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FINDING THE RIGHT BALANCE: Power System Flexibility in an Era of Decarbonisation: An Annotated Bibliography

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The Energy Policy Institute of Australia (EPIA) is Australia's only independent and apolitical energy policy body. EPIA focusses on high-level policy, governance and regulatory issues affecting the national interest, the economy as a whole, the environment and the community.

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Key Points

- *This short annotated bibliography is aimed at facilitating community understanding of the range of economic and technical risks that climate policies can pose for the reliable, flexible operation of power systems.*

- *Excerpts from a cross-section of published materials have been included. Some materials contradict others. They have been selected, not because they are right or wrong, appropriate or inappropriate, but because the Energy Policy Institute of Australia believes they may influence future policymaking and ought therefore to be taken into account.*

- *In compiling this bibliography, the Institute has taken a technology-neutral approach.*

- *Depending on responses to the publication of this bibliography, it could be the first of a number of future editions.*

Introduction

Climate change poses a risk for the reliable, flexible operation of power systems. So do well-intentioned climate policies if they are set incorrectly. But how do you determine the right balance of settings to ensure the reliable, flexible operation of a particular power system? The answer will depend on a number of variables that are canvassed in the published materials that have been chosen for inclusion in this bibliography. There is an increasing mountain of materials from which to choose.

Since the 2016 Paris Agreement, it has become increasingly common for governments to adopt politically determined 'renewables targets' (as distinct from 'emissions reduction targets') for their power systems. The wisdom of most political determinations in this field seems highly dubious. It is certainly not what one would call technology-neutral.

The EU has adopted a renewables target of 32% by 2030. Political leaders elsewhere are advocating higher targets, such as 50% by 2030. Some are even claiming that it will be feasible to reach 100% by 2050. Without entering into the specifics of this issue, the Institute simply notes that renewables targets require a much higher percentage of installed generation capacity in order to achieve the specified production targets.

In some countries, the penetration of renewables has already decreased power system reliability. This has highlighted the need for measures to provide greater power system flexibility.

As the most recent example in Australia, in reviewing the 2018 performance of the National Electricity Market (NEM), the Reliability Panel of the Australian Energy Market Commission reported in April 2019 that:

> *'For the period 2017/18, the Panel has identified a number of continuing and emerging trends, each of which is relevant to the ongoing security and reliability of the NEM. The NEM generation fleet continues to evolve, with entry of large volumes of variable, renewable generation and the expected exit of dispatchable, thermal generation. In addition, a growing number of customers are installing residential rooftop PV and battery storage behind the meter. The scale of these changes is significant, representing a wholesale shift in the structure and function of the NEM power system.*
>
> *This fundamental change in the NEM is having a number of impacts, including a growing requirement for market interventions. For example, interventions were required to maintain security, such as the switching out of transmission lines to manage over voltages in Victoria, as well as the curtailment and direction of multiple generators to maintain system strength in South Australia. Further to this, the Panel notes that the frequency performance of the NEM continued its longer term deterioration over the period 2017/18.'*

In other words, as the level of penetration of VRE has increased, so has the stress on the structure and function of the power system itself.

It is worthwhile noting that parts of a large power system can suffer a greater level of unreliability from the entry of high levels of VRE than the rest of the system. This can occur where regional markets are connected to the main grid via interconnectors. One such case is South Australia, which is one of five NEM regions.

Since 2013, the Institute has published five papers on aspects of this problem:

#2/2013: http://energypolicyinstitute.com.au/images/Policy_Paper_Malcolm_Keay_June2013.pdf
#6/2016: http://energypolicyinstitute.com.au/images/6_Simon_Bartlett.pdf
#1/2017: http://energypolicyinstitute.com.au/images/1_17_Stephen_Wilson_PP.pdf
#3/2017: http://energypolicyinstitute.com.au/images/3_17_Stephen_Wilson_PPv1.pdf
#1/2018: http://energypolicyinstitute.com.au/images/1-18_Robert_Pritchard_PP.pdf
[All Public Policy Papers: http://energypolicyinstitute.com.au/index.php/publications/public-policy-papers]

This bibliography contains short extracts from a small selection of recent papers on the effects on power systems of political determinations of targeted levels of low-carbon power generation. Readers wishing to delve further are encouraged to go to the original papers, not rely on the extracts.

This bibliography may be periodically reviewed, adding papers that provide additional insights and dropping those that become outdated. The Institute will welcome suggestions of additional papers but reserves the right to decide what changes will be made.

Six papers have been selected for this bibliography. They are listed below in alphabetical order. All extracts from the selected papers have been italicised. Underlining has been provided by the Institute.

Extracts:

1. **Agora Energiewende (2016),** Overview of the Debate on the Effects of Adding Wind and Solar Photovoltaic into Power Systems, Agora Energiewende, Berlin, Germany.

The cost to generate electricity from wind and solar has significantly declined in recent years – in fact, the levelised cost of electricity of wind energy and solar PV is now below that of conventional power in many parts of the world, and further cost reductions are expected. Across the globe, more and more countries are therefore planning to add significant amounts of renewable energy to their electricity systems.

Yet wind and solar power plants are different from conventional power plants in one key respect: They provide electricity when the wind blows and the sun shines, but cannot be switched on based on demand. Furthermore, they are often built far away from high demand areas, which may create a need for new grid infrastructure. Therefore, in order to compare the cost of power from wind and solar with that of coal and gas, the term "integration cost" is often used.

Key Insights at a glance

1. *Three components are typically discussed under the term "integration costs" of wind and solar energy: grid costs, balancing costs and the cost effects on conventional power plants (so-called "utilization effect"). The calculation of these costs varies tremendously depending on the specific power system and methodologies applied. Moreover, opinions diverge concerning how to attribute certain costs and benefits, not only to wind and solar energy but to the system as a whole.*

2. *Integration costs for grids and balancing are well defined and rather low. Certain costs for building electricity grids and balancing can be clearly classified without much discussion as costs that arise from the addition of new renewable energy. In the literature, these costs are often estimated at +5 to +13 EUR/MWh, even with high shares of renewables.*

3. *Experts disagree on whether the "utilization effect" can (and should) be considered as integration costs, as it is difficult to quantify and new plants always modify the utilization rate of existing plants. When new solar and wind plants are added to a power system, they reduce the utilization of the existing power plants, and thus their revenues. Thus, in most cases, the cost for "backup" power increases. Calculations of these effects range between -6 and +13 EUR/MWh in the case of Germany at a penetration of 50 percent wind and PV, depending especially on the CO_2 cost.*

4. *Comparing the total system costs of different scenarios would be a more appropriate approach. A total system cost approach can assess the cost of different wind and solar scenarios while avoiding the controversial attribution of system effects to specific technologies.*

2. **Boston, A., Bongers, G. and Byrom, S. (2018)**, [Renewables and the NEM: What are the limits and what else is needed to go zero?]() Gamma Energy Technology, Brisbane, Australia.

'Most Australian states and territories have relied on coal fired power generation for over 80% of their electricity supplies. More recently, Queensland, Victoria, South Australia and ACT have adopted policies to substantively increase sourcing their electricity from renewable energy and, along with NSW, targeting net zero emissions aspirations for the future. The state and territory policy positions are broadly consistent, with a minimum renewable energy target specified and aspire to net zero emissions by 2050 at the latest.

How this impacts on the physical operation of the National Energy Market (NEM) has been examined in this work, an extension of the 2017 study, Managing Flexibility Whilst Decarbonising Electricity: the Australian NEM is changing. In a recent report, the impact of the Queensland and Victorian renewable energy targets (QRET and VRET) has been modelled using MEGS which takes account of the enduring need for grid strength and reliability services. The modelling presented in this report seeks to examine a "very high renewables world" that minimises fossil fuel consumption whilst aiming for 90% decarbonisation.'

The broad conclusions of this work are summarised as follows:

Deep Decarbonisation requires a diverse portfolio of plant

- *<u>It is not possible to go beyond 65% decarbonisation with renewables alone without incurring huge uplift costs to the system. In some capex scenarios it makes sense to avoid going beyond even 40% with renewables alone.</u>*
- *CCS makes a perfect complementary technology for renewables in deep decarbonisation scenarios. Without nuclear, CCS is essential to achieving +90% emission reductions, requiring at least 10GW in a highly favourable scenario for renewables.*
- *In addition, there will need to be an element of flexible, low load factor fossil for meeting peaks, providing grid services and supporting the grid in weeks of low renewable production.*
- *Retaining the option for deep decarbonisation requires immediate and continuing investment in the development of CCS, with a strong emphasis on upgrading existing fossil to improve its flexibility to operate in emerging electricity markets.'*

Performance Metrics for Decarbonisation of a Grid

- *<u>It is increasingly clear from this study that the "Total System Cost" is the better metric by which to assess the affordability of emissions reduction pathways. Although familiar to many, the Levelised Cost of Electricity (LCOE) would be completely out of the context it was designed for and therefore very misleading when comparing generation options.</u>*
- *National electricity pricing and energy competitiveness will be a strong function of Total System Cost. The most effective path to a low emissions grid will be to track the "least cost" pathway for transforming the constituent asset portfolio.*
- *Current Federal and State policy settings drive renewable generation investment. However, in Australia, there are no structural or market mechanisms in place to minimise the Total System Cost and ensure affordability of power. It is recommended that accountability for total system cost is transparently assigned within Australian market and regulatory systems.'*

3. **International Energy Agency, 2018,** *System Integration of Renewables: An Update on Best Practice*, *OECD/IEA, Paris, France 2018 – Part 1, Part 2, Part 3*

'This report combines selected chapters from three existing IEA publication, namely "Next Generation Wind and Solar Power", "Getting Wind and Sun onto the Grid" and "Status of Power System Transformation 2017". These are combined to form a comprehensive overview of system integration strategies, while aiming to provide one single and concise publication.

...

Wind and solar PV capacity has grown very rapidly in many countries, thanks to supportive policy and dramatic falls in technology cost. By the end of 2016, these technologies – collectively referred to as variable renewable energy (VRE) – had reached double-digit shares of annual electricity generation in fifteen countries. In 2016, VRE share in electricity generation reached nearly 45% in Denmark and about 20% in Ireland and Spain. By 2022, in large power systems like those of China, India and USA, the share of VRE is expected to double to more than 10%.

Despite this evidence, discussion of VRE integration is often still marred by misconceptions, myths and in some cases even misinformation. Commonly heard claims include that electricity storage is prerequisite to integrate VRE and that conventional generators are exposed to very high additional cost as VRE share grows. Such claims can distract decision-makers from the real, though ultimately manageable issues; if unchecked they can bring VRE deployment to a juddering halt.

This report, written for policymakers and staff in energy ministries as well as regulatory bodies, has two main objectives: firstly to clarify the true challenges faced in the early days of VRE deployment; and secondly to signal how these can be mitigated and managed successfully. It also provides recent analysis on how to manage VRE integration at higher shares.

It reveals how measures to maintain cost-effectiveness and reliability of the power system differ over four stages of VRE deployment. These phases are differentiated by an increasing impact of growing VRE capacity on power systems, providing a useful framework for prioritisation of tasks, which may otherwise be presented as a wall of challenges at the outset of deployment.

Phase One is very simple: VRE capacity has no noticeable impact on the system. Assuming the system is sufficiently larger than the newly installed solar and wind plants, VRE output and variability go unnoticed compared to daily variations in power demand. Examples of countries in Phase One of VRE deployment at present include Indonesia, South Africa and Mexico; annual VRE shares in these countries reach up to about 3% in annual electricity generation.

In Phase Two, VRE has a noticeable impact, but by upgrading some operational practices this can be managed quite easily. For example, forecasting of VRE plant output can be done so that flexible power plants can balance their variability, along with that of electricity demand, more efficiently.

There is no single threshold in terms of energy share; when a power system will enter Phase Two depends on its own properties. For example, ranging from 3% to almost 15% VRE share of energy, countries in Phase Two at present include Chile, China, Brazil, India, New Zealand, Australia, the Netherlands, Sweden, Austria and Belgium.

It is Phase Three that sees the first significant integration challenges, as the impact of variability is felt both in terms of overall system operation and by other power plants. Power system flexibility now comes to the fore. The term flexibility in this context describes the ability of the power system to *respond to uncertainty and variability in the supply-demand balance, in the timescale of minutes to hours, for example providing power from other sources when the wind drops. Today, the two main flexible resources are dispatchable power plants and the transmission grid; but demand side options and new storage technologies are likely to grow in importance in the medium-term. Examples of countries considered to be in Phase Three of VRE deployment include Kyushu (Japan), ERCOT (USA), CAISO (USA), Italy, the United Kingdom, Greece, Spain, Portugal and Germany; the VRE penetration in these countries ranges from around 10% to 25% in annual generation.*

New challenges emerge in Phase Four. These are highly technical and may be less intuitive in nature than flexibility, relating instead to the stability of the power system. The stability of a power system is its resilience in the face of events that might disturb its normal operation on very short timescales (a few seconds or less). Countries that are seeing challenges primarily related to this phase include Ireland and Denmark, with an annual VRE share of around 25% to 50% in annual generation.'

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4. **IRENA (2018)**, *Power System Flexibility for the Energy Transition, Part 1: Overview for policy makers*, International Renewable Energy Agency, Abu Dhabi.

'To transform our energy system towards one dominated by renewable energy, flexibility has to be harnessed in all parts of the power system.

Power system flexibility spans from more flexible generation to stronger transmission and distribution systems, more storage and more flexible demand. Production of heat and synthetic gas (e.g. hydrogen) from renewable electricity is also key for energy system decarbonisation in the long term and once in place it can be a significant additional source of flexibility for the power system.

Power system flexibility involves varied methods of generation, combined with stronger transmission and distribution networks.

The present report discusses flexibility in the context of the energy transition and proposes an approach in planning for flexibility in power systems expecting to achieve high VRE shares.

In addition to assessing a power system's flexibility level by looking into traditional supply-side flexibility sources, the approach of IRENA incorporates at an equal level demand-side flexibility, grid reinforcements, storage and sector coupling as additional flexibility sources and potential game changers.

Heat and hydrogen production from renewables can also boost system flexibility and help with energy decarbonisation.

The idea is based on the fact that when coupled with a power grid, technologies at the interface also become a component of the power system. That way electric vehicles (Evs), electric boilers, heat pumps and electrolysers for hydrogen production provide extra flexibility for the power system by 1) adjusting their demand profile based on price signals, and 2) making any integrated storage a source of energy storage for the power system, to decouple the timing of demand for final energy from electricity demand.

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The resulting analysis may be useful for countries aiming to test more aggressive deployment scenarios and to explore untapped solar and wind potential. This report aims to inform policy makers on the options available to scale up power system flexibility. It comes as part of a package, along with a FlexTool methodology for technical experts as well as four country case studies on power system flexibility options based on application of the IRENA tool.

Flexibility has to be harnessed in all parts of the power system.' (Executive Summary pp 8/9)

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5. **Nuclear Energy Agency (2019)**, *The Costs of Decarbonisation: System Costs with High Shares of Nuclear and Renewables*, Nuclear Energy Agency, Organisation for Economic Co-Operation and Development, Paris, France, NEA No. 7299.

'Decarbonising the energy system to achieve the climate goals set by the Paris Agreement represents an enormous challenge for OECD countries. To reduce the carbon intensity of the electric power sector to 50 gCO2 per kWh, an eighth of the current levels, requires a rapid and radical transformation of the power system with the deployment of low-carbon emitting technologies such as nuclear, hydroelectricity and variable renewables (VRE). In the absence of mechanisms to capture and store the CO2, this will mean phasing out coal and strictly limiting the use of gas-fired power generation. Given the massive investments that the realization of this transformation requires, it is of paramount importance to create long-term frameworks that provide stability and confidence for investors in all power generation technologies.

... all electricity systems of OECD countries relying on deregulated wholesale markets to ensure adequate investments are currently experiencing great stress in advancing towards the twin objectives of rapid decarbonisation and adequate investment in low-carbon technologies. The reasons are, in particular, the relative disadvantages experienced by technologies with high fixed costs in a deregulated market with volatile prices, the lack of robust and reliable carbon prices, and the out-of-market financing of large amounts of variable renewables with little thought on the impacts on the remainder of the electricity system.

... All low-carbon technologies have a role to play. Based on the cost assumptions used in the main scenarios, this study shows that a mix relying primarily on nuclear energy is the most cost-effective option to achieve the decarbonisation target of 50 gCO2 per kWh. In addition, costs rise over-proportionally with the share of VRE forced upon the system...[and] supports the vision of a future electricity mix that is realistic for a broad range of OECD countries. Such a mix integrating both VRE and dispatchable technologies would be composed of four main pillars:

i. *a share of 30-40% wind and solar PV;*

ii. *a larger share of 40%-60% provided by dispatchable low-carbon technologies such as nuclear or, perhaps one day, fossil-fuelled plants with carbon capture, 10ealized10on and storage (CCUS);*

iii. *the maximum possible amount of low-carbon flexibility resources, including hydro, demand response and grid interconnection;*

iv. *a progressively decreasing share of highly flexible unabated fossil-fuelled technologies ensuring the availability of residual flexibility.*

Between now and 2050, the implicit time horizon of this study, research and development efforts are also likely to reduce the overall cost of power generation. Technologies are likely to be both cheaper and more flexible. Further cost reductions for low-carbon technologies such as nuclear, possibly in the form of small modular reactors (SMRs), VREs and batteries are likely. Largely for intrinsic physical reasons CCUS, for instance, is less likely to be a competitive option, even by 2050, but a decisive breakthrough cannot be excluded. The electricity sector is also likely to be more closely intertwined with other economic sectors due to cogeneration, power-to-gas and the convergence with information and communication technologies.

This study does not claim that the options modelled, their technical performances and their costs will be those eventually realized in 2050 and does not make any predictions about future technology developments. Its objective is to inform policy makers and the wider public about the intrinsic difficulties of achieving ambitious carbon emission reduction objectives with variable generation technologies alone ... nuclear power still remains the economically optimal choice to satisfy stringent carbon constraints despite the economic challenges for nuclear during the changeover between different reactor generations. The reason for nuclear power's cost advantage is not in its plant-level costs. Instead, it resides in its overall costs to the electricity system. Variable renewables have reduced quite impressively their plant-level costs, but their overall costs to the system are not accounted for as their output is clustered during a limited number of high-level hours.' (Executive Summary pp 13-16).

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6. **Zaman, A. (2018),** *100 % Variable Renewable Energy Grid: Survey of Possibilities*, University of Michigan, Ann Arbor, Michigan

Due to favorable public policy and falling technology costs more and more jurisdictions around the world are adopting higher shares of variable renewable energy into their power systems. Although some countries and jurisdictions, as part of larger interconnected systems, have been able to operate for extended periods of time with 100% of their demand covered with VRE, operating a self-sufficient power system annually with only VRE sources is not yet possible (with the exception of a few micro and mini grid systems, with state of the art technologies and practices). This study through a high-level qualitative assessment, identifies limitations of current and future power systems to host very high shares of VRE...

***Power System Stability – a central challenge to achieving high shares of VRE:** As a result of its unique characteristics (variability, uncertainty, modularity, asynchronous), the integration of VRE into today's power systems poses unique challenges. Particularly at high shares maintaining power system stability becomes a critical challenge. Unlike synchronous generators, VRE generators do not inherently provide inertial response or governor response to frequency deviations. A high VRE share grid might not have sufficient reactive power sources to provide voltage stability. Without fault ride through (FRT) capability, VRE generator (such as wind turbine) disconnections in the event of system disturbances negatively affect transient system stability. A 100% VRE grid will require power systems dynamics to remain stable in an inertia-less grid. Grid codes would need to be defined to ensure VRE generators are built in with FRT and voltage control capabilities. Industry and market structures do not yet have experience with this since power systems have historically relied on synchronous machines to provide stability. Even island power systems that have operated with 100% instantaneous share of VRE have always had conventional generators online as back up.*

***Solutions require a paradigm shift:** Experts overwhelmingly reiterated that a large power system operating with a 100% share of VRE would require transformation in technology, operational practices and market design. In terms of technological transformation, solutions that add to system flexibility such as energy storage and demand response, will need to evolve to accommodate the variability and uncertainty associated with VREs at time frames ranging from seconds to days. VRE generators will need to provide grid reliability services through advanced inverters. Grids will need to incorporate information and communications technology into every aspect of electricity generation, delivery and consumption. Institutional transformations would involve changes in power system planning methods from deterministic approaches to probabilistic approaches. Apart from increased coordination between different balancing areas, communication between transmission and distributions systems would also need to evolve. Power markets would need to adequately compensate for services that enhance system flexibility, provide greater grid stability and support VRE integration.*

***Lack of modeling exercises:** Due to the lack of practical examples of large systems with very high penetrations of variable generation, researchers have focused on models to simulate behavior of such systems. However, there are only a limited number of comprehensive studies modeling the behavior of power systems with close to 100% VRE penetration. Some studies use unrealistic* forecasts of energy demand; do not take transmission or ancillary service requirements into account. Most studies do not provide whole system simulation or provide simulations at the hourly instead of sub-hourly time scales. This fails to acknowledge reliability challenges a system might face at sub hourly time scales and during transient events.*

***Majority of experts believe there is no technical limit to VRE penetration level:** Experts cited challenges such as grid strength, frequency stability, and lack of controllability for mid- to long- term operations for achieving a high VRE share grid. However, many of the experts consider these challenges to be solvable. Technical limits are defined by how the system is designed, inputs the system can handle and how the system is operated. 12 out of 17 experts identified no technical limit and asserted the ability of the system to evolve and accommodate new technology and new inputs. Alternatively, experts who did see a technical limit, assumed a static grid and weighed in on the existing system's limitations.*

***Economic limits exist even if technical limits do not:** All of the 17 experts interviewed stressed the importance of economic viability of a 100% VRE grid. Even if there is no technical limit to grid integration of VREs there might be an economic limit. Grid integration studies have found VRE penetration levels well below 100% to be economically desirable for large power systems such as the US, pan-European electricity system. However, the economic limit is not fixed and technological breakthroughs, strategic investments, or evolving social preferences can push the economic limit.*

***The relevance of a 100% VRE grid:** There is a lack of robust modeling studies that examine the technologically and economically optimal pathways to a decarbonized power system; therefore it is still difficult to concretely assess whether or not a 100% VRE grid is one of those pathways. However, most large power systems (peak electricity demand above 1 GW) are still far away from a decarbonized grid with most VRE penetration levels standing at below 20%. Research and conversations around a 100% VRE grid can be significant in stimulating innovation and breaking the institutional inertia that govern our power systems. Research on 100% VRE grids can also be an effective advocacy platform for pushing greater political commitment towards cleaner sources of energy.*

About the Author

***Robert Pritchard** is Executive Director of the Energy Policy Institute of Australia.*

Robert has over 40 years' experience as a lawyer and adviser to industry, governments and organisations on energy projects and policies, both in Australia and overseas, and as a director of companies in the energy sector. This includes serving as chairman of the St Baker Energy Innovation Fund and SMR Nuclear Technology Pty Ltd. Robert was the first chairman of the Energy Law Section of the International Bar Association. He served for nine years on the Finance Committee of the World Energy Council. He is a former member of the CSIRO Energy Transformed Flagship. He is a consultant to the Piper Alderman law firm in Sydney.