumer Paradigm), relying on fuels that are vulnerable to volatile global markets increases the risk of rising wholesale costs. The BAU scenario has a higher fuel cost component than the CA scenario, and a higher non-renewable fuel cost component which could be more volatile than domestically available renewable fuels (biomass and biogas) as can be seen in **Figure 9**.

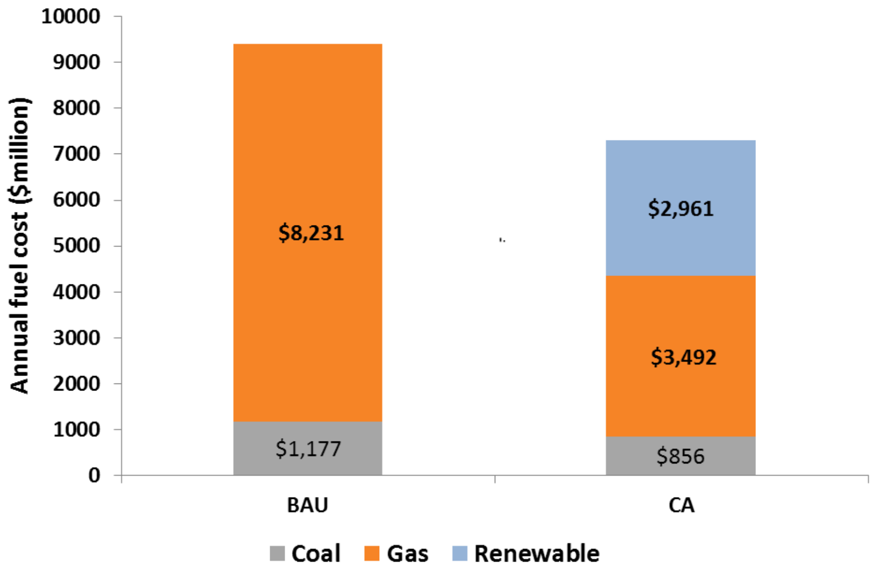

Figure 9: Annual fuel cost

Emissions reductions under BAU are very limited, whereas emissions reductions under CA are much higher. Whilst the emissions under CA are much better than BAU, emissions reductions to 32 mtpaCO2 by 2050 would still pose a substantial challenge for the power industry to achieve. Figure 3.2 shows the difference between the 2 cases.

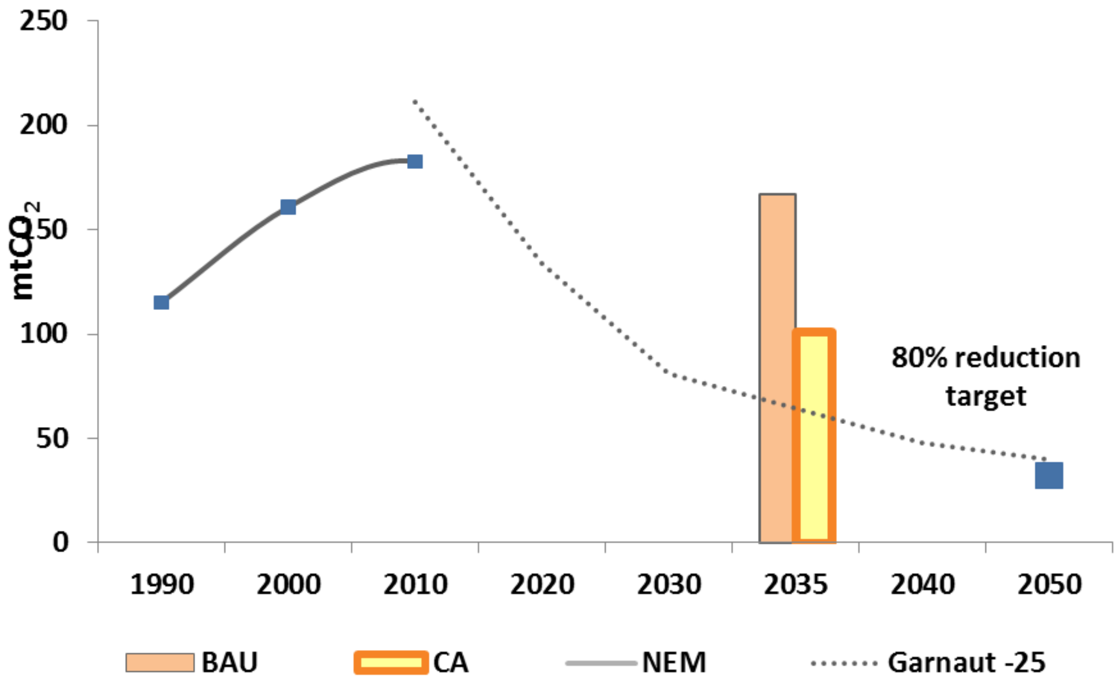

Figure 10: Scenarios proximity to 80% reduction

The scenarios offer very different capital investment and fuel cost profiles. BAU offers relatively low cost capital renewal, versus CA which requires a high upfront capital spend coupled with lower annual fuel costs. Whilst the upfront capital cost for CA appears daunting, it should be noted that it offers the opportunity to spread the costs of generation investment across a wider base thereby reducing the risks associated with having to pick winners from amongst a complicated array of expensive technology options.

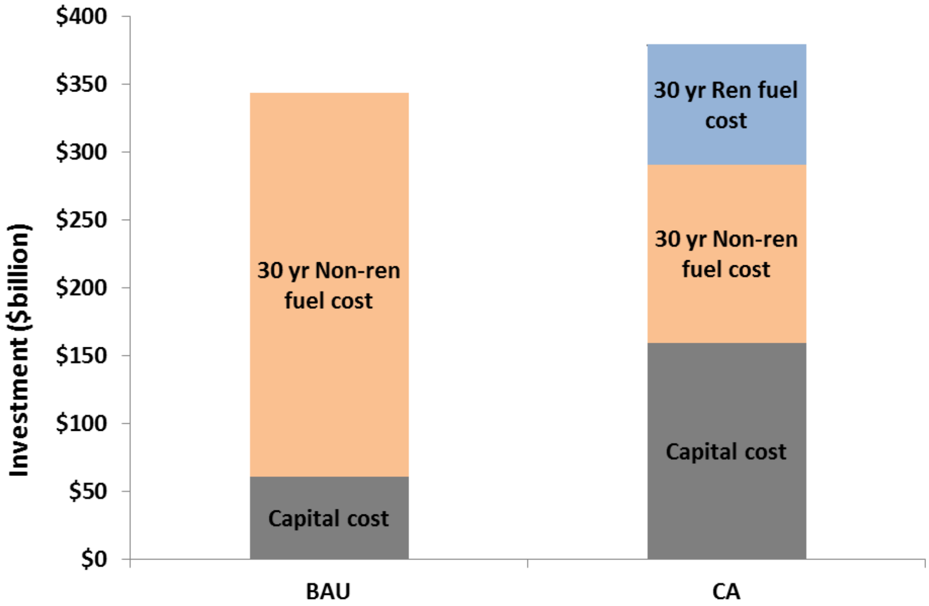

Figure 11: Investment required

The BAU scenario essentially shifts generation from coal to gas whilst the CA scenario deploys generation with a considerably higher diversity of fuel source. Having a higher diversity of generation, adds considerably to resilience, reducing vulnerability to fuel, technology and carbon lock-in. Figure 3.4 provides a breakdown of the proportion of generation from different renewable energy sources

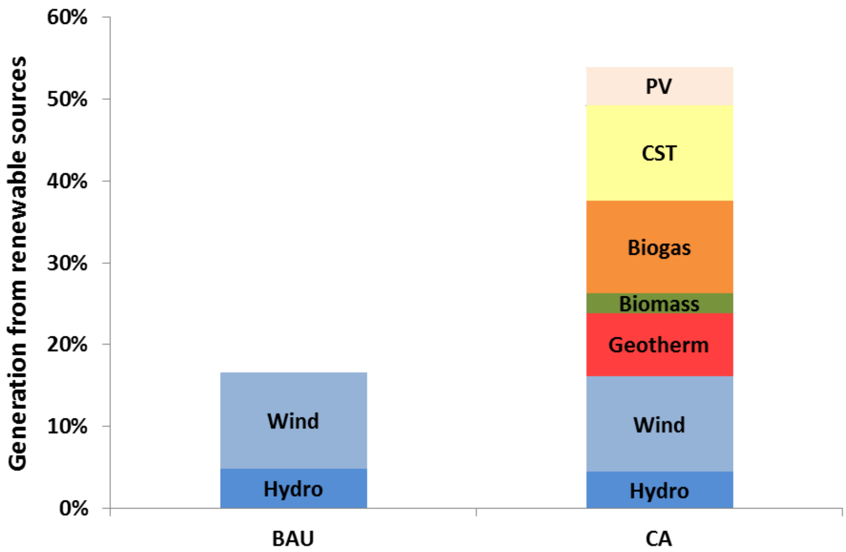

Figure 12: % of Generation from Renewable sources

3.3.2.1 Discussion of Case Study 2 results

The modelling undertaken shows no evidence that a shift from coal-fired generation to gas-fired generation will enable Australia to improve its carbon emissions. Furthermore, there is no apparent justification for the claim that a high proportion of energy sourced from renewable technology will increase wholesale electricity prices in comparison to a power system which would need to be heavily dependent on gas. The results also suggest that if current levels of investment are refocused to create a more robust distribution network that is capable of accommodating more DG rather than meeting peaky demand, then the money would have been well spent.

The results of this case study do somewhat indicate that pursuing a gas-centric grid may lead to increased prices and reduced carbon emissions, there would certainly be much more work needing to be done in order to change the dominant industry view which is appears intent on replacing coal with gas.

4. Conclusion

The delivery of power to all consumers is becoming an increasing difficult responsibility of the energy sector. This task is becoming even more challenging with the rise of consumer response to prices and the rapid deployment of new generation technology on to the electricity grid. However, the breadth of obligations borne by the electricity sector has increasing become more uncertain due to policy stagnation and uncertainty.

While, the primary role of the sector may be changing, the Future Grid will have to be one that is more adaptable to changing technology and consumer responsiveness. The National Electricity Market (NEM), is difficult to conceptualise from a top down perspective. Developing our understanding of how electricity markets will begin to change as we transition towards a disruptive future will require a multidisciplinary approach.

Modelling the NEM in conjunction with the eastern Australian gas market is a difficult process which requires substantial analysis of the physical, financial and economic components of two seemingly different markets [55, 56]. Our results show that a shift towards a gas fired intermediate solution for the reduction of emissions in the electricity sector is unlikely to facilitate long term stability in wholesale electricity prices.

The deployment of renewable generation and its ability to impact the emissions intensity of the stationary energy sector will require continued regulatory enablement. While the capital costs of renewable electricity generation have fallen and continue to fall, international fossil prices slumps will have a negative impact on their deployment rates.

With the potential for a large number of consumers who could potentially leave the grid under a “disconnection scenario” a broad disparity in pricing could emerge. Thus, the prosumer driven methodology in the future will need to encompass a shift to viewing consumers as added potential grid support. This approach will engage consumers and highlight their need to be more active in managing their demand behaviour while facilitating many of the policy requirements of maintaining the grid at large. Furthermore, this project continues to develop a broader understanding of the social benefits of grid connection. It must be emphasised that connection to the grid is undervalued not only as back stop technology, but also as a societal good

The energy modelling frameworks developed by this project have shown that energy policy must evolve constantly. The outcomes of this project make it clear that the National Electricity Market will be better able to plan for changing international conditions coupled with shifting consumer energy needs.

5. Bibliography

[1] Foster, J., L. Wagner, and A. Liebman, *Modelling the Electricity and Natural Gas Sectors for the Future Grid: Developing Co-Optimisation Platforms for Market Redesign*. 2015.

[2] Foster, J., et al., *Delivering a competitive Australian power system Part 2: The challenges, the scenarios*. 2013, School of Economics, University of Queensland, Australia.

[3] Foster, J., A. Liebman, and L. Wagner, *Deliverable 2a: The Scenarios. 2014*. 2014.

[4] Foster, J.L., Ariel; Wagner, Liam, *Deliverable 3: Cluster Scenarios and Relationship with the CSIRO Future Grid Forum.* 2014, University of Queensland: Brisbane. p. 14.

[5] Foster, J., et al., *Delivering a competitive Australian power system Part 3: a better way to competitive power in 2035.* 2013.

[6] Foster, J., L. Wagner, and A. Liebman, *Modelling the Electricity and Natural Gas Sectors for the Future Grid: Developing Co-Optimisation Platforms for Market Redesign.* 2015.

[7] Molyneaux, L., et al., *Australian power: Can renewable technologies change the dominant industry view?* Renewable Energy, 2013. **60**: p. 215-221.

[8] Graham, P., Brinsmead, T., Dunstall, S., Ward, J., Reedman, L., Elgindy, T., Gilmore, J.*, Cutler, N.*, James, G., Rai, A., and Hayward, J. , *Modelling the Future Grid Forum scenarios*. 2013, CSIRO: Newcastle, NSW, Australia.

[9] Defeuilley, C., *Retail competition in electricity markets.* Energy Policy, 2009. **37**(2): p. 377-386.

[10] Joskow, P.L., *Lessons learned from electricity market liberalization.* The Energy Journal, 2008. **29**(2): p. 9-42.

[11] Lilley, W., et al., *An economic evaluation of the potential for distributed energy in Australia.* Energy Policy, 2012. **51**(1): p. 277–289.

[12] Wagner, L.D. and L. Reedman. *Modeling the Large Scale Deployment of Distributed Generation onto Electricity Markets*. in *29th USAEE/IAEE North American Conference, "Energy and the Environment: Conventional and Unconventional Solutions" October 14-16, 2010*. 2010.

[13] Wagner, L.D. and L. Reedman. *Modeling and Analysis of Spot Market Volatility Following the Large Scale Deployment of Distributed Generation onto Australia's National Electricity Market*. in *36th International Energy Economics Association Conference, Stockholm Sweden, June 2011*. 2011.

[14] Reedman, L. and L.D. Wagner. *Can the Large Scale Deployment of Distributed Generation Onto Electricity Markets Reduce Carbon Emissions: An Australian Case Study*. in *36th International Energy Economics Association Conference, Stockholm Sweden, June 2011*. 2011.

[15] Wagner, L. and L. Reedman. *Modeling the deployment of plug-in hybrid and electric vehicles and their effects on the Australian National Electricity Market*. in *Innovative Technologies for an Efficient and Reliable Electricity Supply (CITRES), 2010 IEEE Conference on*. 2010. IEEE.

[16] Wagner, L.D. and L. Reedman. *Estimating Grid Impacts from the Deployment of Plug-in Hybrid and Electric Vehicles: Results for South-East Queensland*. in *2nd Asian Conference of IAEE, Perth November 2008*. 2008. International Association of Energy Economics.

[17] Wagner, L.D. and L. Reedman. *Establishing the potential grid benefits and detractions of the deployment of vehicles to grid electric vehicles*. in *IAEE Conference, Perth, Australia, June 2012*. 2012. International Association of Energy Economics.

[18] Byrnes, L., et al., *Australian Renewable Energy Policy: Barriers and Challenges.* Renewable Energy, 2013. **60**: p. 711-721.

[19] Foster, J.L., Ariel; Wagner, Liam, *Deliverable 2a: The Scenarios*. 2014, University of Queensland: Brisbane. p. 14.

[20] Chermack, T., S. Lynham, and W. Ruona, *A review of scenario planning literature.* Futures Research Quarterly, 2001. **17**(2).

[21] Godet, M. and F. Roubelat, *Creating the future: the use and misuse of scenarios.* Long range planning, 1996. **29**(2): p. 164-171.

[22] Morrison-Saunders, A. and J. Pope, *Conceptualising and managing trade-offs in sustainability assessment.* Environmental Impact Assessment Review, 2013. **38**(0): p. 54-63.

[23] Fligstein, N. and D. McAdam, *Toward a General Theory of Strategic Action Fields.* Sociological Theory, 2011. **29**(1): p. 1-26.
[24] Kahn, H. and R. Aron, *Thinking about the Unthinkable*. 1962: Horizon Press New York.
[25] Wohlstetter, R., A.W. Marshall, and J.J. Martin, *On not confusing ourselves: essays on national security strategy in honor of Albert and Roberta Wohlstetter*. 1991: Westview Pr.
[26] Kahn, H., *On thermonuclear war*. 2007: Transaction publishers.
[27] Kahn, H. and A.J. Wiener, *The next thirty-three years: a framework for speculation.* Daedalus, 1967: p. 705-732.
[28] Kahn, H.M., Irwin, *War Gaming*. 1957, The RAND Corporation: Santa Monica. p. 14.
[29] Foster, J., et al., *Analysis of institutional adaptability to redress electricity infrastructure vulnerability due to climate change.* 2013.
[30] Foster, J., L. Wagner, and A. Bratanova, *LCOE models: A comparison of the theoretical frameworks and key assumptions*. 2014, University of Queensland, Australia: Brisbane, Australia.
[31] Foster, J., et al., *Market and economic modelling of the impact of distributed generation.* Energy Economics and Management Group, The University of Queensland, Brisbane, Australia, 2011.
[32] Wagner, L., L. Molyneaux, and J. Foster, *The magnitude of the impact of a shift from coal to gas under a Carbon Price.* Energy Policy, 2014. **66**: p. 280-291.
[33] Ball, B., et al., *Delivering a competitive Australian power system Part 1: Australia's Global Position.* 2011.
[34] Foster, J., L. Wagner, and L. Byrnes, *A Review of Distributed Generation for Rural and Remote Area Electrification.* Energy Economics and Management Group, The University of Queensland, Brisbane, Australia, 2014.
[35] Wagner, L., *Impacts and Benefits of DG on the NEM*, in *Intelligent Grid: A Value Proposition for Distributed Energy in Australia, CSIRO Report ET/IR 1152*. 2009, CSIRO. p. 368-405.
[36] Wagner, L.D., *The effects of large scale deployment of distributed generation on the national electricity market.* Uniquest Project, 2009(16018).
[37] Wagner, L.D. and L. Reedman. *Can the Large Scale Deployment of Distributed Generation Onto Electricity Markets Reduce Carbon Emissions: An Australian Case Study*. in *36th International Energy Economics Association Conference, Stockholm Sweden, June 2011*. 2011.
[38] Froome, C., L. Wagner, and J. Foster. *Energy Storage Technology Options for Distribution Networks - More Than Just the Economic Cost*. in *32nd USAEE 2013, Anchorage Alaska*. 2013. US Association of Energy Economics.
[39] Froome, C. and L.D. Wagner. *Energy Storage and its Ability to Add Stability to Intermittent Generation and Reduce Distribution Network Costs*. in *29th USAEE/IAEE North American Conference, "Energy and the Environment: Conventional and Unconventional Solutions" October 14-16, 2010. Calgary, Canada*. 2010.
[40] Froome, C. and L.D. Wagner. *The Benefits of Embedded Storage within a Localised Distribution Network*. in *8th Asia Pacific Conference on Sustainable Energy & Environmental Technologies, Adelaide July 2011*. 2011.
[41] Froome, C., L.D. Wagner, and J. Foster. *The effectiveness of energy storage to reduce peak demand on the Australian national electricity market*. in *IAEE Conference, Perth, Australia, June 2012*. 2012. International Association of Energy Economics.
[42] Wagner, L.D., C. Froome, and J. Foster. *Modeling the Broader Deployment of Demand Side Management onto the Australian National Electricity Markets*. in *30th USAEE/IAEE Conference, Washington DC., USA, October 9-12 2011*. 2011. International Association of Energy Economics.
[43] Foster, J., et al., *Institutional adaptability to redress electricity infrastructure vulnerability due to climate change.* 2012.
[44] Alkire, S. and J. Foster, *Counting and multidimensional poverty measurement.* Journal of public economics, 2011. **95**(7): p. 476-487.

[45] Foster, J., L. Wagner, and A. Liebman, *CSIRO Intelligent Grid Cluster Interim Report 1 January 2009.* 2009.

[46] Foster, J., et al., *CSIRO Intelligent Grid Cluster April 2011.* 2011.

[47] Foster, J., et al., *CSIRO Intelligent Grid Cluster: Milestones 7 & 8 Combined Report.* 2011.

[48] Foster, J., et al., *Final Report: Market and Economic Modelling of the Intelligent Grid.* Energy Economics and Management Group, The University of Queensland, Brisbane, Australia, 2011.

[49] Foster, J., et al., *Market and economic modelling of the impact of distributed generation.* Energy Economics and Management Group, The University of Queensland, Brisbane, Australia, 2011.

[50] Foster, J., et al., *Market and economic modelling of the intelligent grid: interim report.* 2011.

[51] Foster, J., et al., *Intellegent Grid Research Cluster-Project 2: marketing and economic modelling of the impacts of distributed generation.* 2011.

[52] Foster, J., et al., *Market and Economic Modelling of the Intelligent Grid: End of Year Report 2009*. 2011, School of Economics, University of Queensland, Australia.

[53] Foster, J., et al., *CSIRO Intelligent Grid Cluster End of Year Final Report August 2009.* 2009.

[54] Foster, J., et al., *CSIRO Intelligent Grid Cluster End of Year Final Report July 2010.* 2010.

[55] Wagner, L., *ATESHGAH: A Mixed Complementarity model of the Eastern Australian Domestic Natural Gas Market.* Energy Economics and Management Group, Working paper Series, 2014.

[56] Wagner, L. *Modelling the Australian Domestic Gas Market: A Mixed Complementarity approach with Oligopolistic Behaviour'*. in *IAEE Conference*. 2014. New York, USA.

[57] Wagner, L., L. Molyneaux, and J. Foster, *Magnifying uncertainty: the impact of a shift to gas under a carbon price.* Energy Economics and Management Group Working Papers, 2012(11-2012).

[58] Wagner, L.D. *Modelling the Australian Domestic Gas Market: A Mixed Complementarity approach with Oligopolistic Behaviour*. in *IAEE Conference, New York, 2014*. 2014. IAEE.

[59] Wagner, L.D., A. Liebman, and J. Foster. *Examining the future of nature gas usage in the Australian National Electricity Market*. in *32nd International Conference of the International Energy Economics Association, San Francisco, CA USA 21-24th June 2009*. 2009. International Association of Energy Economics.

[60] Wagner, L.D., et al. *Forecasting the long term emissions intensity factor for electricity markets: an Australian case study*. in *10th IAEE European Conference, Vienna, Austria, 7 - 10 September 2009.* 2009. International Association of Energy Economics.

[61] Molyneaux, L., J. Foster, and L. Wagner, *Australian coal v renewables: how much will it cost to bring electricity to India's poor?* 2016.

[62] Molyneaux, L., C. Froome, and L. Wagner. *Where is Australian power headed in 2035?* in *Australian solar energy society conference, Melbourne, Australia, December 2012.* 2012. Australian Solar Institute.

[63] Molyneaux, L., et al., *Measuring resilience to energy shocks.* Energy Economics and Management Group Working Paper Series, 2015.

[64] Molyneaux, L., et al., *Measuring resilience in electricity generation: An empirical analysis*. 2016.

[65] Molyneaux, L., et al., *Measuring resilience in energy systems: Insights from a range of disciplines.* Renewable and Sustainable Energy Reviews, 2016. **59**: p. 1068-1079.

[66] Bratanova, A., J. Robinson, and L. Wagner, *Energy cost modelling of new technology adoption for Russian regional power and heat generation.* 2012.

[67] Bratanova, A., J. Robinson, and L. Wagner, *New technology adoption for Russian regional energy generation.* 2013.

[68] Bratanova, A., J. Robinson, and L. Wagner, *New Technology Adoption for Russian Regional Energy Generation: Moscow Case Study.* 2013.

[69] Bratanova, A., J. Robinson, and L. Wagner, *Modification of the LCOE model to estimate a cost of heat and power generation for Russia.* Energy Economics and Management Group Working Papers, 2015.

[70] Byrnes, L., et al., *Reviewing the viability of renewable energy in community electrification: The case of remote Western Australian communities.* Renewable and Sustainable Energy Reviews, 2016. **59**: p. 470-481.
[71] Wagner, L. and J. Foster, *Is There an Optimal Entry Time for Carbon Capture and Storage? A Case Study for Australia's National Electricity Market.* Energy Economics Management Group, School of Economics,: The University of Queensland, Australia, 2011.
[72] BREE, *Australian energy technology assessment 2012*, B.o.R.a.E. Economics, Editor. 2012, Bureau of Resources and Energy Economics: Canberra, ACT.
[73] BREE, *Australian energy technology assessment 2013*, B.o.R.a.E. Economics, Editor. 2013, Bureau of Resources and Energy Economics: Canberra, ACT.
[74] AEMO, *2012 National Transmission Network Development Plan (NTNDP)*, A.E.M. Operator, Editor. 2012, AEMO, Australian Energy Market Operator: Australia.
[75] AEMO, *2015 Electricity Statement of Opportunities for the National Electricity Market*, A.E.M. Operator, Editor. 2012, AEMO, Australian Energy Market Operator: Australia.
[76] AEMO, *2013 Electricity Statement of Opportunities for the National Electricity Market*, A.E.M. Operator, Editor. 2013, AEMO, Australian Energy Market Operator: Australia.
[77] AEMO. *Maps and Multimedia*. 2013 1/10/2013]; Available from: http://www.aemo.com.au/Maps-and-Multimedia.
[78] AEMO, *2015 National Transmission Network Development Plan (NTNDP)*, A.E.M. Operator, Editor. 2014, AEMO, Australian Energy Market Operator: Australia.
[79] AEMO. *Electricity Market Data*. 2014 [cited 2014 November 2014]; Available from: http://www.aemo.com.au/Electricity/Data.
[80] AEMO, W., *Cost of ConstructionNew Generation Technology*. 2012, AUSTRALIAN ENERGY MARKET OPERATOR: Melbourne.
[81] IEA, *World Energy Outlook 2012*. 2012: OECD Publishing.
[82] IEA, *Technology Roadmap: Energy Storage*, in *Energy Technology Perspectives*. 2014, International Energy Agency: Paris.
[83] IEA, *Technology Roadmap: Solar Photovoltaic Energy*, in *Energy Technology Perspectives*. 2014, International Energy Agency: Paris.
[84] IEA, *World Energy Outlook*. 2014, International Energy Agency: Paris.
[85] IEA, *World Energy Outlook 2014 Power Generation Investment Assumptions*. 2014, International Energy Agency: Paris.
[86] EIA, *International Energy Outlook. US Energy Information Administration*. 2013, DOE/EIA-0484 (2013) Edition.
[87] AEMO. *Regulatory Investment Tests for Transmission (RIT-Ts)*. 2014 [cited 2015 01/05/2015]; Available from: http://www.aemo.com.au/Electricity/Planning/Regulatory-Investment-Tests-for-Transmission/.
[88] Acil Tasman, *Fuel resource, new entry and generation costs in the NEM: Final Report 9*, in *Report prepared by ACIL Tasman for the Interregional Planning Committee (IRPC)*. 2009.
[89] Acil Tasman, *Economic significance of Coal Seam Gas in Queensland*, in *Australian Petroleum Production & Exploration Association*. 2012.
[90] AEMO, *2012 Electricity Statement of Opportunities for the National Electricity Market*, A.E.M. Operator, Editor. 2012, AEMO, Australian Energy Market Operator: Australia.
[91] AER, *State of the Energy Market: 2014*. 2014.
[92] BREE, *Australian energy statistics: energy update 2012*, B.o.R.a.E. Economics, Editor. 2012: BREE, Canberra.
[93] AEMO, *2013 Gas Statement of Opportunities for the National Electricity Market*, A.E.M. Operator, Editor. 2013, AEMO, Australian Energy Market Operator: Australia.
[94] AEMO, *Gas Market Operations*. 2015, Australian Energy Market Operator: Melbourne.
[95] BREE, *Gas Market Report 2013*, BREE, Editor. 2012, Department of Industry, Commonwealth of Australia.
[96] Wagner, L., *Woodside's failed Papua New Guinea power play shows the growing desperation in the gas sector*. 2015.

[97] Eydeland, A. and K. Wolyniec, *Energy and power risk management.* John Whiley and Sons, 2003.
[98] Molyneaux, L., C. Froome, and L. Wagner, *Where is Australian Power headed in 2035?* 2012, School of Economics, University of Queensland, Australia.
[99] Smil, V., *Energy myths and realities: bringing science to the energy policy debate*. 2010: Government Institutes.
[100] Sharman, H., B. Leyland, and M. Livermore, *Renewable Energy: Vision or Mirage.* The Scientific Alliance, Cambridge, 2011.
[101] Hearps, P., M. Wright, and B.Z. Emissions, *Australian sustainable energy: Zero carbon Australia stationary energy plan*. 2010: University of Melbourne.