Australian Government
Australian Renewable Energy Agency

ARENA

Achieving cost-effective abatement from Australian electricity generation
Project results and lessons learnt

Lead organisation:	University of Melbourne		
Project commencement date:	July 1 2012	**Completion date:**	31 July 2016
Date published:	Mar 2017		
Contact name:	Roger Dargaville		
Title:	Dr		
Email:	rogerd@unimelb.edu.au	**Phone:**	0416 528 437
Website:			

Table of Contents

Executive Summary

The purpose of this study has been to address three key questions:

a) What combination of generation, transmission and storage technologies will achieve the least cost transition from existing infrastructure to a low carbon economy by 2050, and
b) How effectively will the National Energy Market (NEM) function under this new mix of technologies, and is a re-design on the market going to be required.
c) What is the value of distributed generation and storage technologies?

The key results show that:

a) A low carbon energy system for the NEM is technically and economically feasible, and under certain circumstances may be cheaper than a business as usual scenario energy system with mostly fossil generation.
b) The model configuration and the cost assumptions that go into the simulations are very important and strongly affect the results.
c) In one reference case, the transition from today's infrastructure to a low carbon energy system involves a rapid decline in capacity for black and brown coal generation over the period 2015-2030 while wind capacity ramps up, then an increase in combined cycle gas turbines and concentrating solar thermal from around 2030 onwards while the remaining coal capacity is retired.
d) A scenario with nuclear power and carbon capture and storage (CCS) included in the generation mix shows that at the Australian Energy Technology Assessment report (AETA, published by BREE) cost estimates, nuclear power is an attractive option, however CCS is not cost competitive. In none of the scenarios is geothermal power selected as cost competitive.
e) The cost implications for the average wholesale price of electricity are modest for an 80% emission abatement, but again the results depend on the modelling study: for the Jeppesen et al. model results show an increase from $70/MWh for no abatement in 2050 to $105/MWh for 80% reduction. However to get to 100% emission reduction would cost $160/MWh without nuclear, or $110/MWh with nuclear. For the 80% target, nuclear is slightly cheaper at just under $100/MWh. For Elliston et al., prices increase from $40/MWh to $55/MWh for 80% emission reduction, and then to $70/MWh for 100%
f) The implications for the design of the energy only market are significant, but there is not yet a clear consensus on whether the current market design is suitable or not for high penetration renewable energy cases.
g) Using the developed models, the implications of distributed battery storage have been examined. Using the assumption that uptake of rooftop PV and batteries will result in savings in network costs, the modelling study shows that in an optimal generation mix, the role of batteries and rooftop PV is sensitive to the assumptions regarding how much the network savings will be. Using three scenarios with low, medium and high network costs, the uptake of rooftop PV and batteries only occurs when the network costs are high (figure 5). By 2050, in the high network cost scenario, there is around 16GW of rooftop PV and 12GW of storage.

Project Overview

Project summary

In this project we developed a suite of modelling tools that were used to investigate the questions:

a) What combination of generation, transmission and storage technologies will achieve the least cost transition from existing infrastructure to a low carbon economy by 2050,
b) How effectively will the National Energy Market (NEM) function under this new mix of technologies, and is a re-design on the market going to be required, and
c) What is the value of distributed generation and storage technologies?

These models included three separate but complimentary energy systems models for finding the least cost combination of available generation technology to meet demand while constrained by various emission reduction targets. The approach is technology agnostic, with costings for various technologies taken from published reports such at the Australian Energy Technology Assessment (BREE, 2013) and the National Transmission Network Development Plan (AEMO, 2015). The second part of the study involved market models that simulated the behaviour of the NEM with the technology mix determined in the first part of the question. These models showed that with higher penetrations of wind and solar PV, market volatility increased. However the different approaches from the project partners resulted in different conclusions as to whether the current market rules would allow the market to continue to function. This remains a contentious are of research and more detailed work is required to assess the best options for the NEM design going into the future.

Project scope

The NEM is on the cusp of a major reform, with the beginning of closure of existing coal-fired power stations such as Northern in South Australia, Munmorah and Wallerang in NSW and Energy Brix and Anglesea in Victoria resulting in a loss of 2700MW over he past 5 years with another 1600MW to go when Hazelwood shuts down in March 2017. At the same time approximately 5 GW of wind and 5 GW of solar photovoltaics has been added to the NEM. The Federal Government has pledged to a 26-28% reduction in emissions on 2005 levels by 2030, and a majority of these reductions can be expected to come from the electricity sector. By 2050 it is likely that 80% or more of the emissions from the electricity sector will be abated.

The question that therefore arises is as the existing coal and gas generation is retired, what mix of technologies is required to keep the system operating? This question is not trivial as different technologies have different characteristics, with the cheaper renewables such as wind and solar PV unable to load follow and only the more expensive and emerging technologies such as concentrating solar thermal, geothermal and bioenergy able to provide dispatchable power. Storage may be able to manage some of the variability from the non-dispatchable technologies, but again, storage is still an expensive option. The questions of cost need to be considered at the same time as transmission constraints and requirements of system stability (inertia).

The project has developed capacity in the energy system modelling space, with several models now available for simulating different configurations of the NEM which can be used to test assumptions around the cost effectiveness of various new technologies or market mechanisms.

Outcomes

The project has developed three models of the generation mix in the NEM and three models of the dispatch market that determines market prices and volatility. These models are available for download.

The results from the study have been written up in eight peer reviewed publications, and it is expected that several more papers will follow in the coming months as the researchers continue to work with the models and write up new results.

Transferability

The models and understanding of systems gained under this project are applicable in other regions of the world, and the model developers are expected to work with other research groups internationally to conduct similar work.

Publications

- Elliston, B., I. MacGill, M. Diesendorf, "Comparing least cost scenarios for 100% renewable electricity with low emission fossil fuel scenarios in the Australian National Electricity Market", *Renewable Energy*, **66**, 196-204, 2014.
- Jeppesen, M., M.J. Brear, D. Chattopadhyay, C.G. Manzie, , R. Dargaville and T. Alpcan Least cost, utility scale abatement from Australia's National Electricity Market (NEM). Part 1: problem formulation and modelling. *J. Energy*. doi:10.1016/j.energy.2016.02.017, 2016.
- Brear, M. J., M. Jeppesen, D. Chattopadhyay, C.G. Manzie, T. Alpcan and R. Dargaville. Least cost, utility scale abatement from Australia's National Electricity Market (NEM). Part 2: scenarios and policy implications. *J. Energy*. doi:10.1016/j.energy.2016.02.017, 2016.
- Elliston, B., J. Riesz, I MacGill. "What cost for more renewables? The incremental cost of renewable generation - an Australian National Electricity Market case study". *Renewable Energy*, **95**, 127-139, 2016.
- Chattopadhyay D. and T. Alpcan. "A game-theoretic analysis of wind generation variability on electricity markets". *IEEE Trans. on Power Systems*, **29** (5), 2069-2077.
- Chattopadhyay D., T. Alpcan, M. Jeppesen and M. J. Brear. "Electricity Market Implications of a Least-Cost Carbon Abatement Plan: An Australian Perspective". *The Electricity Journal*, **27** (8), 105-115, 2015.
- Chattopadhyay D. and T. Alpcan. "Capacity and Energy-Only Markets under High Renewable Penetration" *IEEE Trans on Power Systems*, **31**, 1692-1702, 2016
- Riesz, J. and M. Milligan "Designing electricity markets for a high penetration of variable renewables". *Wiley Interdisciplinary Reviews: Energy and Environment,* **4(3),** p. 279-289. doi: 10.1002/wene.137, 2015.

Conclusion and next steps

This ARENA funded project has produced state of the art modelling tools to be used to examine the pathway to a low carbon electrical energy system. The models have demonstrated that the pathway to large carbon abatement is technically feasible and viable from an economic point of view. The implications for the incumbent generators however are very significant, with large-scale retirement of all the existing coal fired generators. Managing this transition will be complex. This study has not considered the policy framework that will be required to achieve the abatement goals, but there is little doubt that incentives via carbon pricing, emission restrictions or renewable energy targets are required to achieve the system restructuring required.

Next steps in this work could include (non-exhaustive):

- Sensitivities to future cost curves for the different technologies – the models could be run with more or less optimistic curves to test the sensitivities of the different technology costs.
- More detailed assessment of the role of storage. Some storage work had been done in this study, but extensions to explore the role of different storage options (small scale batteries, i.e. Tesla Powerwall, larger scale batteries within the distribution network, and large scale storage, i.e. pumped hydro).
- Impact of demand-side management. This is an area that is has had very little research done. Understanding how different industrial, commercial and residential scale processes could be modified to respond to pricing signals and thereby allow greater penetration of variable renewables is poorly understood.
- Large scale transmission extensions. This study has only considered augmentation of the existing transmission network. However additional network capacity to remote areas or even connecting the currently separate grids within Australia has not been considered. These options are generally considered to be expensive, but under high penetration renewable energy systems, the potential benefits might outweigh the costs.
- Application of the models to other regions. The models could be used to investigate optimal pathways for other established networks, or even for emerging economies in the developing world. Initial work looking at Chile and Brazil is currently being undertaken.
- Extension of the models to include the natural gas system so that interactions between demand for gas for residential heating, industrial processes, electricity generation and international export can be studied.

Lessons Learnt

Lessons Learnt Report: 80-100% renewables is achievable

Project Name: *Achieving cost-effective abatement from Australian electricity generation*

Knowledge Category:	<Choose an Item>
Knowledge Type:	<Choose an Item> Technical
Technology Type:	<Choose an item>
State/Territory:	<insert state/territory> All

Key learning

By taking multiple approaches to simulating the least cost technology mix to meet projected demand using only renewable energy generation technologies, the project has demonstrated that by optimally placing wind and solar PV plant around the NEM the variability in output can be minimised, and that combined with hydro, concentrating solar thermal and biogas to provide dispatchable generation for times of low output from wind and PV, the system can be run in a stable fashion. The overall levelised wholesale costs are higher than present days costs, however depending on input assumptions the increase in these costs are on the order of 60 to 130% in 2050 compared to today, or between 4 and 11c/kWh higher.

Implications for future projects

Future projects can now look at more subtle differences in the configuration of the energy system models, such as including demand side management, different projections of demand and fuel costs, inclusion of differing amount of utility scale and distributed storage etc. The policy implications are also profound – in the electricity sector at least, it can be shown that a 100% emission reduction target will be possible by mid-century.

Knowledge gap

At the commencement of this project, it was unclear as to whether it was technically feasible to build a 100% renewable energy system for Australia. Previous studies has suggested is was possible, but this study took into account additional complexity (transmission constraints, economic dispatch, inertia constraints) and succeed in demonstrating that the transition to a low carbon electricity system is achievable.

Background

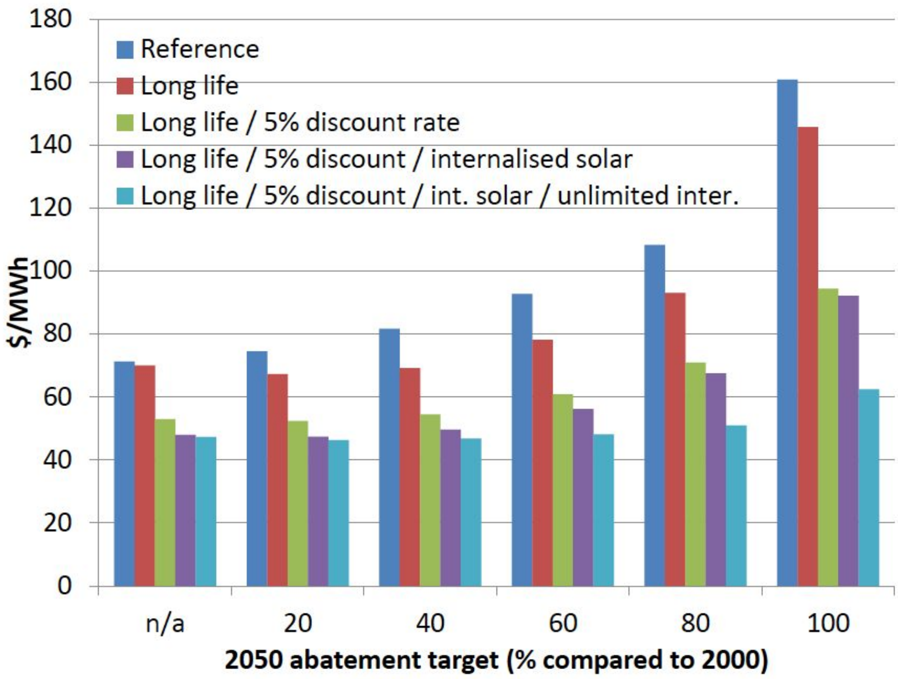
Objectives or project requirements

Determining the technical possibility and economic cost of a 80-100% emission reduction pathway formed the main objective of this project. The was meet though the project requirements of developing open access energy system models.

Process undertaken

This finding is the key result *of the overall project and comes out of the bulk of work carried out. This includes the development of the suite of modelling tools for the generation and markets, collating the input data and running the various scenarios.*

Supporting information



This figure shows the range of levelised cost of electricity in 2050 for the range of emission reduction targets for a range of scenarios starting with the reference case, then variations with increasingly reduced constraints of inertia, discount rate and plant life.

Lessons Learnt Report: A Renewable Energy Target is suitable up to about 2030

Project Name: *Achieving cost-effective abatement from Australian electricity generation*

Knowledge Category:	<Choose an Item>
Knowledge Type:	<Choose an Item> Policy
Technology Type:	<Choose an item>
State/Territory:	<insert state/territory>

Key learning

The modelling simulations included scenarios where the emission reduction target was replaced with a renewable energy portfolio target, with simulations with 80% emission reduction targets compared to simulations with an 80% renewable energy contribution. These simulations demonstrated that up to 2030 the impacts of the different policy options are quite simular. This shows that the current policy of a renewable energy target is an appropriate 'second best' option to a price of carbon or other such form of emission reduction target. However, beyond 2030, the results diverge significantly showing that the lack of a price on carbon after this point in time will result is a sub-optimal generation mix and lower emission reductions at higher costs.

Knowledge gap

Prior to these studies being undertaken, there was limited evidence and supporting information as to the relative benefits of a RET versus a carbon price in terms of the transition to a low carbon energy system. These results show that the RET policy results in a similar signal to the market to the price on carbon – the increase in wind and solar PV forces the retirement of the less flexible supply which happens to also be the more carbon intensive. However, without a policy to create *a direct disincentive for carbon intensive generation, after 2030 the emission reduction is less than when a direct emission constraint is applied.*

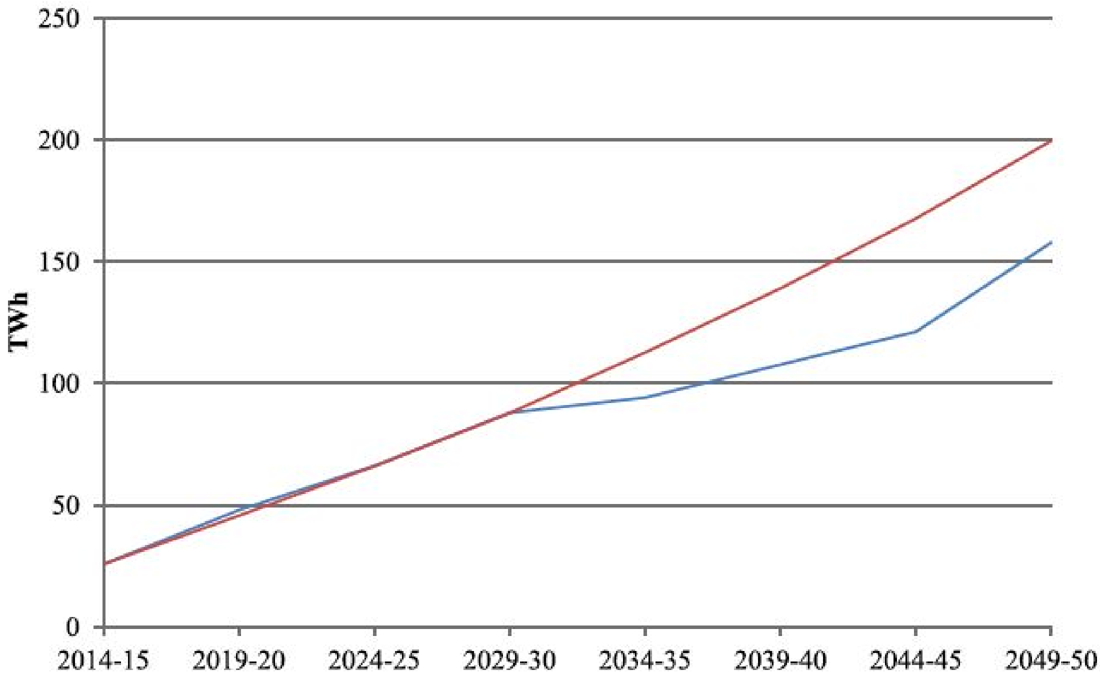
Background

Process undertaken

The linear programming optimisation can accept a broad range of constraints, and it is not particularly onerous to adjust the configuration to make the ratio of renewable energy technology in the mix one of the constraints (along with meeting demand, not exceeding transmission capacity, having sufficient inertia) instead of a total carbon emission constraint. In a simular fashion, the effects of other policy mechanisms (e.g. emission intensity) could also be tested.

Supporting information

a)



b)

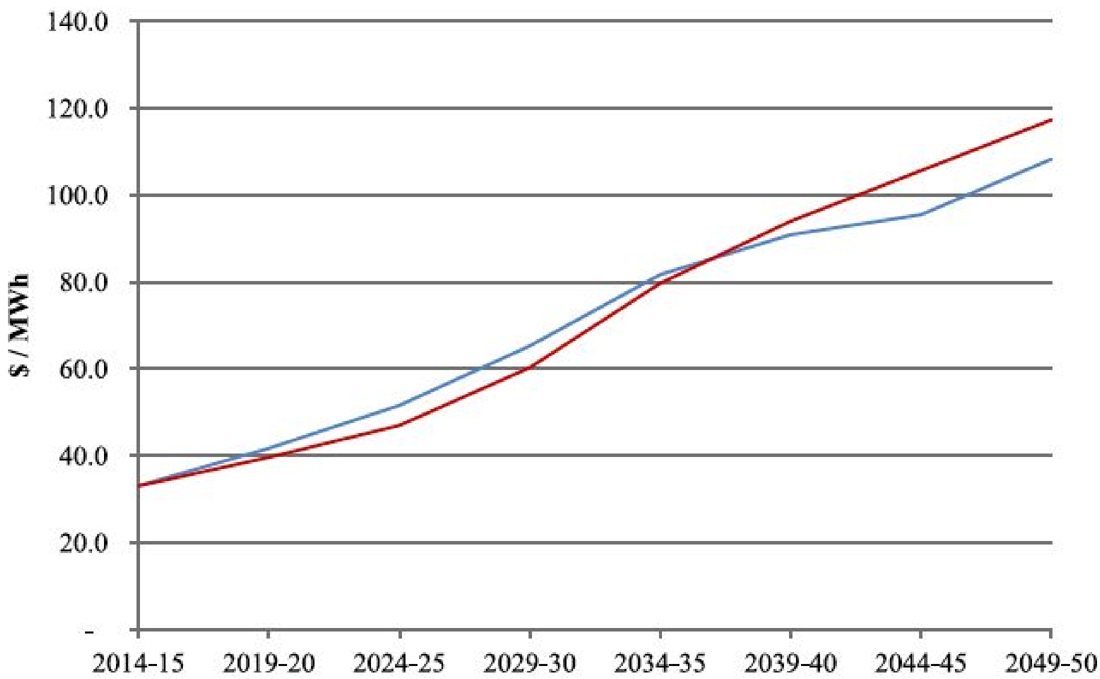


Figure: a) Total TWh generated prior to curtailment in the RET scenario (red) and the emission reduction scenario (blue) and b) levelised cost of electricity for the two scenarios.

Lessons Learnt Report: Rooftop PV and battery storage might be cost effective under certain scenarios.

***Project Name:** Achieving cost-effective abatement from Australian electricity generation*

Knowledge Category:	<Choose an Item>
Knowledge Type:	<Choose an Item>
Technology Type:	<Choose an item>
State/Territory:	<insert state/territory>

Key learning

In the extension work, the models were modified to simulate the effect of adding distributed battery storage and rooftop PV into the technology mix. In the previous model version only utility scale PV was explored, and pumped hydro storage was available but was limited to existing plant. The modelling was done on the basis that by including distributed generation; the distribution network cost could be reduced. The first simulation with distributed PV but not batteries showed that the peak demand was similar with and without PV (due to peak demand occurring after the output of PV declines) and as such increasing rooftop PV did not reduce the overall system costs. Therefore the optimisation did not include it in the least cost calculation.

For the simulation including battery storage, the results were dependant on the assumptions around the network costs themselves. Three scenarios with low, medium and high distribution network costs were run. Only in the scenario with high network costs were distributed batteries and rooftop PV shown to be beneficial to the overall system cost. However in this scenario, the uptake of batteries and rooftop PV was very large, with up to 22GW of rooftop PV and 17 GW of batteries installed.

Implications for future projects

Understanding the benefits to distribution networks resulting from installation of distributed technologies and the cost savings is very important. If these benefits are high, then it is a sensible approach to incentivise installation of these technologies. However, if the avoided network costs are low or medium, then it is more cost effective from an overall system level to focus on building utility scale PV and not to invest in batteries.

Knowledge gap

Prior to these simulations, it may have been assumed that installing rooftop PV and batteries would in general be a good outcome in the energy system. The results show that it is dependant on the assumptions on the network savings.

Background

Network cost scenario	Overnight build cost $/kW	Overnight build cost $/kVA	Annualised build cost $/kVA/year	Example distributor annualised costs $/kVA/year
Low	960	864	95	Citipower ($94) [9]
Medium	1,556	1,400	154	Ausgrid ($152) [10] SA Power Networks ($156) [10]
High	3,444	3,100	341	Endeavour Energy ($348) [10]

Table 1: Network cost scenarios.

Battery cost scenario	Storage quantity (hours)	Storage capacity cost $/kWh	Generating capacity cost $/kW	Notes
Reference	2	560	1,120	Current cost (Lazard 2016 [10])
Low	2	1,120	2,240	50% of current cost

Table 2: Battery storage cost scenarios.

Table showing the input assumptions applied to the modelling of distributed PV and batteries.

Supporting information

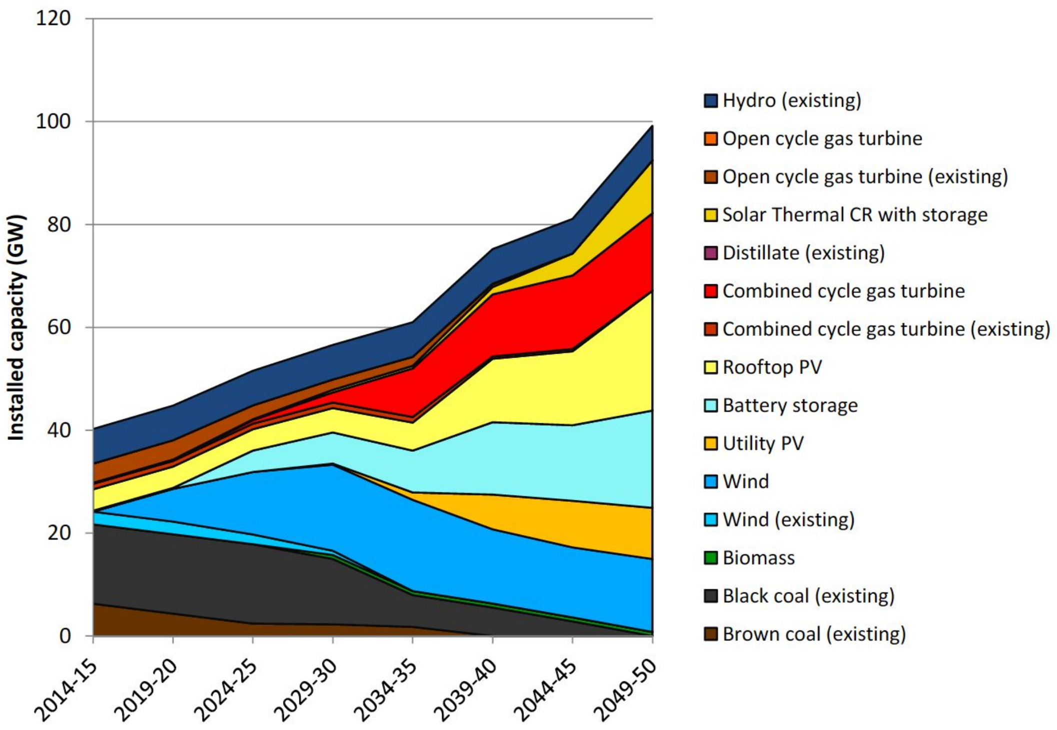


Figure: Generation mix in the high network and inertia exemption scenario showing high uptake of rooftop PV and batteries.

Appendix

Keywords

National Energy Market
System modelling
Emission reduction pathways
Dispatchable generation
System security
Storage
Distribution and Transmission