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Least cost, utility scale abatement from Australia's NEM (National Electricity Market). Part 2: Scenarios and policy implications

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ABSTRACT

This paper is the second of a two part study that considers least cost, greenhouse gas abatement pathways for an electricity system. Part 1 of this study formulated a model for determining these abatement pathways, and applied this model to Australia's NEM (National Electricity Market) for a single reference scenario. Part 2 of this study applies this model to different scenarios and considers the policy implications. These include cases where nuclear power generation and CCS (carbon capture and storage) are implemented in Australia, which is presently not the case, as well as a more detailed examination of how an extended, RPS (renewable portfolio standard) might perform. The effect of future fuel costs and different discount rates are also examined.

Several results from this study are thought to be significant. Most importantly, this study suggests that Australia already has utility scale technologies, renewable and non-renewable resources, an electricity market design and an abatement policy that permit continued progress towards deep greenhouse gas abatement in its electricity sector. In particular, a RPS (renewable portfolio standard) appears to be close to optimal as a greenhouse gas abatement policy for Australia's electricity sector for at least the next 10–15 years.

1. Introduction

When considering the decarbonisation of electricity, all aspects of the policy and technology debates have their proponents and opponents. On policy, some advocate different forms of carbon price, whilst others argue for RPSs (renewable portfolio standards), reverse auctions, direct regulation or other measures [1–3]. There is also significant disagreement as to what our abatement targets should be. Some argue that, for high income countries at least, zero emission and/or completely renewable electricity is essential [4–6]. Others argue that since cheaper abatement is available internationally [7,8] or in other domestic sectors [9], we should therefore target less abatement in electricity as part of an overall, more cost-effective approach.

Australia is a case study of such differing policy views. In 2014, our Federal Government became the first government in the world to remove a legislated price on carbon; legislation that had been in place for only two years. It has also recently completed a lengthy negotiation on its legislated RET (Renewable Energy Target), which is the domestic form of a RPS, whilst implementing its ‘Direct Action plan’, which is a form of reverse auction that will pay for abatement across the economy [2]. Finally, even though Australia has one of the world's largest proved economic reserves of uranium and is a large uranium exporter, it does not produce any electricity from nuclear energy.

The technology debate is no less charged or confusing. In particular, it is common to find advocacy of specific technologies without fully acknowledging the difficulties that they face. At utility scale, these technologies include the several forms of renewable generation, CCGTs (combined cycle gas turbines), nuclear, coal and gas with CCS (carbon capture and storage) and different forms of energy storage, to name only a few. Of course, no technology is without problems. Even though the direct CO_{2e} emissions of CCGTs are significantly lower than those of coal plant, the fugitive emissions of methane from the well to the plant remain a topic of debate [10,11]. Intermittent renewables can create problems of network and market performance [12–16]. Biomass and biogas often face issues of resource availability [17]. Whilst some argue that nuclear power is significantly safer than alternatives, the public's perception of its risks – rightly or wrongly – remains a major challenge to

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its future prospects [18–20]. More broadly, some of these technologies are deployed at a significant scale and have a known record of performance, whilst others do not. Whilst these latter technologies may be very deserving of support for further research, development and demonstration, it is important not to overstate the role that presently undeployed technologies will play, particularly since any new energy technology usually takes decades to reach significant levels of deployment [21,22].

Following on from Part 1 of this study [23], this second part therefore considers different technology, financial and policy scenarios for achieving abatement from Australia's NEM (National Electricity Market). These include cases where nuclear power generation and CCS (carbon capture and storage) are implemented in Australia, which is presently not the case, as well as a more detailed examination of how an extended RPS might perform. The effect of future fuel costs and different discount rates are also examined. Policy implications arising from these scenarios for both the nearer (i.e. to roughly 2030) and the longer term (i.e. to 2050) are then discussed. As detailed in Part 1, all model inputs are from the most current, publicly available and authoritative Australian sources and the results presented are therefore intended to be transparently derived and both policy and technology neutral.

2. Method

The method used in this paper was presented in Part 1 of this study [23]. This includes use of a constrained LP (linear program) that minimises the net present costs of the new build and operating costs from 2015 to 2050 subject to numerous constraints.

Part 1 of this study [23] also listed the existing and new build generation and storage technologies that are included in the model. For the cases where nuclear generation is considered, it can only commence generation in 2025 or after. Nuclear electricity generation does not presently exist in Australia, and 10 years is assumed to be the shortest plausible period over which to commence nuclear powered electricity generation assuming immediate public acceptance. This includes the time required to make regulatory changes, identify suitable sites, build and commission the first plants and train personnel. Following the AETA report [24], all CCS plant (including oxy-combustion) plant can also only commence generation in 2025 or after. Once again, this is considered to be reasonable since these plant types are not presently in the NEM and, indeed, are not yet an established generating technology.

3. Results and discussion

Let us first consider the *annual* GHG (greenhouse gas) emissions from any electricity system M_y (t CO_{2e}) expressed in terms of other parameters,

$$M_y = E_y^a \left(1 - \frac{\sum^{\neq\mathcal{F}} E_{py}^a}{E_y^a}\right) \left(\frac{\sum^{\mathcal{F}} M_{py}}{\sum^{\mathcal{F}} E_{py}^{fuel}}\right) \left(\frac{1}{\overline{\eta}}\right). \tag{1}$$

The first term on the right hand side shows the direct proportionality between annual demand – and therefore annual generation E_y – and annual GHG emissions. However, electricity demand is exogenous at the utility scale, and is therefore outside the scope of the present study.

The second term on the right hand side of Equation (1) quantifies the effect of zero emission generation. If we assume that there is no nuclear generation in the system, as is currently the case in Australia, this quantifies the effect of renewable energy generation, with M_y varying in proportion to the annual electricity generated from zero emission sources $\Sigma^{\neq\mathcal{F}} E_{py}^a / E_y^a$.

The third term on the right hand side of Equation (1) is the annually averaged GHG intensity (t CO_{2e}/MWh) of the fuel burnt by all fossil fuelled plants in the system. This term can also be written in terms of input parameters for this study as

$$\frac{\sum^{\mathcal{F}} M_{py}}{\sum^{\mathcal{F}} E_{py}^{fuel}} = \sum^{F} \left\{ \left(\frac{M_{py}}{E_{py}}\right) \left[\frac{\left(E_{py}^a / \overline{\eta}_{py}\right)}{\sum^{\mathcal{F}} \left(E_{py}^a / \overline{\eta}_{py}\right)}\right] \right\}. \tag{2}$$

When written in this form, the GHG intensity M_{py}/E_{py} is a physical property of a given fuel consumed by a given fossil fuelled plant, e.g. the combustion of natural gas produces less CO_{2e} than coal per unit of thermal energy released. However, this term is not the sole determinant of the annually averaged GHG intensity of the fuel burnt by all fossil fuelled plants, with each plant's annual generation and annually averaged thermal efficiency also playing roles.

Finally, $\overline{\eta}$ in Equation (1) is the annually averaged thermal efficiency of all fossil fuelled plants in the system. It can be written in terms of individual plant parameters as follows.

$$\overline{\eta} = \frac{\sum^{\mathcal{F}} E_{py}^a}{\sum^{\mathcal{F}} \left(E_{py}^a / \overline{\eta}_{py}\right)}. \tag{3}$$

Equation (1) therefore summaries the principal means by which we can reduce GHG emissions from any electricity system. In order, these are *demand management*, *integration of zero emission generation* (e.g. renewables, nuclear or CCS), *fuel switching* (particularly from coal to natural gas) and *efficiency measures* for any fossil plant.

We also note that, over the course of the year, the instantaneous demand, the instantaneous proportion of zero emission generation, the instantaneous fleet-averaged fossil fuel intensity and the instantaneous fleet-averaged fossil plant efficiency will all vary such that total present costs are minimised whilst this annual emissions constraint is met along with other constraints. In this case, all four of the terms on the right hand side of Equation (1) can contribute to meeting the annual emissions constraint, and thus zero emission plant, fuel switching and efficiency measures can compete for a share of generation on a least-cost basis.

With this in mind, Equation (1) therefore highlights two conceptual shortcomings of RPS measures. First, by only subsidising renewable plant, the first term on the right hand side of Equation (1) is the *only* term by which a RPS can achieve the targeted abatement. RPS measures provide no incentive for fuel switching or increasing the efficiency of any non-renewable thermal plant, as might occur with a price on carbon. Thus, renewables gain a certain level of market penetration via the RPS subsidy, leaving the remaining demand to be met by the cheapest, non-renewable alternatives, regardless of their GHG emissions. In practice, this means that higher emission coal plant is advantaged over lower emission gas plant because they are usually of lower cost. Similarly, older plants that are cheaper, less efficient and emit more are advantaged over newer plants. Thus, Equation (1) shows that an RPS can only lead to optimal, utility scale abatement in a least-cost sense if the system level benefits of investment in new, renewable plant is superior to that achieved by other investments in some combination of zero emission plant, fuel switching and efficiency measures.

There is a second conceptual shortcoming of RPS measures that is inherently dynamic in nature. The dynamic nature of demand and the dynamic performance of each plant both affect the dynamic performance and therefore the annually averaged performance *of all other plants in the system*. Intermittent renewable plants that are justified by a RPS then must force other, dispatchable generators to ramp up and down more often, be committed and decommitted more often, and operate at part load more often. These effects must increase the annually averaged emissions (CO_{2e}/MWh) and increase the average operating costs ($/MWh) of any dispatchable plant. These effects are additional to the need of dispatchable plant to provide reserves and inertia.

3.1. Definition of the scenarios used in this study

We now define the following scenarios:

(1) The reference scenario

All inputs in this scenario are defined in Part 1 of this study [23], with nuclear and CCS plant disallowed. This means that renewables are the only type of zero emission plant in this scenario, with renewable integration, fuel switching and efficiency measures all allowable means of achieving an absolute abatement target.

(2) The nuclear and CCS scenario

This scenario adds the option of nuclear and CCS to the *Reference Scenario*. We include these two generating technologies together in one scenario since neither are presently deployed in Australia, both offer zero emission, dispatchable and inertia providing generation and we estimate that both are likely to implementable in Australia at around the same time, as discussed earlier. By comparing the results obtained with those of the *Reference Scenario*, we estimate the relative, system level benefits of nuclear, CCS and renewables.

(3) The cheap fossil fuel scenario

This scenario assumes that the cost of all forms of coal and natural gas remain at their lower bound presented in the AETA report [24] from today to 2050, with all other inputs as per the *Reference Scenario.* This scenario allows us to estimate the sensitivity of our results to potentially low fossil fuel prices and the greater share of fossil generation that they will encourage.

(4) The low discount rate scenario

This scenario features a 5% discount rate and is otherwise the same as the *Reference Scenario.* This scenario allows us to estimate the sensitivity of our results to potentially low discount rates and the technologies that they support.

(5) The RPS (renewable portfolio standard) Scenario

This scenario replaces the absolute abatement constraint in the *Reference Scenario* with an equivalent penetration of renewable energy. By comparing the results obtained with those of the *Reference Scenario* and the *Nuclear and CCS scenario*, we estimate the relative, system level performance of an RPS measure.

Figs. 1–2 present summary information on all scenarios studied in this paper. The estimated wholesale market cost is determined as previously in Part 1 [23]. We also formulate RPS (renewable portfolio standards) by mandating that a proportion of total demand in 2050 is met by renewable energy (Fig. 3),

$$RPS_{X\%} = \frac{\sum_{\substack{p \in \textbf{renewable} \\ r \in \mathscr{R}}} E^{a}_{pr2050}}{\sum_{r \in \mathscr{R}} E^{d}_{r2050}}. \tag{4}$$

In keeping with our approach to the absolute abatement trajectory, we then assume a linear increase in the mandated annual renewable energy generation from today to a given 2050 target.

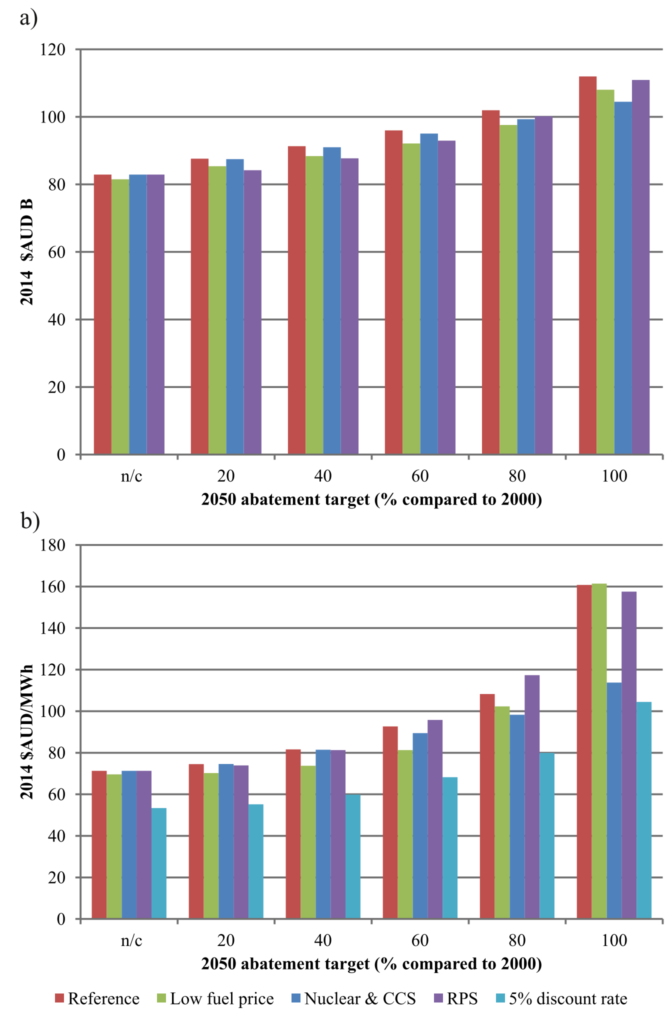

Fig. 1. a) Present value of total costs and b) estimated wholesale electricity market cost in 2050 for all scenarios with different 2050 abatement targets. Note that 'n/c' means 'no constraint'.

3.2. The nuclear and CCS scenario

Fig. 3 shows that nuclear, when permitted, only takes up a large share of annual generation in cases with deeper abatement. However, Fig. 1 shows this only reduces wholesale market costs by more than 1c/kWh relative to alternatives if we require greater than 80% abatement by 2050. Further, CCS is not projected to play a role in any abatement target, because the AETA data [24] estimates that it will provide more expensive abatement than nuclear.

We emphasise that these results regarding the prospects of nuclear and CCS are likely peculiar to Australia. Australia has a large land area and a low population density by international standards. Most countries are therefore less likely to have similar renewable resource availability per capita, and some of these countries already have nuclear operating with significant sunk costs. In such cases, provided that our cost inputs [24] are reasonable, analysis should find that existing nuclear plant should be kept operating for as long as it is economic to do so, and that new build nuclear will take up a greater market share relative to alternatives.

3.3. The cheap fossil fuel scenario

Fig. 1 shows that the total costs and 2050 wholesale market price for a given level of abatement are similar for the *Reference* and

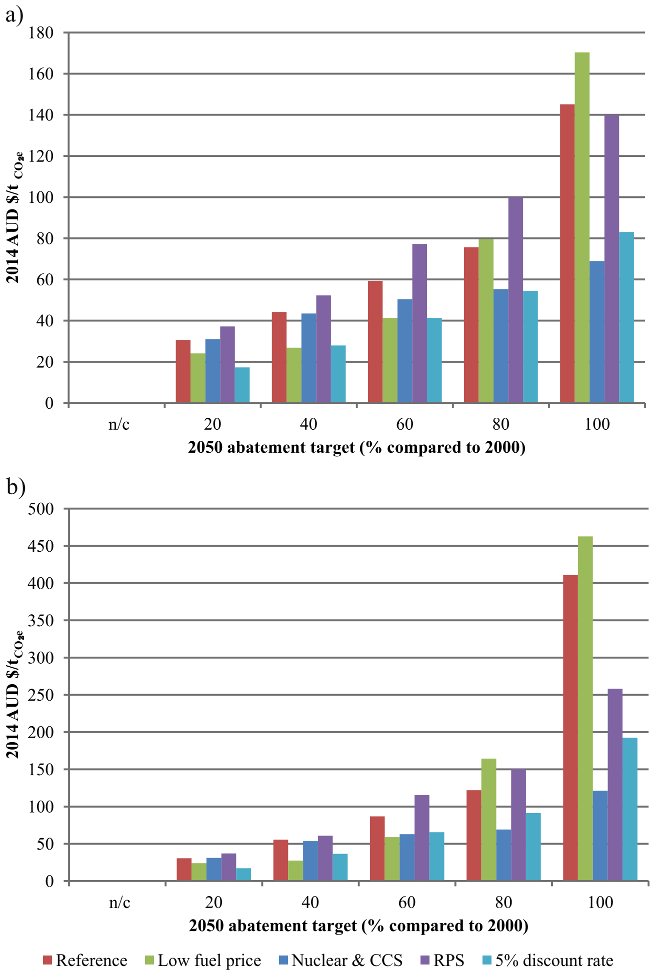

Fig. 2. a) Absolute and b) marginal costs of abatement for all scenarios with different 2050 abatement targets.

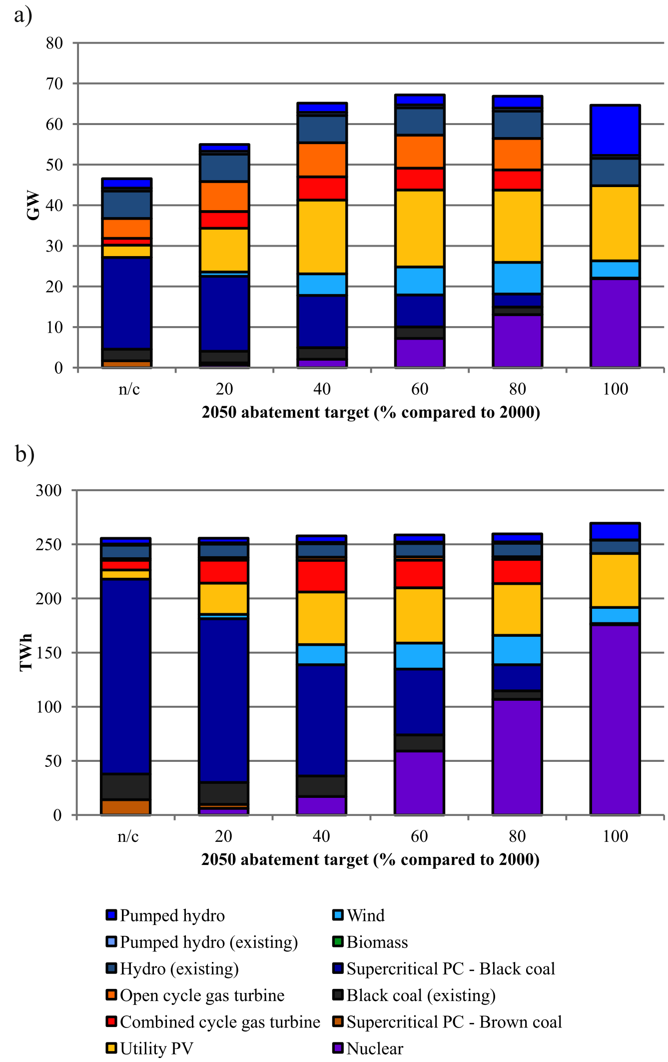

Fig. 3. a) Installed capacity and b) annual generation in 2050 for the *Nuclear and CCS Scenario* with different abatement targets.

the *Cheap Fossil Fuel Scenarios* at deeper levels of abatement. This is because, in these cases, capital expenditure dominates total system costs and the emissions constraint tends to limit greater coal generation, *regardless of fuel prices*. Thus, whilst there is large uncertainty regarding the future price of fossil fuels, our results suggest that the total costs and the required investment decisions for deeper abatement are more certain. In particular, low fossil fuel prices *do not* appear to force out renewable investment.

3.4. The low discount rate scenario

Since different technologies have different capital expenditures, operating costs and different learning rates, it is not obvious how sensitive any optimal investment/divestment trajectory will be to variations in the discount rate. Further, determining the most appropriate discounting for each technology from first principles is a complex task and technology specific [25]. We therefore intentionally avoid such complexity by assuming that all technologies have the same discount rate, as almost all similar studies have assumed, and then consider results over a plausible range of discount rates. The 10% discount rate specified in the AETA report [24] and used throughout the rest of this study is higher than that in most studies, which tend to be in the range of 5–10%, e.g. Refs. [26–28]. We therefore consider a 5% discount rate to be a reasonable lower bound for examination in this *Low Discount Rate Scenario*.

A comparison of the optimal trajectories for the *Reference Scenario* (with a 10% discount rate) and the *Low Discount Rate Scenario* is shown in Fig. 4. These results differ particularly by the deployed, new build CCGT plant in 2050. The higher discount rate result deploys more CCGT since a high proportion of CCGT's total costs are fuel costs, which are discounted more significantly, and thus CCGT is favoured over new build coal. Since CCGTs have lower GHG emissions than coal plant, less renewable plant then needs to be built in order to meet a given absolute abatement target.

3.5. The RPS (renewable portfolio standard) scenario

Our model, as detailed in Part 1 [23], incorporates features that allow us to test the significance of the two conceptual shortcomings of RPS measures discussed earlier. In addition to incorporating intermittent renewable generation, all dispatchable plants have ramping and unit commitment constraints and associated costs, the efficiency of all thermal plants falls with reduced load of each plant type and the age and representative thermal efficiencies of current, new and future plants in the NEM are included.

With such a model, we can therefore test the performance of a RPS by comparing the results of two equivalent optimisations. The first of these optimisations constrains the system by an absolute

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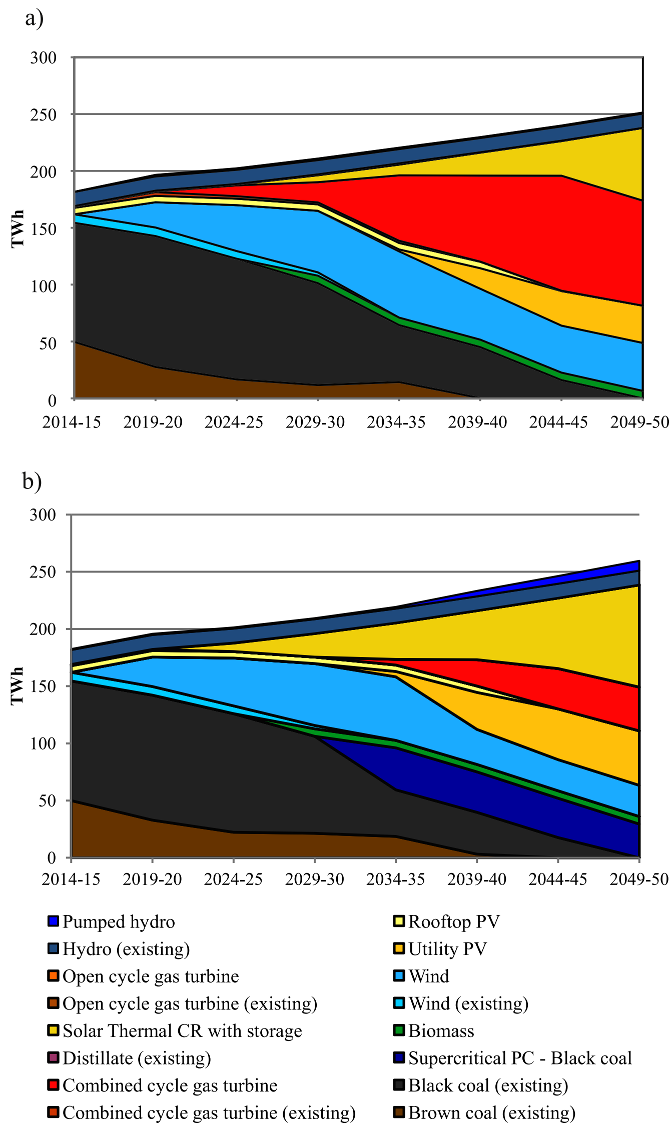

Fig. 4. Annual generation by year to 2050 for the a) *Reference Scenario* of Part 1 [23] and b) the *Low Discount Rate Scenario*, both with an 80% abatement target.

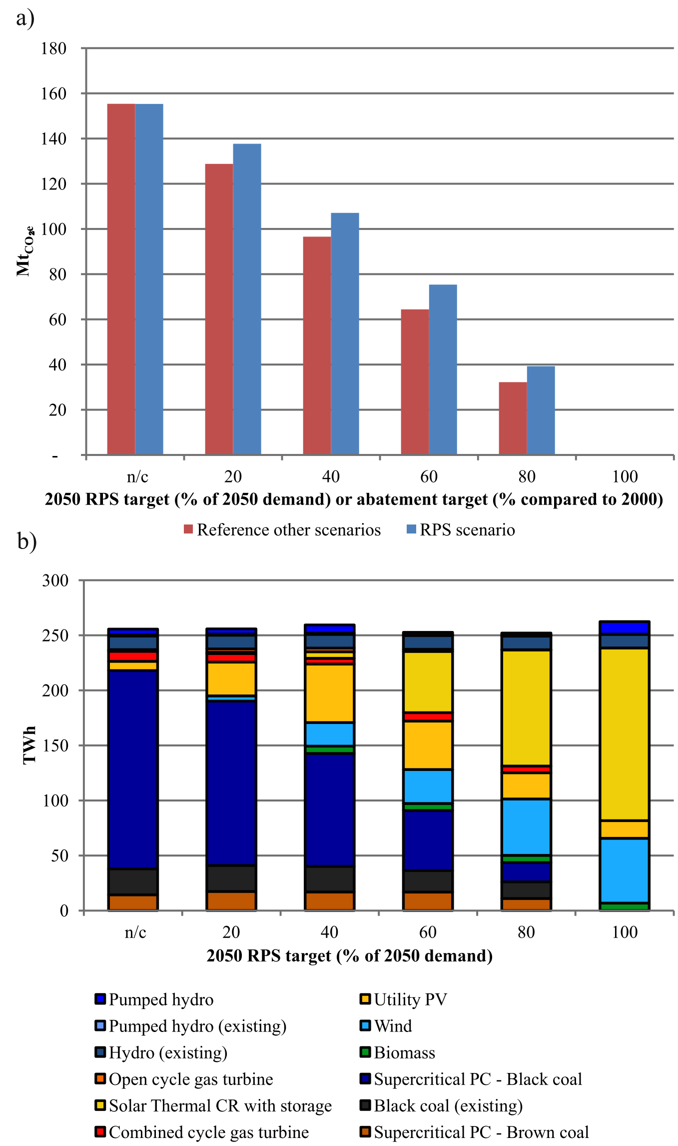

Fig. 5. a) Annual GHG emissions and b) annual generation in 2050 for the *RPS Scenario* with different 2050 RPS targets.

emissions trajectory. We then undertake another optimisation in which we replace this absolute abatement constraint with an equivalent prescribed uptake of renewable generation in each year, with all other aspects of the optimisation unchanged. If these two optimisations give similar results in terms of costs and total GHG emissions, then the *RPS Scenario* is close-to-optimal and the two conceptual shortcomings of RPS measures that were discussed earlier should not be significant.

Figs. 4a–6 compare key results from the *Reference Scenario* and the *RPS Scenario* for different 2050 targets. Note that these *RPS Scenario* targets mandate a penetration of renewable energy that is a prescribed fraction of total demand in 2050, as defined earlier in this paper, and *not* a level of GHG abatement. For the cases featuring less than 100% renewable generation, the total GHG emissions in all *RPS Scenario* results is higher than in the equivalent *Reference Scenario* because coal plant remains in the generation mix since it is cheaper to operate than gas plant and fuel switching is not encouraged.

However, we find that such differences are small over the next decade and a half. Fig. 7 shows the annual renewable energy generation and the estimated wholesale market price by year for equivalent *Reference* and *RPS scenarios* and a given 2050 target. Both results start from current market conditions, and are very close up until 2030, when less renewable generation occurs in the scenario with constrained absolute GHG emissions.

The observed similarity up to 2030 in Fig. 7 is due to several reasons. Most importantly, the existing, dominant coal plant in Australia's NEM features a significant proportion of sunk costs that have a significant impact on the current, relatively low wholesale market price. This makes it harder for any new build plant to complete in any scenario. Further, domestic, wholesale natural gas prices are forecasted to be relatively high over the period considered (see Part 1 [23] for further detail). This means that relative to the existing, coal dominated generating fleet, minimising the total cost therefore requires a large growth in renewable generation whilst existing coal plant is progressively decommissioned. The divergence around 2030 in Fig. 7 is then because some of the existing coal plant must be retired by this date. Coupled with the intermittency, inertia and absolute GHG emissions constraints in the *Reference Scenario*, the model then builds substantial CCGT around this time (Fig. 6). This means that less renewable build is

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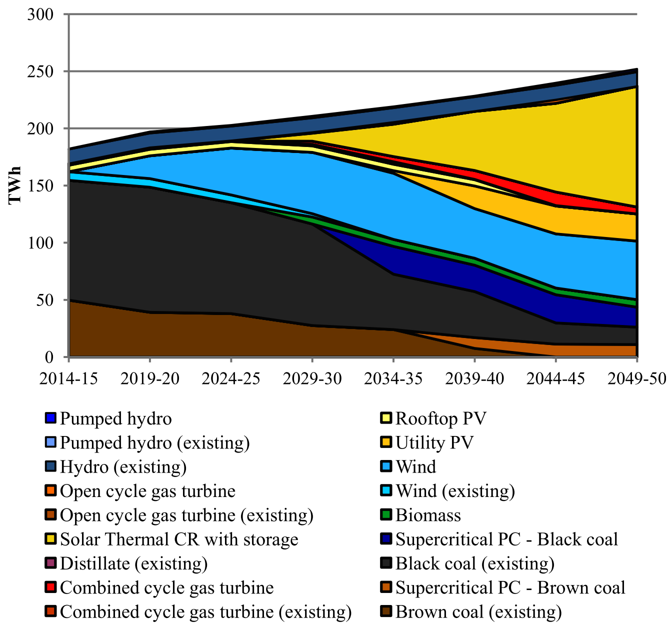

Fig. 6. Annual generation by year to 2050 for the *RPS Scenario* with an 80% RPS target.

required to meet a given absolute emissions constraint in the *Reference Scenario*, since this CCGT replaces higher emitting, existing coal plant. In contrast, the *RPS scenario* does not have a GHG constraint, and so minimises total costs by building a combination of lower cost, inertia providing coal plant and higher cost, inertia providing renewable plant (particularly solar thermal with storage) rather than CCGT. Costs are therefore minimised in the longer term in the *RPS Scenario* at the expense of higher GHG emissions than in the equivalent *Reference Scenario* (Fig. 5).

3.6. Policy implications

3.6.1. RPS (renewable portfolio standards) as nearer term, 'second best' abatement policy

Overall, the results in Fig. 7 show that the potential shortcomings of RPS measures discussed earlier are not expected to be significant for roughly the next decade and a half. Indeed, whilst RPS measures do not appear to be optimal for deeper abatement in the longer term, it appears that they can be good, second best abatement policies under certain conditions, i.e. they can be close-to-optimal absolute abatement policies, and not just a means of promoting renewable penetration. Australia's current NEM appears to be one example in which a form of RPS can be close to optimal, with equivalent absolute abatement and RPS measures having very similar least cost trajectories until about 2030 when deep abatement in 2050 is targeted.

Whilst some form of carbon price is commonly considered to be the best means of achieving abatement, its recent abolition in Australia is evidence of the political challenges of such policies (Carbon pricing has also proved politically difficult in other countries.). Since Australia already has a form of RPS — its RET (Renewable Energy Target) — these results then suggest that it is both economically and environmentally reasonable to continue to work with and refine this policy for some time yet.

As part of this, we also note that the optimal pathways of equivalent RPS and absolute abatement policies converge as the 2050 absolute emissions target *increases*. This is because less renewable energy is then required to meet a given 2050 absolute emissions target, meaning that cheaper, dispatchable and inertia providing coal plant can generate more electricity whilst more expensive gas plant will generate less. Because of this, the results presented in Fig. 7 should be seen as a more challenging test of the performance of a RPS policy and, perhaps counter-intuitively, *less ambitious* absolute abatement targets are *more achievable* by RPS measures.

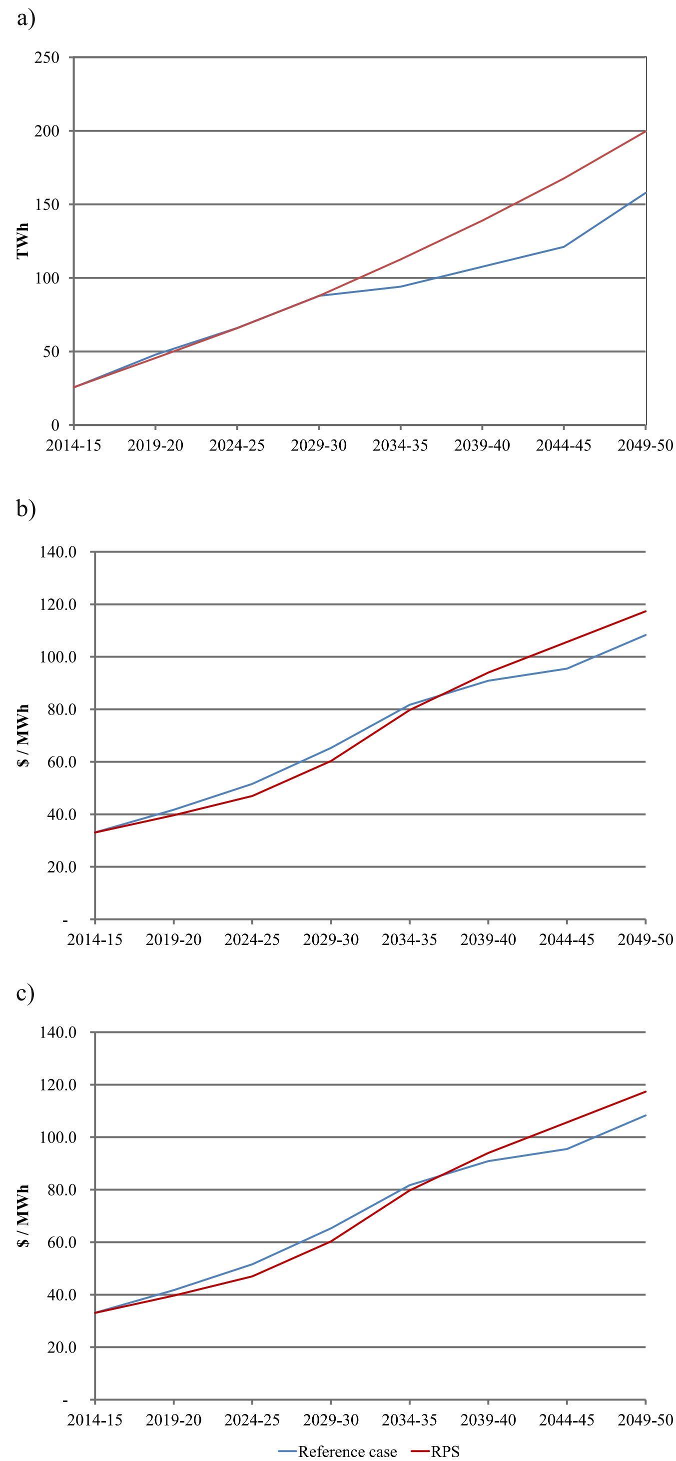

Fig. 7. a) Annual renewable energy generation and b) estimated wholesale market price by year to 2050 for the *RPS Scenario* with a 80% RPS target and the *Reference Scenario* with an 80% abatement target.

3.6.2. Longer term abatement technologies and policies

There have been several studies that have examined whether a zero emission or 100% renewable electricity generation is technically feasible in Australia [6,29,30] and internationally [31–34]. However, these studies do not normally consider whether the *marginal* cost of achieving 100% renewable generation relative to a less ambitious target for the sector is merited; achieving zero emissions in any sector is only worthwhile if other domestic *and* international alternatives all offer more expensive abatement.

Irrespective of the permitted technology mix, likely discount rate/s, likely fuel prices or the abatement policy, Fig. 2 showed that achieving 80% or greater absolute abatement of 2000 levels by 2050 always required absolute costs that were greater than 50 $/(t CO_{2e}) in current terms. Some absolute costs of abatement were significantly higher than this, as were all marginal costs of achieving greater than 80% abatement. These costs of abatement are higher than those estimated in other Australian sectors today, e.g. Refs. [9,35–37]. Thus, achieving a zero emission NEM does not *presently* appear to be desirable given these lower cost alternatives.

However, in the longer term, if lower cost alternative forms of abatement in other sectors become more rare as total emissions reduce, achieving a zero emission NEM may again become attractive. Should this occur, the implementation of nuclear power generation in Australia should then be considered. This is because the inclusion of nuclear significantly reduced the marginal cost of abatement relative to renewable-only options. Whether these potential cost savings justify the establishment of a nuclear power industry in Australia needs to be considered. This is outside the scope of the present study, since a more detailed analysis should consider many factors such as the costs of developing a domestic nuclear generating capability, waste storage, site decommissioning and remediation, nuclear security and insurance.

Alternatively, in the longer term, should the marginal costs of abatement incurred by a zero emission NEM remain relatively high, using *solely* renewables or resolving the *nuclear question* for Australia cease to be priorities.

Given these longer term uncertainties, and since it appears that we already have an effective abatement policy for the next 15 or so years, Australia appears to be in the fortunate position of being able to view emissions abatement as a *receding horizon* problem, i.e. we could identify a longer term abatement target and then continuously refine and/or adopt policies that are consistent with this target in the nearer term. This allows us to then become more certain about future demand, all costs and market operations, and thus continuously update our input assumptions, prior to undertaking future modelling and policy change. As part of this, future analysis should focus on whether a transition from a form of RPS to a price on carbon or some other efficient measure is necessary prior to roughly 2030.

4. Conclusions

This paper is the second of a two part study that considers least cost, greenhouse gas abatement pathways for an electricity system. Part 1 of this study [23] presented a bottom up model for determining these abatement pathways, and applied this model to Australia's NEM (National Electricity Market) as an example. Part 2 of this study examined several different scenarios for achieving abatement from Australia's NEM. These included cases where nuclear power generation and CCS (carbon capture and storage) are implemented in Australia, which is presently not the case, as well as a more detailed examination of how an extended, RPS (renewable portfolio standard) might perform. The effect of future fuel costs and different discount rates were also examined.

Part 1 of this study found that for targets of less than 100% abatement and without nuclear or CCS, minimising the total cost of achieving any significant 2050 abatement target required a large growth in renewable generation acting in concert with combined cycle natural gas (CCGT) whilst existing coal plant was progressively decommissioned. This meant that the uptake of renewable generation was not an artefact of an RPS or other policy that directly supports renewables, but should also occur for any abatement policy that is close-to-optimal in terms of minimising total costs.

Building on the findings from Part 1, several of the results observed in Part 2 are also thought to be significant.

(1) Using the most recent, independent technology cost assumptions for Australia [24], the inclusion of nuclear power only reduced estimated wholesale market costs in 2050 by more than 1c/kWh if the 2050 abatement target was greater than roughly 80% absolute abatement of 2000 emissions, and CCS (Carbon Capture and Storage) did not play a role in any scenario because alternatives offered cheaper abatement.
(2) Irrespective of the permitted technology mix, the likely discount rate, likely fuel prices or the abatement policy, achieving 80% or greater absolute abatement of 2000 levels by 2050 always required absolute costs that were greater than \$50/t CO_{2e} in current terms. Some *absolute* costs of abatement were significantly higher than this, as were all *marginal* costs of achieving greater than 80% abatement. Thus, achieving zero GHG emissions from the NEM using solely renewables or resolving the *nuclear question* for Australia are only priorities if other domestic or international sectors do not offer cheaper abatement in the longer term.
(3) Whilst fossil fuel prices and the discount rate affect total costs, optimal system configurations that achieve deep abatement in 2050 are less sensitive to these parameters because the emissions constraint and other, non-financial effects also play a strong role in determining the technology mix.
(4) With our best estimates of plant life, inertia and intermittency constraints, we estimate that an RPS will remain a close-to-optimal absolute GHG abatement policy until around 2030 if an 80% abatement target in 2050 is intended, and later if less abatement is targeted. This is in part because of the already relatively high, domestic natural gas prices that are forecasted to remain in place during this period, and the significant amount of existing coal fired capacity in the NEM. Further, as we better understand system-level performance with higher levels of intermittent, renewable generation, relaxing the minimum permitted inertia and maximum permitted intermittency will only serve to reduce total costs and extend the duration over which a RPS is close-to-optimal for any absolute abatement target.

When viewed as a whole, and acknowledging the significant uncertainties over the longer term, this study therefore suggests that Australia is currently in a fortunate position. It appears to already have utility scale technologies, renewable and non-renewable resources, an electricity market design and an abatement policy (a form of RPS) that permit continued progress towards deep greenhouse gas abatement in its electricity sector. Future, more comprehensive analysis will determine whether a transition from a form of RPS to a price on carbon or some other efficient measure is necessary prior to roughly 2030.

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References

[1] Garnaut R. The Garnaut review 2011: Australia in the global response to climate change. Cambridge University Press; 2011. http://www.garnautreview.org.au/update-2011/garnaut-review-2011/garnaut-review-2011.pdf.

[2] Emissions Reduction Fund Expert Reference Group (Australia). Australia, department of environment, emissions reduction fund white paper. Commonwealth of Australia, Canberra, A.C.T; 2014.

[3] Ruff L. The economic commonsense of pollution. In: Economics and the environment. New York: Norton; 1993.

[4] Sovacool BK, Watts C. Going completely renewable: is it possible (Let alone desirable)? Electr J 2009;22(4):95–111.

[5] Jacobson MZ, Delucchi MA. Providing all global energy with wind, water, and solar power, part I: technologies, energy resources, quantities and areas of infrastructure, and materials. Energy Policy 2011;39:1154–69.

[6] Beyond Zero Emissions, Zero Carbon Australia 2020 Stationary Energy Report, 2011. URL http://media.bze.org.au/ZCA2020_Stationary_Energy_Report_v1.pdf.

[7] Burniaux J-M, Chteau J, Dellink R, Duval R, Jamet S. The economics of climate change mitigation, Paris. 2009. http://www.oecd-ilibrary.org/content/workingpaper/224074334782.

[8] Wilder, Martijn, Curnow, Paul, The clean development mechanism, University of New South Wales Law Journal 41.

[9] McKinsey. An Australian cost curve for greenhouse gas reduction. 2008. http://www.mckinsey.com/~/media/mckinsey/dotcom/client_service/sustainability/cost/%20curve/%20pdfs/australian_cost_curve_for_ghg_reduction.ashx.

[10] Hultman N, Rebois D, Scholten M, Ramig C. The greenhouse impact of unconventional gas for electricity generation. Environ Res Lett 2011;6(4):044008.

[11] Howarth RW, Santoro R, Ingraffea A. Methane and the greenhouse-gas footprint of natural gas from shale formations. Clim Change 2011;106(4):679–90. 00536.

[12] Ackermann T, Kuwahata R. Lessons learned from international wind integration studies [Tech. rep.]. Energynautics; 2011. http://www.uwig.org/aemo-wpa4-report-by-energynautics-nov2011.pdf.

[13] AEMO. Integrating renewable energy – wind integration studies report 2013. 2013. http://www.aemo.com.au/Electricity/Planning/~/media/Files/Electricity/Planning/Reports/Integrating/%20Renewable/%20Energy/%20-/%20Wind/%20Integration/%20Studies/%20Report/%202013.pdf.ashx.

[14] DIgSILENT. All island TSO facilitation of renewables studies [Tech. rep.], Prepared for Eirgrid. 2010. http://www.uwig.org/Faciltiation_of_Renwables_WP3_Final_Report.pdf.

[15] Poncelet K, Delarue E, Duerinck J, Six D, Dhaeseleer W. The importance of integrating the variability of renewables in long-term energy planning models. 2014. p. 1–17. https://www.mech.kuleuven.be/en/tme/research/energy_environment/Pdf/wp-importance.pdf.

[16] Milligan M, Holttinen H, Kiviluoma J, Orths A, Lynch M, Sder L. Market designs for high levels of variable generation. NREL; 2014. http://www.nrel.gov/docs/fy15osti/62280.pdf.

[17] Tilman D, Socolow R, Foley JA, Hill J, Larson E, Lynd L, et al. Beneficial biofuels the food, energy, and environment trilemma. Science 2009;325(5938):270–1.

[18] Sailor WC, Bodansky D, Braun C, Fetter S, van der Zwaan B. A nuclear solution to climate change? Science 2000;288(5469):1177–8.

[19] J. Deutch, E. Moniz, S. Ansolabehere, M. Driscoll, P. Gray, J. Holdren, et al., The future of nuclear power, MIT Interdisciplinary Study. URL http://www.tuumajaam.ee/public/documents/MIT_nuclearpower-update2009.pdf.

[20] Kharecha PA, Hansen JE. Prevented mortality and greenhouse gas emissions from historical and projected nuclear power. Environ Sci Technol 2013;47(9):4889–95.

[21] Rogers Everett. Diffusion of innovations. New York: Free Press; 1962.

[22] Jacobsson S, Johnson A. The diffusion of renewable energy technology. Energy Policy 2000;28(9):625–40.

[23] M. Jeppesen, M. Brear, D. Chattopadhyay, C. Manzie, T. Alpcan, R. Dargaville, Least cost, utility scale abatement from Australia's National Electricity Market (NEM). Part 1: Modelling, submitted for peer review.

[24] BREE. The Australian energy assessment (AETA). 2013. Model update, http://www.bree.gov.au/sites/bree.gov.au/files/files//publications/aeta/AETA-Update-Dec-13.pdf.

[25] Lind Robert C, Arrow Kenneth J, Corey Gordon R, Dasgupta Partha, Sen Amartya K, Stauffer Thomas, et al. Discounting for time and risk in energy policy. Routledge; 2013.

[26] Borenstein S. The private and public economics of renewable electricity generation. Working Paper 17695. National Bureau of Economic Research; Dec. 2011. http://www.nber.org/papers/w17695.

[27] U.S. Energy Information Administration. Levelized cost and levelized avoided cost of new generation resources in the annual energy outlook. 2014. http://www.eia.gov/forecasts/aeo/pdf/electricity_generation.pdf.

[28] Cory KS, Schwabe P. Wind levelized cost of energy: a comparison of technical and financing input variables. CO, USA: National Renewable Energy Laboratory Golden; 2009. http://www.nrel.gov/docs/fy10osti/46671.pdf.

[29] Elliston B, Diesendorf M, MacGill I. Simulations of scenarios with 100% renewable electricity in the Australian National Electricity Market. Energy Policy 2012;45:606–13.

[30] AEMO. 100 percent renewables study – modelling outcomes [Tech. rep.]. Department of Climate Change; 2012. http://www.climatechange.gov.au/sites/climatechange/files/documents/08_2013/100-percent-renewables-study-modelling-outcomes-report.pdf.

[31] Mason IG, Page SC, Williamson AG. A 100% renewable electricity generation system for New Zealand utilising hydro, wind, geothermal and biomass resources. Energy Policy 2010;38(8):3973–84.

[32] SRU, Pathways towards a 100% renewable electricity system: [Technical Report], German Advisory Council on the Environment. URL http://www.umweltrat.de/SharedDocs/Downloads/EN/02_Special_Reports/2011_08_Pathways_renewables_Summary_for_policy_makers.pdf?__blob=publicationFile.

[33] Liu W, Lund H, Mathiesen BV, Zhang X. Potential of renewable energy systems in China. Appl Energy 2011;88(2):518–25.

[34] Mai T, Mulcahy D, Hand MM, Baldwin SF. Envisioning a renewable electricity future for the United States. Energy 2014;65:374–86.

[35] Sharma R, Manzie C, Bessede M, Brear MJ, Crawford RH. Conventional, hybrid and electric vehicles for Australian driving conditions part 1: technical and financial analysis. Transp Res Part C Emerg Technol 2012;25:238–49.

[36] Sharma R, Manzie C, Bessede M, Crawford RH, Brear MJ. Conventional, hybrid and electric vehicles for Australian driving conditions. Part 2: life cycle CO_2-e emissions. Transp Res Part C Emerg Technol 2013;28:63–73.

[37] Brear M, Dennis P, Manzie C, Sharma R. A technical and financial analysis of potentially near-zero greenhouse gas emission passenger vehicles. SAE Int J Passeng Cars Mech Syst 2013;6:61–77.

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