CSIRO FutureGrid Research Project – Planning for Change and Choice

Introduction

Background – Scope and Purpose

The three-year CSIRO Future Grid Research project – a collaboration between CSIRO and four leading Australian universities supported by $3M from CSIRO's Flagship Collaboration Fund – was set up to enhance Australia's capacity to plan and design the most efficient, low emission electricity grid for Australia up to the year 2050.

The existing electric power grid was developed from early last century with significant expansion occurring in the last six decades based on improving large scale generation and network options and growing industrial, commercial and domestic demands. The existing electricity grid is structured to carry power efficiently and reliably from remote centres of power generation to the major load centres and then to distribute the power to the end use consumers. The primary power sources include groups of relatively large coal-fired power stations located in coal-mining areas, hydro power stations located at large water storages (including the Snowy Mountains Hydro Scheme) and smaller generating centres sourced by gas and run of river energy. The load centres are concentrated in Australia's major coastal cities and industrial regions.

The grid has been designed and built to carry power from a relatively small number of large-scale, dispatchable generators to energy consumers largely in one direction. Industrial centres have provided constant and predictable loads while the great diversity of millions of commercial and residential consumers offered, in aggregate, reasonably predictable load patterns. The power transferred across the grid has progressively grown following an underlying trend of growth of energy demand in the economy.

Much, however, has changed over the past decade and the future grid will need to evolve and operate under a potentially very different environment from the grid of today. Key has been the growing capabilities of new renewable generation technologies and decentralised energy options, and growing concerns regarding the environmental impacts of the present electricity sector. The future grid will likely be powered by multiple energy sources, including significantly more renewables and gas, both centralised and distributed, with a range of supply and demand side technologies, business and operating models. The renewable energy sources will include both large and small wind farms and solar farms scattered across Australia, sometimes remote from the existing grid, and with very different operating characteristics from conventional generation options. The nature of the loads is also changing with increasing roof top solar PV installations (currently modelled as a negative load), end user battery storage systems and the ability of consumers to tailor their energy use patterns in response to the market price of energy at any time of day.

The FutureGrid research project brought together the engineering, economic and policy aspects of future grid modelling, optimisation and planning, focusing on four project areas:

P1 Power and Energy Systems Modelling and Security (University of Sydney - USyd)
P2 Grid Planning and Co-optimisation (with gas networks) (University of Newcastle and USyd)
P3 Economic and Investment Models for future grids (University of Queensland)
P4 Robust energy policy frameworks for investment into future grids (University of New South Wales)

Building on the outcomes of the earlier CSIRO-led Future Grid Forum, the Future Grid Research project has developed models and tools that enable rigorous analysis of different energy network configurations for a range of future scenarios.

While the major emphasis of the research has been directed to the detailed development of models and tools, a number of insights that have come out of the work are presented and discussed below.

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Key messages from the Research

1. **Answering the key questions about future grids demands a strong, scientific, multi-disciplinary analysis framework, and new methods of modelling and analysis that can handle high levels of uncertainty.**

The framework must be capable of integrating policy, economics, and power system security across a wide range of possible scenarios. The modelling must be "whole of system", including the gas system, from generation to consumers, and covering all systems and processes in between.

The multi-disciplinary research undertaken in the Future Grid research project has developed models and tools that provide a sound basis for continuing work in this area. A core component of the research was development by Project P1 of a simulation platform for security analysis of a large number of future grid scenarios dominated by a high penetration of renewable generation. Project P2 and P3 focussed particularly on the integration of gas and electricity models while P3 also considered options for mapping the scenario space through extensive parallel simulations. Project P4 modelling developed techniques for valuing potential trade-offs between energy security, emissions and economic outcomes of future grid. Modelling from the four projects has established a promising if yet still partial framework for analysing a wide range of possible future grid scenarios across a wide range of issues.

While significant progress has been made in the research to date, more work is required to build an enhanced "whole of system" multi-disciplinary model for the NEM power system, and which also incorporates the gas system. Specific enhancements include the need to refine models and computational techniques to reduce scenario run-times to reasonable lengths, and to use open source software modelling tools wherever possible. The latter would enable wider collaboration between researchers, industry analysts and decision-makers.

A "whole-of-system" model would need to account for long-term system integration costs and benefits, including network impacts, of renewable energy, energy storage and other technologies that may be applied in the future NEM. This has been noted by Kevin Scarce in the South Australian Nuclear Fuel Cycle Royal Commission final report (SANFCRC Final Report, Item 53, pg65: http://www.nuclearrc.sa.gov.au):

"*At present there is no analysis of a future NEM that examines total system costs based on a range of credible low-carbon energy generation options…*"

Planning for optimal long term power system development is critical, given the long-lived nature of system assets (current and future) as against the disruptive impact of new technologies. There is a real risk that short-medium term or locally-biased solutions that do not take into account system-wide issues on a multi-disciplinary basis, may lock in new infrastructure that is sub-optimal in the long term.

2. A strong and robust transmission system is a key requirement for successful integration of high penetrations of renewables and decentralised generation into the grid.

Regional interdependence across Australia's National Electricity Market (NEM) will become increasingly important and necessary as renewables penetration increases – for energy transport to balance variable supply and load, and for grid stability. Policy and regulatory settings will need to address this.

Increasing penetration of wind and solar PV generation into the grid presents challenges for grid stability, with increased disturbance potential in local regions. The challenges have at least two dimensions: the highly variable and somewhat unpredictable nature of non-dispatchable renewables, and their non-synchronous interface to the grid. Much of the public policy debate and media commentary have focused on means to address the former. These include maximising geographical diversity, augmenting and strengthening networks, and a growing role for energy storage. Until relatively recently, less has been said about addressing the latter issue: as the penetration of non-synchronous renewables into the grid increases, a corresponding reduction in synchronous generation reduces system inertia and fault levels, affecting system stability and the current means for maintaining it.

Grid stability was in fact one of the key focus areas identified for study within the FutureGrid research project (through Project P1), with potential challenges in this area envisaged to become significant over the medium term. Actual events since the FutureGrid project was initiated in 2012 have borne out the need for stepping up the pace of regulatory and market review. The May 2016 shutdown of South Australia's (SA's) last remaining coal-fired power station in Port Augusta provides an example. The shutdown has resulted in less locally provided inertia in SA's grid during periods of high renewable power generation. This increases the state's reliance on the Heywood Interconnector with Victoria to provide access to inertia. In June 2016 the SA state government announced funding for an investigation into greater transmission interconnection with other states, to "improve wholesale market competition and power system security for South Australia, as well as providing renewable energy for Australia".[1] Greater interconnection of SA with the rest of the NEM would provide higher electricity export and import capacity for SA. This could provide greater flexibility in balancing supply and demand in light of SA's high and increasing penetration of renewables. An additional interconnector would also provide for greater power system security, reducing reliance on locally sourced Frequency Control Ancillary Services (FCAS). This is currently a more urgent issue for SA than for other states in the NEM due to the higher proportion of variable renewables on SA's grid. As the penetration of non-synchronous renewables increases across the NEM, managing grid stability will become a more significant issue. Unless other solutions are developed and implemented, the cost of providing services such as FCAS are likely to rise accordingly. For example, National Grid in the UK has recently estimated additional FCAS costs associated with increased deployment of renewables to be in the order of £200-250m a year.[2]

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[1] http://www.premier.sa.gov.au/index.php/jay-weatherill-news-releases/697-state-budget-2016-17-study-into-new-interconnector

[2] National Grid UK - SMART Frequency Control Project: http://www.nationalgridconnecting.com/The_balance_of_power/index.html

3. **Energy storage is likely to play a key role in future grids at all scales, from utility to household.**

Energy storage at both household and utility scale promises significant benefits, yet also poses significant integration and control challenges. Other forms of large scale energy storage are also important areas of investigation.

Aggregated across the grid, household battery energy storage has the capability of smoothing out short term fluctuations in energy flows. Our modelling shows that it can also exacerbate fluctuations around the step changes in intervals within Time of Use tariffs, depending on whether and how it is controlled. This work demonstrates the importance of detailed modelling of the interaction of battery control systems and consumer behaviours with tariff structures and other retail market features to assess local and broader system impacts.

Under current arrangements, increasing deployment of “opaque” behind-the-meter solar PV and battery systems poses increasing challenges for AEMO and network service providers in controlling grid stability, and in planning the power system for the future. This relates not only to the size and type of equipment installed, but also how it is configured and programmed to interact with the grid. Development of systems, protocols and appropriate regulation for addressing these issues needs to be accelerated.

Development of large scale energy storage solutions continues to be an important area of study. This includes investigating new opportunities for pumped hydro-electricity storage. Also of interest is the role that gas networks and gas storage (possibly including compressed air storage) can play in balancing variable electricity supply with loads. Closer integration of planning and operation of gas and electricity networks would benefit understanding of the potential in this area. This is discussed further below.

4. **Existing policy and regulatory frameworks require timely – yet careful - review and change to ensure they facilitate appropriate technology and business model developments while being robust to the growing range of future grid possibilities.**

“External” energy and climate policies, added to the other disruptions in the electricity industry, are applying significant stress to a market framework that was designed and then evolved under very different conditions. Policy and regulatory reform needs to continue apace to facilitate an effective, efficient and robust transition to the future grid.

Disruption in the electricity sector, from new technologies, evolving market arrangements, heightened consumer involvement, climate policy drivers and other issues, is challenging an industry previously characterised by relative stability and long, “slow and steady” planning horizons.

Restructuring of the Australian electricity industry in the late 1990’s towards more market based arrangements provides a powerful yet challenging context for appropriately facilitating the changes already underway. Technologies such as rooftop solar PV and the much-anticipated battery storage, as well as the growing deployment of smart metering, have brought energy consumers into focus. However, present regulatory and market arrangements were developed at a time when end-users

had little opportunity or apparent interest in greater electricity industry engagement. The extent and ultimate value of these consumer driven changes in the electricity sector will critically depend on future regulatory, market and policy settings.

In addition to this, energy and climate policies designed to reduce greenhouse gas emissions in the electricity sector are currently enacted as 'external' drivers to a set of electricity industry objectives and arrangements that focus on the 'long term interests of consumers' in a relatively narrow and supposedly technology neutral way. This is unlikely to appropriately facilitate the fundamental transformation of the electricity sector required to meet our climate goals, while still ensuring energy security and accessibility is maintained. As these disruptive changes and external policy influences continue to grow in magnitude, the need for reform of policy and regulatory frameworks becomes both more urgent and more in need of careful consideration. Research by Project P1 has highlighted the need for energy security to be better integrated into policy efforts that seek to drive major industry transformation while P1, P2 and P3 have established the value of better integration across electricity and gas, and between networks, generation and demand. P4 has provided important insights into the need for comprehensive and coherent efforts within and across the regulatory, market design and broader policy domains, and assessment frameworks that can establish the robustness of these settings for a wide range of potential future grids.

5. **'Stretch' scenarios including modelling of 100% Renewable Energy scenarios in the NEM – updated regularly - are needed to inform and guide policy as technologies, systems and business models evolve**

Rigorous analytical studies of high renewables scenarios – as part of a "whole of system" approach - are essential for identifying the technical and policy challenges and opportunities to be addressed in transitioning to a low emissions future grid.

Researchers in Project P4 (UNSW) have modelled potential 100% renewable energy (100% RE) generation scenarios in the NEM, and have also surveyed other recent 100% RE studies, including by AEMO, Beyond Zero Emissions, and the University of Sydney. The results, summarised in a working paper [3], indicate that future scenarios with 100% renewables appear to be technically feasible, provided the generating portfolio has the right mix of technologies, including sufficient firm, synchronous generation such as hydro, biogas, concentrating solar thermal and geothermal.

A wide range of cost estimates has been reported by the studies surveyed, from $80 - $200 per MWh (wholesale electricity cost, including transmission costs). This points to a significant diversity of views as to how a 100% renewable NEM might be achieved. It also indicates a need for ongoing research to address the challenges of efficiently integrating renewables technologies into the NEM.

Exploration of 'stretch' scenarios such as these are essential to test the likely effectiveness and robustness of different policy, market design and regulatory frameworks for driving fundamental transformation of the future grid towards a low carbon future.

[3] J. Riesz, B. Elliston, P. Vithayasrichareon, I. MacGill (2016), "***100% Renewables in Australia: A Research Summary***". CEEM Working Paper, March 2016.

6. **Closer interaction between electricity and gas networks - in planning, market design and operation - is essential for optimising economics, reliability and sustainability in Electricity Markets in Australia and internationally.**

As the penetration of variable renewables into the grid increases, co-optimisation of electricity and gas networks – and later, transport networks with electric vehicles - will become more important.

It has been recognised that coupling electricity grids and gas pipelines, while utilising common energy resources such as hydro systems, can significantly increase energy trade, reduce costs of energy and improve energy supply security. Co-optimised planning and operation of electricity and gas systems can also underpin environmental benefits, for example through support for variable renewable generation sources. Enhancing the coordinated operation of electricity and gas networks, already established under AEMO's remit, facilitates ongoing market development in the NEM.

In general, energy market infrastructure is required to provide non-discriminatory service to all energy suppliers. An emissions constrained economy is likely to promote substitution from coal- and oil-fired generation to gas-fired power generation (GPG). A reliable gas network and sufficient, competitively priced gas supply are required to ensure the viability of gas-fired units in wholesale electricity markets. The co-optimisation and planning model will have important application in other electricity markets internationally. It will be a key tool for ensuring energy security, given that coal currently has the largest market share in power generation around the world. As natural gas gradually increases its market share in base-load generation, greater diversity in the generation mix will improve energy security.

The co-optimisation of gas and electricity systems will also effectively contribute to greenhouse gas emissions reduction objectives, with GPG facilitating decarbonisation of the energy system. In addition to this, as the uptake of electric vehicles grows, the co-optimisation model can be extended to achieve a three-fold co-planning framework involving electricity, gas and transportation networks.

Key Outputs from the Research

Some key research outputs from each project are outlined below. A more detailed summary of the research in each of the four project areas follows the recommendations section.

Project P1 Grid security and stability for high penetration renewables and storage

A simulation platform has been developed for evaluating network stability for a large number of future grid scenarios in the NEM. The highlights are observations on how the network structure - including strength - as compared to use of storage and demand response, help overcome the challenges arising from high renewables scenarios. Key outcomes from the simulations are:

- Network strength improves system damping, transient stability, voltage-constrained loadability, and frequency stability; it also significantly improves capacity factors of renewable generation.

- High penetration of residential PV without residential battery storage gives rise to potentially difficult operating conditions, including high ramp rates for load, and impacts on voltage and frequency stability. However, the impact on small-signal and transient stability is less pronounced.

- High penetration of demand response, on the other hand, reduces load ramp rates and significantly improves all aspects of system stability.

For energy storage, the research has led to the development of a decision support tool to assist end-users and other third-parties in selection and operation of low voltage solar PV-battery systems. A key finding from the modelling work is that where Time of Use electricity tariffs are in place, increasing levels of storage can result in large, short duration step-changes in demand around the transition times between low and high grid electricity prices. These potentially put system stability at risk. This example indicates the need for detailed modelling of the impacts of tariff designs as new technologies and business models evolve.

Project P2 Electricity and Gas Network co-optimisation

Increasing use of gas-fired generation in the NEM – albeit subject to significant gas supply/demand/pricing uncertainty – will require more detailed gas network planning and management strategies, integrated more closely with electricity network planning and management. A model framework for coupled gas and power systems has been developed to provide a holistic approach to the interdependent assessment of gas and electricity networks. The model forms the basis for further development of advanced simulation and decision making tools to co-optimise electricity and gas networks.

Emission constraints play an important role in the viability of GPG units by changing the merit order of generation and promoting investment in gas fired generators and gas transmission infrastructure. The proposed grid planning and co-optimisation framework can be used to guide the energy industry to form a holistic approach to the strategic planning of future grids, subject to various interacting physical and economic constraints.

Compared with the separate planning approaches, the co-optimisation approach can achieve higher social welfare and energy network reliability, although extra computational effort might be required.

Project P3 Investing in future grids and generation

Future deployment of renewable generation to the extent that it significantly reduces the emissions intensity of the stationary energy sector will require continued regulatory enablement (as opposed to market-based technology-agnostic approaches alone being expected to deliver the needed changes).

The "internationalisation" of natural gas prices in the NEM through LNG "net-back" prices amplifies the uncertainties faced in making investment decisions in grid-scale electricity generation assets. This reinforces the importance of scenario analysis on energy supply in international markets – particularly as it involves and affects gas – and how this feeds back into the Australian gas and electricity sectors.

Project P4 Policy, regulation and market design - "External policy drivers"

The regulatory market design and policy settings for the NEM have proved reasonably successful to date in ensuring secure, reliable and affordable electricity provision in the face of considerable technology and market change. The NEM has successfully integrated almost 5GW of wind generation over the past fifteen years, with a considerable proportion of this going into the relatively small market region of South Australia. Governance arrangements have progressively brought wind generation more formally into wholesale market arrangements amongst other changes. Market arrangements were also able to manage the introduction and then later removal of a carbon price.

Gas industry arrangements have proven more challenging in some regards. The NEM saw considerable gas-fired generation investment since its introduction in 1999, driven by a range of policy mechanisms, growing peak demand and expanding gas supply. However, the introduction of export LNG facilities on the East Coast has dramatically changed the local market with adverse impacts on gas generation.

NEM retail market arrangements have been shaken up by the deployment of 1.5 million household PV systems over the past seven years – the highest household penetration in the world. Consumer battery systems show potential for similar growth while smart appliances offer further options for greater energy consumer engagement. Together, these developments pose both challenges and opportunities for the present consumer interface with the NEM. Governance stakeholders such as the AEMC have, as a consequence, had to greatly strengthen their retail and network regulatory and market design efforts. It is difficult enough to keep up, let alone proactively shape future outcomes.

The greatest challenge, however, would seem to have been in the broader 'energy and climate' policy space where high levels of policy uncertainty and change have markedly hampered efforts towards a low carbon future grid.

Project P4 work has highlighted the need for 'stretch scenarios' that consider the potential range of possible future grids and more formal incorporation of future uncertainties into electricity sector

investment modelling efforts. It has also identified the value of financial portfolio techniques to identify robust future grid scenarios in the face of such uncertainties and hence risks.

P4 has also explored policy assessment frameworks for ensuring greater comprehensiveness within and across the regulatory, market design and broader policy domains, with an emphasis on ensuring robustness. A series of case studies in areas including transmission investment, network tariffs and ‘renewables versus gas’ NEM futures have highlighted key challenges for policy makers in these areas including the importance of facilitating ‘new entrant’ technologies and business models to support industry innovation while carefully managing the necessary transition between current and possible future arrangements.

Recommendations for Next Steps

In addition to the specific research outcomes from this project, this work also provides a firm basis for additional necessary investigation in this field. Recommended further work includes:

1. **Develop models and undertake "whole of system" modelling for the NEM Electricity System and Gas System.**

   The models are to be used to analyse total system costs for a wide range of potential low-carbon energy generation options. The modelling must be multi-disciplinary, and needs to be able to account for long-term system integration costs and benefits of renewable energy, energy storage and any other technologies that may be applied in the future NEM.

   A key sub-set of this work would include developing ongoing models and studies of 100% Renewables "stretch" scenarios in the NEM. Rigorous studies in this area are needed to enable informed policy debate and development, and to identify technologies and systems necessary for evolving to a low emissions future grid.

2. **Implement a national gas and electricity co-planning practice for the Australian NEM.**

   Gas and electricity systems are critical national infrastructure; they form the backbone of the national energy market in Australia. In order to achieve optimal economic outcomes while delivering emissions reductions and maintaining system security, co-optimisation and planning of both systems as interdependent systems is needed.

3. **Maintain collaborative multi-disciplinary approaches for future energy system planning**

   The challenges facing the energy industry in general, and the electricity system in particular, are extensive and complex. This calls for high levels of collaboration between governments, regulators, energy industry stakeholders and research institutions in planning for the future energy system. Such collaboration should become the new norm, and as such must be guided by an independent statutory body with a specific remit to maintain it.

4. **Refine models and computational techniques to reduce scenario run-times to reasonable lengths**

   Much effort has been made in this project to minimise simulation run times so as to be able to analyse an adequate range of scenarios and sensitivities in a timely way. While significant results have been achieved in this project, more needs to be done. Developing more efficient algorithms and computational techniques to reduce scenario run times will be a key requirement for future models.

5. Use open source software modelling tools wherever possible

This will enhance collaboration between researchers in building and refining models. It will also enable greater transparency and ability to vary inputs for different scenarios and design assumptions.

6. Equip more engineers and researchers with high level skills in power system planning and operation

After a long period of stability, the power industry is facing a period of rapid and disruptive change. Research projects and training across multiple disciplines (eg STEM, economics/finance, policy, social) are required to equip people to effectively manage the complexity challenges.

7. Investigate opportunities to maximise use of “excess” renewable energy.

Increased penetration of variable non-dispatchable renewable generation into the electricity system will result in periods of “excess” or curtailed energy – available at effectively zero Short Run Marginal Cost. Technologies and systems that can consume or store electricity on a variable, flexible basis should be developed.

Analytical studies in this area should research technologies as well as appropriate enabling market design and regulatory frameworks. Such studies should be part of the “whole of system” modelling approach discussed in Recommendation 1.

Detailed Research Summary for all Four Projects P1 – P4

FutureGrid Research Project P1 – University of Sydney

Power & Energy Systems Modelling & Security

Introduction

This part of the CSIRO Future Grid Research Cluster deals with the modelling and security analysis of the Australian power grid with a long-term view, i.e. taken to be from 2020-2050. Accordingly, the focus is on the high voltage grid and in particular that major part associated with the East Coast or NEM, augmented by possibilities for renewable energy generation and grid-connected storage. Nevertheless, given the likely importance of demand-side technologies such as rooftop solar PV, electric vehicles (EVs) and other household storage, methods to represent such at higher voltage levels have been given serious attention in our research. In particular, methods for aggregated household storage modelling have been developed. Questions of security involve the typical issues of balancing (energy, power and ramping), contingency analysis, system stability (angle, frequency and voltage) as well as emerging concerns with cyber-security.

Power system analysis in the past has focussed on a relatively small number of scenarios of power system operation and future power system development, given that future power sources and loads have been reasonably predictable. The future power system is now far less predictable. Following the CSIRO Future Grid Forum, a scenario-based framework and algorithms have thus been developed to scan the potentially large numbers of possible future states of the grid. Sensitivity analysis processes and contingency analysis techniques have been developed to assess power system capability and stability.

Key Outputs

Key outputs apply in two areas: the power system as a whole and more specifically with respect to the characteristics of energy storage.

For Power systems

We have developed a simulation platform for security analysis of a large number of future grid scenarios dominated by a high penetration of renewable generation – see Figure 1 below. As part of this, we considered a 100% renewable scenario for the National Electricity Market representing the year 2040.

Unlike in conventional power system planning, where only a handful of the most critical scenarios is analysed, we used a time-series approach to capture the impact of inter-seasonal variations in renewable generation on power system stability. The approach used in the project is a major departure from the existing power system planning practices, and is, to the best of our knowledge, the first such approach internationally. The difference between our approach and the established practice is that we analyse scenarios that are not merely “linear extrapolations” of business-as-usual

scenarios, as was the case in major national studies in the USA and Europe. Further, these studies required a number assumptions, usually simplifying the grid or ignoring it altogether. First, our approach is market structure agnostic. Second, to identify the underlying structural issues, dynamic models of the system scenarios were simplified by elimination of the controllers with minor impact on the system behaviour. Third, the sheer number of the degrees of freedom concerning generation and transmission technologies, grid topology, the uptake of emerging demand-side technologies and utility storage, did not allow us to cover comprehensively all possible future scenarios. Instead, we chose one representative scenario and performed a comprehensive sensitivity analysis, which we believe captures a wide range of possible future outcomes. The simulation platform consists of three parts: (i) market model based on a modified unified unit commitment problem to take into account the uptake of the emerging demand-side technologies, such as integrated PV-battery systems; (ii) load flow calculation; and (iii) comprehensive stability assessment. We have considered all four stability types: (i) small-disturbance angle (oscillatory) stability; (ii) large-disturbance angle (transient) stability; (iii) long-term voltage stability (loadability); and (iv) frequency stability.

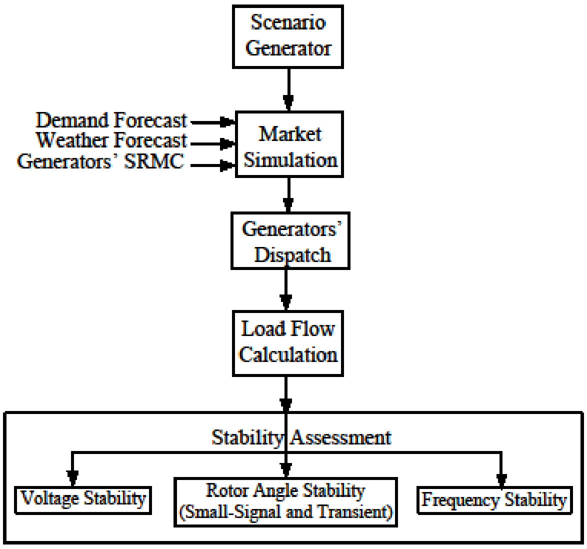

Figure 1: Simulation platform for the performance and stability assessment of FG scenarios.

The sensitivity analysis considered the following parameters: (i) network strength; (ii) uptake of demand response; (iii) uptake of residential PV; and (iv) uptake of residential battery storage. The results are quantitative in terms of specifically defined stability indices but can be summarised in general terms with the following key points:

1. Network strength improves damping, transient stability, voltage-constrained loadability, and frequency stability (frequency nadir and rate of change of frequency). It also significantly improves capacity factors of renewable generation.

2. High penetration of residential PV without residential battery storage gives rise to potentially difficult operating conditions. For example, the now familiar “duck-shaped” load profile resulting from high PV penetration requires high ramp-rate backup generation to take up demand late in the afternoon as PV generation drops off. It also significantly affects loadability (voltage stability) and frequency stability. However, the impact on small-signal and transient stability is less pronounced.

3. High penetration of demand response, on the other hand, results in a flatter demand curve due to users shifting consumption to off-peak hours, which reduces the ramping stress on backup generation. It also significantly improves all aspects of system stability.

For Energy Storage

Rapidly declining prices of solar PV and battery storage systems in recent years has led to increased interest in grid-connected solar PV-battery systems, particularly at the residential level. However, the process of identifying the right technology, optimal size and operation of the selected system is a complex economic problem. We have developed a rigorous decision support tool to assist end-users and other third-parties in selection and operation of solar PV-battery systems. The model is capable of identifying feasible options for investment in solar PV and/or battery systems and the specifications of the system best suited to an individual house.

Our investigations demonstrated that the feasibility of grid-connected solar PV-battery systems is highly sensitive to parameters such as solar PV/battery installation costs, electricity tariff, feed-in tariff, geographic location, and load profile. Within a range of credible price scenarios for solar PV systems and electricity tariffs that we modelled for Sydney, including a battery in the system returned a positive benefit only when installed costs fell below $500/kWh.

We studied systems with different combinations of solar PV and batteries, and modelled the impacts of these systems on hourly load profiles at feeder level. One of the key findings is that where Time of Use (ToU) electricity tariffs are in place, increasing levels of storage have a significant impact on grid performance as users time-shift their grid electricity demand to minimise their costs. In particular, ToU pricing with step function transitions could prove problematic for future system operation due to the potential for large, short duration step-changes in demand around the transition times.

The decision support tool was also used to assess the economic feasibility of grid disconnection by small-scale electricity consumers (eg households and small businesses). The decision facing a consumer can be summed up in the "disconnection paradox": If their PV-Battery system is too small to cover all of their consumption, then they need a grid connection for reliability of supply. However if their PV-Battery system is so large that it is able to cover all consumption, then they would benefit from a grid connection to sell excess self-generated power back into the grid rather than wasting it. (Adding a backup generator into the system can resolve the paradox, but it does not necessarily win the economic argument). Thus, while some consumers will choose grid-independence for other than economic reasons, many customers will choose to remain connected and install a PV-Battery system sized to minimise their electricity purchases from the grid. In a paper published in the July 2015 *Energy Policy* journal [4] (which attracted commentary in *The Washington Post* [5] [5]), the researchers concluded that customers leaving the grid on "a widespread scale might not be a realistic projection of the future, if economics is assumed as the main driver of customer behaviour. Rather, a significant reduction of energy demand per connection point is a possible option [as] PV-battery prices decline." The study indicates that, for most small-scale consumers, there is more to be gained – by both the individual and by society - from sharing energy and energy services locally and across the NEM than there is from grid disconnection and self-sufficiency. Rural and fringe-of-grid applications remain a grey area.

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[4] Leaving the grid: An ambition or a real choice? *Energy Policy*, 82, 207-221.

[5] The Washington Post, "Why going off the grid may not actually be such a good idea".

We have also developed a unit commitment model for operation of the NEM when integrated with utility-scale battery systems. Our model included 301 generation units in the NEM, with 1.5 GWh of lithium-ion battery capacity added. We found that this storage capacity, though relatively small compared with total NEM generation capacity, is able to improve the overall capacity utilisation of generators, and also reduces the carbon footprint of the NEM. Given that wind accounted for less than 5% of the grid capacity in the model, and there was only one unit of solar generation, it is expected that with future addition of wind/solar generators, the positive impact of storage would be further enhanced. Additional modelling of scenarios at higher levels of renewables is required to further explore this effect.

Although batteries are currently the most promising storage option in the low-voltage area, other types of energy storage such as pumped hydro or compressed air energy storage (CAES) might be feasible for high-voltage levels. We have introduced a methodology for a gas-fired power generation plant with both a compressed air and a natural gas storage system. Such a plant could utilise the stored energy from both systems to capture arbitrage opportunities in the gas and electricity markets.

Areas where further research is needed

For Power Systems

Further research is required to develop a more complete model of the NEM and also to explore more sophisticated numerical techniques and algorithms to deal with the resulting scale, e.g. Taguchi methods and the like. Several publications with students undertaking work associated with the project have been prepared. Also spinoff projects are taking shape which could continue the work with further funding.

An important area where further research is needed is to understand the impact of high penetration renewables on system inertia and frequency response. Specifically, more investigation is required to:

- Identify the minimum inertia requirement of the whole system as well as different regions of the system.
- Include the minimum inertia requirements of the system in the market model as a constraint.
- Explore advanced techniques for participation of wind farms in frequency control; and explore other sources of FCAS.
- Understand the impact of different locations of large-scale renewables on system dynamic behaviour, which provides decision support for renewable power generation planning.
- Include these impacts and dynamic performance constraints into the system dispatch process, which contributes to enhanced system security.

For Energy Storage

Our study indicates that ToU pricing with step function transitions might not be an appropriate tariff structure for future grids with high penetrations of distributed behind-the-meter storage. Other tariff structures (eg including changes arising from the AEMC Power of Choice review) also need to be modelled and evaluated. Design of “smart” tariffs that consider the impact of renewable and storage systems on grid operation is a gap, and an important issue for ongoing research.

In cooler regions, household electricity management should be modelled concurrently with natural gas. The household decision option of switching gas/electricity for heating is a critical issue for future grid modelling which we did not consider in our research.

Future grid planning is computationally limited if rigorous models (unit commitment formulation) are used. Smart relaxation methodologies are required and would need to be developed in further research.

FutureGrid Research Project P2 – University of Newcastle & Univ of Sydney

Grid Planning and Co-optimisation

Introduction

It has been recognised that the importance and effectiveness of connecting national electricity grids and gas pipelines, while exploring common energy resources such as hydro systems, can significantly increase energy trade, reduce costs of energy and improve energy supply security. Benefits to the environment can also be achieved by co-optimised operation and planning of the electricity and gas systems.

It is assumed that the national electricity grid and the natural gas network will be interdependent, and that net benefits can be achieved by co-optimised planning of the electricity and natural gas networks.

Key Outputs

The key outputs gained from the research are:

(i) An increasing use of gas-fired power generators (GPG) would change the cold-weather-driven gas consumption pattern, requiring advanced gas line-pack management strategies. In addition to peak electricity demand, peak gas demand is likely to push up the generation costs of gas-fired power generators, thus increasing electricity prices;

(ii) Gas transmission congestion (e.g. pipeline flow limits, gas production rate limits, gas storage shortfalls, etc.) and contingencies (e.g. pressure losses, supply interruption, pipeline outage, etc.) may constrain multiple GPG capacities, which may lead to reduced power supply and jeopardise power system security as a whole;

(iii) Emission constraints play an important role in encouraging investment in gas-fired generators and gas transmission infrastructure. The proposed grid planning and co-optimisation framework can be used to guide the energy industry to form a holistic approach to the strategic planning of future grids, subject to various interacting physical and economic constraints.

(iv) Compared with the separate planning approaches, the co-optimisation approach can achieve higher social welfare and energy network reliability, although extra computational effort might be required.

Gaps and shortcomings identified in current models, tools and approaches

The simulation tool used in the project for the energy market is an educational version of a commercial software tool. This has introduced a number of potential constraints for further research

and development. Some open source tools may be more flexible and more suitable for future development to accommodate more complex and detailed modelling needs.

Areas where further research is needed

- Development of more research-friendly simulation tools for the electricity as well as the gas market.
- Investigation of probabilistic planning methodologies for both gas and electricity networks for planning purposes, to accommodate the intermittency and uncertainties involved in this co-planning process.
- As electric vehicle uptake increases, it will become important to study the interaction and interdependency between the transportation and electricity distribution networks, with EVs providing a mobile energy storage option as well as being a transportation vehicle. The modelling of the two networks and the linkage through EVs can be further incorporated into this co-optimisation planning model to achieve a three-fold co-planning framework involving electricity, gas and transportation networks.

Other areas for further research into co-optimisation with gas

a. Natural gas is used to provide flexible reserves and balance the intermittency of renewable energy - how to expand the existing energy infrastructure, i.e., identifying expansion plans regarding where, when and what types of gas power plants, gas pipes and power transmission lines to be built.

b. Diversified energy demands (e.g. gas or electric heating) impose new challenges on load forecast and system security and reliability evaluation.

c. Conversions between gas and electricity may become bidirectional (e.g. power to gas technology as energy storage) in the future.

FutureGrid Research Project P3 – University of Queensland

Economic and investment models for future grids

Introduction

This project's goal is to examine the economic and market consequences for Australia in its task of developing the Future Grid. As the societal need to reduce greenhouse gas emissions is realised, the transition to lower emission technologies and higher energy efficiency standards will require significant structural change and economic reforms. Moreover, the expected outcomes of this project will provide outputs into electricity market behavioural changes, investment timing and infrastructure needs for Future Grid.

Key Outputs

The outputs from the modelling of the Future Grid scenarios can be used as key informants for decision makers and key stakeholders. Energy policy formulation when designing the regulatory and policy frameworks for adapting the electricity market into the future will also specifically benefit from the results, which include:

- 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 fuel price slumps will have a negative impact on their deployment rates.
- The shift towards a gas-fired generation 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 fluctuate with our major LNG consumers. This cyclical price behaviour of natural gas amplifies the uncertainties faced in making investment decisions in electricity generation.
- The prospect of large numbers of consumers potentially leaving the grid under a "disconnection scenario" could lead to a broad disparity in pricing. The effects of this could be quite concerning for state policy makers and distribution networks when designing connection charges. Moreover, the societal and economic benefits of remaining connected to the grid must be emphasised such that connection is valued not only a back stop technology, but also as a societal good.
- The rise of the prosumer model and its effective integration into the electricity market at the distribution level could in the long term counter-act many of the significantly undesirable consequences of mass disconnection. Using the prosumer not as a methodological shift in grid support but also as a way of engaging with consumers to be more active in managing their demand behaviour will facilitate many of the policy requirements of maintaining the grid at large.

Gaps and shortcomings identified in current models, tools and approaches

The main gap in this project's methodology and suite of models is the integration of consumer behavioural pattern change at the distribution network level. Understanding how consumers can be transformed into a prosumer ideation will form some of the future research of this group. Furthermore, the limited availability of data on the Australian energy sector remains an issue when compared to the efforts of the US Energy Information Agency and many of their state based equivalents.

Areas where further research is needed

The development of prosumer models and their integration into distribution networks will play a large part in designing the future grid to meet electricity consumer needs. The integration of Australia's multi-state, multi-commodity energy sector is under-recognised and requires more research.

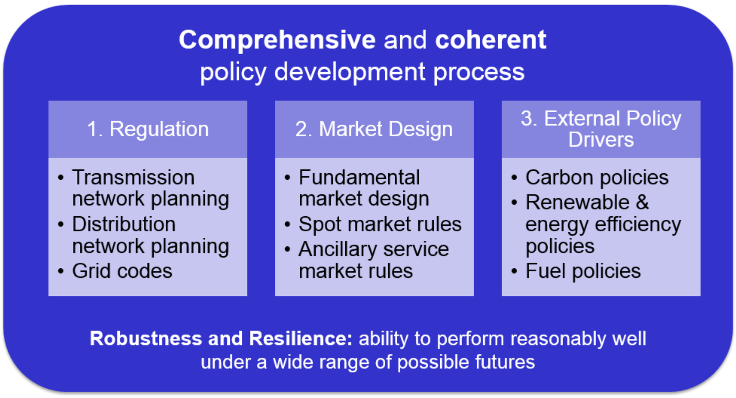
FutureGrid Research Project P4 – University of New South Wales

Robust energy policy frameworks for investment into future grids

Introduction

This project aimed to establish a unifying policy analysis and design framework for future grids to assist policy makers navigate the challenges and opportunities of our future electricity industry choices. It involved the development of an interdisciplinary policy assessment framework to better understand and assess existing and proposed regulatory, market design and policy options for driving appropriate investment in the future grid. This included the development of a high level quantitative policy analysis tool for exploring the potential economic impacts and uncertainties of different regulatory, market and policy settings on least-cost and least-risk electricity generation portfolios. This, and more qualitative work analysing the performance of current regulatory, market and policy settings have highlighted the importance and the challenge of establishing a more coherent and comprehensive policy development process that maximises the opportunities while minimising the risks of future grid transformation.

Key Outputs



The past decade has highlighted the challenges of predicting technology, market and policy developments in the Australian electricity sector. Given present uncertainties that only expand as we look further into the future, our challenge is to establish a comprehensive and coherent policy framework across regulation (notably with network planning), market design (wholesale, future, retail and ancillary services) and 'external' policy drivers (notably with regard to renewables) that is robust and likely to perform reasonably well in delivering future grid investment appropriate to such options and uncertainties.

The work has highlighted that renewable energy provides a highly valuable hedge against both future fuel price and carbon policy settings but that high penetrations raise a range of challenges for existing wholesale market design, particularly with regard to ancillary services as well as existing markets for managing future risk. While a range of existing and prospective renewable technologies could all play valuable roles in the future grid, currently available options already provide a basis for a low carbon future electricity industry. The rapid progress seen with distributed photovoltaics and great promise of distributed storage creates entirely new opportunities, yet also challenges for what are presently arguably rather dysfunctional retail markets, and highlight the need to better integrate distribution network and retail market arrangements. Current efforts to change network planning

and market arrangements are making progress but pose risks as well. For example, moves to 'cost reflective' network tariffs that involve growing fixed charges may have the adverse effect of dis-incentivising end-user engagement in the electricity industry by limiting their ability to reduce network bills through the use of distributed energy options. The key limitations of current arrangements, however, are the present 'external' energy and climate policy settings, and the processes for progressing them. These are, unfortunately, entirely inadequate to the scale and urgency of our challenges, particularly in appropriately allocating risk to those best placed to manage them. They also don't appear easily scalable to support high renewable penetrations, whilst lacking coherence with network developments despite efforts including the NTNDP.

Gaps and shortcomings in current tools and approaches; Areas for further research

The rapid progress of distributed energy technologies and renewed focus on end-user energy productivity highlight the need for tools that better integrate across wholesale, retail and network domains. In the regulatory, market design and policy space, the current divide between NEM processes and explicitly 'external' environmental policy development creates significant challenges for regulators and rule makers in establishing and enforcing appropriate settings for a clean energy future grid. Available frameworks also fail to appropriately consider risk allocation across different stakeholders and the key role that government leadership must play.

Future work should include market design analysis and exploration for changing, and perhaps eliminating, the presently limited and clearly inadequate interfaces between wholesale and retail market arrangements, and between energy and network services.

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