Assessing Long-term Security of Electricity Supply and the Role of Renewable Energy: A Probabilistic Generation Portfolio Analysis Approach

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Abstract

A modelling tool is applied to assess long-term energy security in the Australian National Electricity Market (NEM). The potential role of renewable energy in increasing the security of electricity supply is examined, with a focus on two aspects: price risk and physical supply risk. Optimised portfolios with no renewable energy (RE) are found to have a diversity index suggestive of a highly concentrated system which could potentially threaten supply security. Increasing the RE penetration from 0% to 50% makes generation portfolios more diversified as well as reducing expected costs, cost risks, and CO_2 emissions. The expected cost is minimised at around 50%-70% RE penetration level, which is approximately the level that results in the most diversified generation portfolio. This analysis suggests that cost risk and fuel diversity are good indicators for determining generation portfolios that can contribute in addressing energy security concerns in both cost and physical supply aspects. The modelling indicates that renewables such as solar photovoltaics (PV) and wind can play an important role in addressing long-term energy security concerns by reducing electricity price uncertainty and physical supply risk through fuel diversification.

1. Introduction

Energy security is one of the main goals of energy policy in many countries as it plays a key role in social and economic welfare and development. There are multiple aspects of energy security and the concept can vary significantly across different energy industries. Nevertheless energy security is often defined as the access to uninterrupted availability of energy supply at an affordable price [1-3]. Within this definition, energy security may therefore be categorised into two main components: physical supply availability and affordable pricing. In addition, an environmental dimension is often included as well given the strong policy interactions between energy security and climate change [1, 4-6].

While the focus of energy security in the past has primarily been on oil and gas, electricity has emerged as one of the most critical forms of energy supply around the world during the last decade, making it a vital component of energy security [7]. Energy security is inherently concerned with risks to the continued availability and affordability of energy, and management of such risks [7, 8]. In relation to electricity, energy security risks can include the risk of physical disruption of electricity supply; the risk of unaffordable and sharp electricity price fluctuations; and the risk of reliance on unsustainable options that will eventually no longer be available or will have to be abandoned. This suggests that electricity generation portfolios that reduce exposure to cost, physical supply and environmental risks can play a key role in strengthening energy security [9]. Finally, there are also different time frames over which energy security needs to be considered. Short-term security of supply is concerned with the mitigation of unexpected disruptions and operational reliability while long-term security is related to more structural aspects of the system such as timely investment in electricity supply infrastructure in line with economic development and environmental considerations [1, 10].

A well-diversified electricity generation portfolio of different technologies and fuel types is often argued to be able to assist in mitigating energy security risks arising from fuel price fluctuations as well as physical supply disruption due to resource concentration [11-13]. Over-dependence on particular types of fuels can have potentially serious consequences for long-term continuity of supply. Diversity, however, is a complex concept with respect to energy security where issues include the particular fuel types, the sources of these fuels by geographic regions or supplier, and the technology types using these fuels which can also be country and region specific [14]. Uncertainties in future fossil-fuel prices also have significant implications for energy security given the considerable reliance on fossil fuels, particularly coal and gas, for generation in many electricity industries around the world. These fuels have experienced generally increasing volatility and underlying price growth over the last decade [15]. They are also major contributors to national and global climate change emissions.

Given concerns over climate change, renewable energy (RE) technologies such as solar and wind are increasingly being recognized as important low-carbon complements to existing generation technologies, since they produce no operational greenhouse gas emissions. Moreover, and of particular focus in this paper, they have the potential to help address energy security concerns since they do not rely on fossil-fuels whose future availability and pricing have become increasingly uncertain over recent decades. In addition, RE may potentially reduce security threats arising from resource scarcity since they can be spread across different geographical locations [8]. Geographical spread of RE sources can also contribute to smoothing the inherent variability of some key RE generation outputs, notably wind and solar [16].

This paper presents a study that employs a probabilistic portfolio modelling tool developed in [17] as a quantitative framework for assessing long-term security of electricity supply. In particular, the paper is focused on exploring the potential role of RE, particularly solar and wind, within future generation portfolios in addressing energy security concerns in both the cost risk and physical supply risk components. The analysis focuses on long-term energy security of supply and does not consider short-term operational reliability aspects. The modelling tool is applied to a case study of future generation portfolios with different levels of RE penetrations in the Australian National Electricity Market (NEM). The analysis applies the concept that the price risk component of energy security can be determined from a spread of possible future electricity prices (based upon costs in this analysis). The risk of physical supply disruption is determined based upon the degree of fuel diversification of various electricity generation portfolios.

The rest of the paper is structured as follows. Section 2 describes the modelling tool and the methodology adopted to explore the potential energy security implications of different generation technology mixes. Section 3 describes the case study of the Australian NEM that is used for the quantitative analysis. The modelling results are then presented and their implications discussed in Section 4 followed by conclusions in Section 5.

2. Methodology - Monte Carlo Based Generation Portfolio Modelling

The modelling tool employed in this study extends the commonly applied load duration curve (LDC) based optimal generation mix techniques by using Monte Carlo simulation (MCS) to incorporate key uncertainties which directly impact overall generation costs. Outputs from the modelling tool consist of many thousands of simulations of generation costs and CO_2 emissions for each of the different possible generation portfolios. The *"expected"* cost and emissions for a particular portfolio represent the average of all the simulated costs and emissions from every Monte Carlo run. The cost spread is denoted by the standard deviation (SD), which represents associated *'cost risk'*. This cost risk can be used to quantitatively assess energy security in terms of the risk of electricity price fluctuations. Note that this study assumes that changes in electricity generation costs translate directly to changes in electricity prices.

The tool then applies portfolio analysis techniques to determine an Efficient Frontier (EF)[1] of expected (i.e. mean) costs and associated cost risks (i.e. SD) for each of the different generation portfolios. EF techniques provide a basis for explicitly analysing cost and cost risk tradeoffs among different generation technology portfolios. The EF is made up of those generation portfolios which offer the lowest expected cost for some level of cost risk. The methodology and mathematical formulation of this modelling tool are presented in detail in [17].

Modifications of this EF approach can also be used to highlight other potential trade-offs between different generation portfolios, such as their expected overall costs versus CO_2 emissions as demonstrated in [19]. In this study, the EF approach has been extended to analyse trade-offs between expected costs and fuel diversity for the different generation portfolios in order to assess the risk of physical supply unavailability, which is another component of energy security. The fuel mix captures the balance of fuel types in a country's electricity generation portfolio and, as such, fuel diversity is a useful indicator in assessing long-term security of electricity supply [11].

The Shannon-Wiener Index (SWI) is chosen for this study to measure fuel diversity. It is recognised as one of the most useful diversity indices and has been applied in many studies to assess various dimensions of security of supply in the electricity industry [14, 20-24]. Higher values of SWI imply greater diversity. Diversity can be calculated by fuel sources (by geographical location or supplier or proportions of import/export) or technology types; this study focuses solely on diversity by fuel types. SWI is calculated via the following mathematical expression:

$$SWI = -\sum_i p_i . \ln \, p_i \tag{1}$$

where p_i is the proportion of annual electricity generation from fuel source i.

RE generation is incorporated in the model through the use of residual load duration curve (RLDC) techniques where simulated hourly RE generation outputs in the time-sequential domain are subtracted from demand in the same time period. The resulting (net) demand after accounting for RE generation is then rearranged in order of magnitude to obtain a RLDC. It is this curve which has to be met by conventional dispatchable technologies in the portfolios.

3. Case Study

A case study of the Australian National Electricity Market (NEM) presented in [25] is used to illustrate the concept of the modelling tool in assessing energy security and the role of RE in addressing energy security concerns. The case study considers different generation investment scenarios for the year 2030 under highly uncertain future fuel prices, carbon prices and electricity demand. The investment scenarios range from investing only in gas generation (no new RE) to different mixes of RE and gas investment, through to investing primarily in RE (with minimal gas).

3.1 Investment Scenarios and Modelling Inputs

Four new generation investment options are considered: wind (on shore), utility scale solar PV (single axis tracking), combined cycle gas turbine (CCGT) and open cycle gas turbine (OCGT). The study assumes that there will be no new investment in coal-fired generation due to a growing consensus that its high greenhouse emissions intensity poses too great a capital investment risk [26]. Investment costs of the existing generation capacity are considered 'sunk' and therefore are not included in the

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[1] The efficient frontier concept is used in the Mean Variance Portfolio (MVP) theory for financial portfolio optimization [18].

calculation of annualised generation costs. The cost of transmission network augmentation is not included in the model.

Six different investment scenarios in 2030 are assumed, each corresponding to a different RE penetration ranging from 0% to 90% of total annual energy demand. These scenarios are shown in Table 1.

Table 1. Different generation investment scenarios.

Investment Scenario	**% of RE generation**		**All other** (coal, gas, hydro, distillate, cogen)
	New PV	*New Wind*	
Gas World 1	0%	0% [a]	100%
Gas World 2	5%	10%	85%
Medium mix 1	10%	20%	70%
Medium mix 2	20%	30%	50%
RE World 1	30%	40%	30%
RE World 2	40%	50%	10%

For each investment scenario (i.e. RE penetration level), different possible thermal generation portfolios were considered by varying the share of each fossil-fuel technology (black coal, CCGT and OCGT) in the portfolio from 0% to 100% of total installed fossil-fuel capacity.

For each possible portfolio, generation output of each thermal technology in each period in the LDC (or RLDC) is determined using merit order dispatch based on short run marginal costs (SRMC) of each thermal technology in 2030. PV and wind generation are given priority dispatch due to their low operating costs. As noted earlier, therefore, they are considered exogenous and treated as negative load. To ensure realistic dispatch outcomes, the modelling assumes a hypothetical minimum of 15% synchronous generation in any one hour period. Synchronous generation is provided by conventional generating plants, which are coal, CCGT, OCGT, hydro, distillate and cogeneration. This 15% represents an estimate of the minimum amount of synchronous generation required to maintain system stability, based upon previous assumptions applied in the NEM [27]. Hence, PV and wind generation are 'capped' at 85% of demand in each hourly dispatch interval. For high RE penetration cases, there are periods during which combined PV and wind outputs were greater than total demand. In these periods energy from PV and wind is spilled. PV is given priority over wind in the dispatch due to the assumption of lower variable operations and maintenance costs for PV [28].

Hourly electricity demand for the year 2029-2030 was obtained from the 100% RE study undertaken by the Australian Energy Market Operator (AEMO) for the case of moderate growth, and corresponding to a 50% 'probability of exceedance' (POE) [27]. The demand profile provided by AEMO is based on the historical 2009-10 demand pattern. Hourly wind and solar output profiles in 2030 for each investment scenario (i.e. each PV and wind penetration) were simulated based on historical hourly traces of on-shore wind and solar PV (single axis tracking) generation in different locations across the NEM and scaled to 1-MW, provided by AEMO [27]. This captures the geographical diversity of wind and PV plants in Australia. Hourly PV and wind generation was scaled up to the desired penetration level.

RLDCs for different PV and wind penetrations are illustrated in Figure 1. As shown in the figure, minimum synchronous generation has been taken into account.

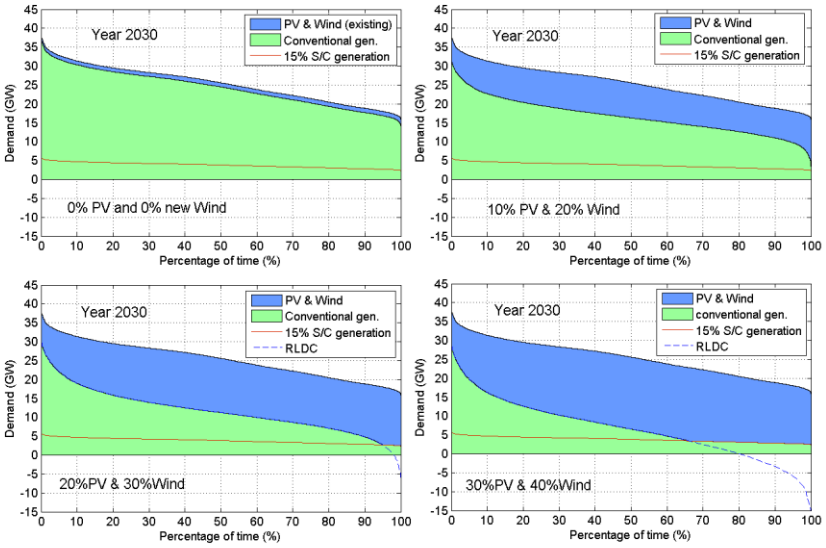

Figure 1. Residual load duration curves for different RE penetrations.

3.2 Modelling Uncertainties

Lognormal distributions were applied to future gas and carbon prices to reflect the asymmetric downside risks associated with their future value. Electricity demand uncertainty was modelled by assuming a normal distribution of residual peak demand in the RLDC for each case of RE penetration. Both lognormal and normal distributions can be characterized by their mean (expected value) and SD.

The mean and SD of fuel prices were determined from the 2030 estimates provided in the 2012 AETA report, which also provides projections for low, medium and high price scenarios [28]. The central projection of fuel prices was applied as the mean, while the SD was approximated based on the spread between the low and high case scenarios.

For carbon prices, mean and SDs were obtained from Australian Treasury Modelling of carbon prices in Australia in 2030 [29]. This modelling included two scenarios: a low carbon price case (corresponding to a 5% reduction in emissions by 2020) and a high carbon price case (corresponding to a 25% reduction in emissions by 2030). For this modelling, the mean carbon price was based upon a scaling between these two scenarios (adjusted by CPI to March 2013 dollars). The SD was obtained using the same approach as the fuel prices.

Correlations between fuel and carbon prices were also accounted for when modelling these uncertainties, given that their movements have exhibited a considerable historical correlation in the EU and UK markets [30]. Correlations were estimated from historical trends in OECD countries.
Table 2 shows the assumed expected fuel and carbon prices as well as their SDs.

Table 2. Fuel and carbon prices in 2030

Fuel and Carbon Price	**Expected value**	**Standard deviation**	
		%	*Absolute*
Black coal ($/GJ)	1.9	6%	0.1
Natural gas ($/GJ)	11.7	30%	3.5
Carbon price ($/tCO$_2$)	91	40%	36

Correlated samples of black coal, gas and carbon prices are generated from their marginal lognormal distributions using a multivariate Monte Carlo simulation technique described in [17]. The distributions of 10,000 simulated coal, gas and carbon price simulations as well as scatter plots highlighting their correlations are shown in Figure 2.

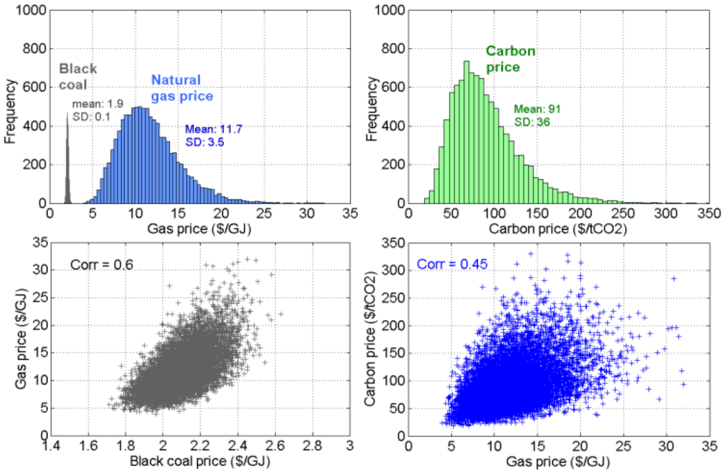

Figure 2. Assumed distributions of fuel and carbon prices over 10,000 Monte Carlo simulations, and scatter plots showing the impact of correlations between gas, coal and carbon prices.

4. Modelling Results and Discussion

Modelling results are presented to reflect both cost and physical supply components of energy security. The cost component is measured by cost risks (SD of generation costs) whereas the physical supply risk component is determined using the SWI based on fuel types.

For each investment scenario, the costs and CO_2 emissions of each possible conventional generation portfolio were calculated for 10,000 simulations of uncertain fuel prices, carbon price and electricity demand. The analysis is focused on generation portfolios on the *Efficient Frontier* (EF) which are considered optimum in terms of expected costs, cost risks and fuel diversity. Other generation portfolios are not presented in the paper.

Optimal generation portfolios on the EFs for expected cost versus cost risk (SD of cost) and expected cost versus fuel diversity (SWI) are presented in Figure 3 and 4 respectively. The percentage share of and capacity of PV, wind and hydro generation for each RE penetration level are shown in each coloured box. In Figure 4, the x-axis, which represents the SWI diversity index, has been reversed to enable meaningful comparisons – a method similar to that presented in a similar Irish case study [21].

In Figure 3, the tradeoffs in terms of expected overall portfolio cost versus its associated cost risk (SD of cost) among portfolios are evidenced on the EF. As the combined PV and wind penetration increases from 0% to 70%, reductions in both the overall generation cost and cost risk are observed, as indicated by the diagonally downward movements of EF. However, the expected costs start to increase once the RE penetration is greater than 70 %. In terms of cost risk, higher RE penetrations result in significantly lower cost risk as shown by lower SD of cost (a near five-fold reduction as RE’s energy contribution is increased to 90%).

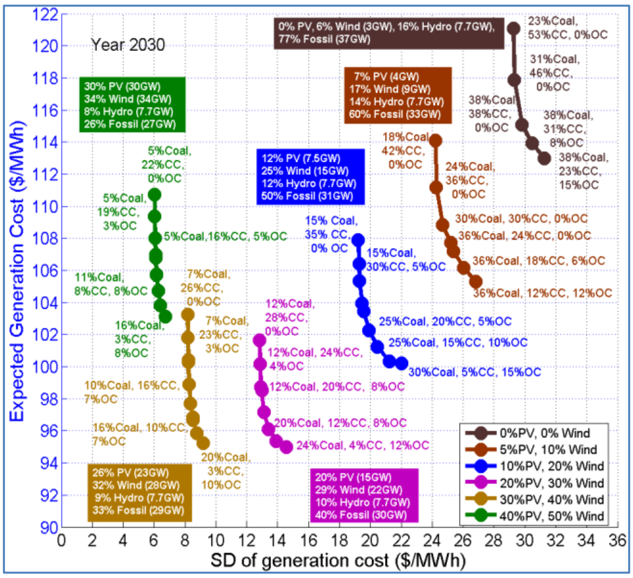

Figure 3. EFs containing optimal portfolios in terms of expected costs and cost risks for each RE penetration.

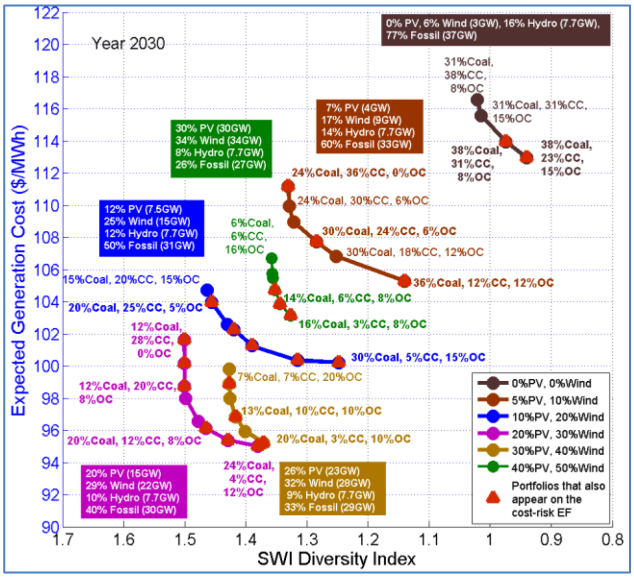

Figure 4. EFs containing optimal portfolios in terms of expected costs and fuel diversity for each RE penetration.

In Figure 4, the EFs in terms of cost versus SWI highlight that there are also tradeoffs between expected portfolio costs and their fuel diversity. For a particular RE penetration level, the cost cannot be reduced without resulting in a less diversified portfolio. The expected costs of optimal portfolios in the case of 0% RE penetration are in the range of \$113 – \$117/MWh while the fuel diversity index is between 0.95 and 1.0. It has been suggested that a SWI value below 1.0 indicates a highly concentrated system which could potentially threaten security of electricity supply [14], implying that these low renewable portfolios are not well diversified in terms of fuel mix. The results also suggest that increasing the RE penetration from 0% to 50% makes generation portfolios more diversified (as indicated by higher SWI value) as well as reducing expected cost as shown by the decreasing EFs. At these levels, adding RE increases the number of fuel sources and reduces dependence on fossil fuels. The modelling results also show, however, that increasing RE penetrations beyond 50% will result in portfolios becoming marginally less diversified, with expected costs also increasing. Nevertheless, the diversity index for portfolios in the case of high RE penetrations remain within an acceptable range (i.e. well greater than 1.0).

The portfolios that appear on the cost versus cost risk frontier are also highlighted by red triangles in Figure 4, which shows that the majority of optimal generation portfolios on the cost versus cost risk EFs are also considered optimum in terms of expected cost and fuel diversity. This suggests that cost risk and fuel diversity are both good, and highly correlated, indicators for determining generation portfolios that can contribute in addressing energy security concerns in both cost and physical supply aspects.

Figure 5 provides a graphical representation of the generation mix, expected cost, associated cost risk, fuel diversity and CO_2 emissions of the 'least cost" generation portfolio for each RE penetration level. The figure shows that the cost risk and CO_2 emissions decline markedly as RE increases. The expected cost is minimised at around 50%-70% RE penetration level, which is approximately the level that results in the most diversified generation portfolio. Although expected costs start to rise and the fuel mix becomes more concentrated as RE penetrations rise higher than 70%, the cost is still lower and the fuel mix is more diversified than scenarios with very low RE penetration (i.e. 0% – 15% RE).

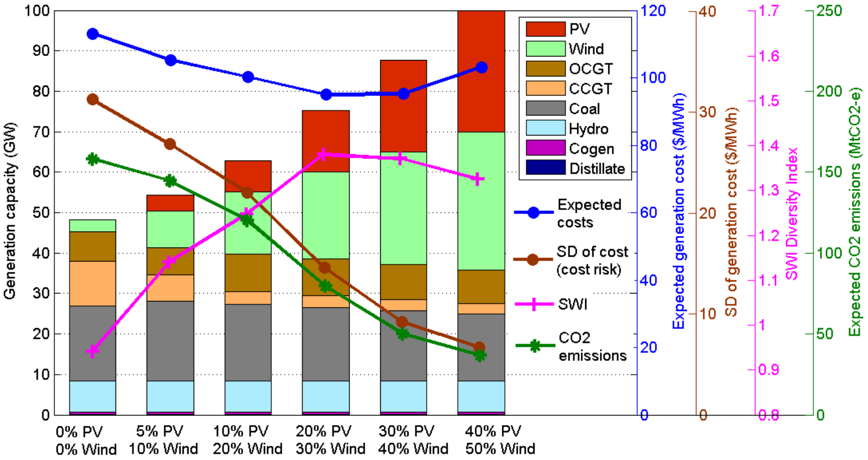

Figure 5. Installed capacity, expected costs, SD of generation costs (cost risk), fuel diversity index and CO_2 emissions of the least cost generation portfolios for each scenario of RE penetration.

Although the results suggest that portfolios would become less diversified in the case of extremely high RE penetration (i.e. 90% RE), this does not necessarily means that the system is less secure. Variable renewables face supply risks of a very different nature to fossil fuel technologies. There is always a risk of unusual weather conditions that may reduce the availability of wind and solar generation in a particular year, but this is typically taken into account in system reliability assessments, and appropriate reserve margins could be maintained to ensure that the reliability standard is maintained. However, fossil fuel supply risk is less frequently taken explicitly into account in long term reliability and system security assessments. These system threats can emerge suddenly and without warning, such as in the 2008 gas crisis in Western Australia, caused by the rupture of a corroded pipeline and subsequent explosion at a processing plant on Varanus Island. This led to the sudden loss of 30% of gas supply, causing significant electricity prices spikes for the following several months [31]. The 1973 oil crisis provides another example of the possible implications of dependence upon fossil fuels. System-wide threats of this nature are unlikely to affect renewable technologies in the same way. The SWI index has some potential limitations in that it does not take this fundamental difference into account. The SWI also does not take into account the degree of diversification in the geographical locations chosen for solar PV and wind plants[2]. Geographical distribution of primary fuels, including RE resources can potentially reduce security of supply risks [12, 14].

5. Conclusions

This paper employs a probabilistic generation portfolio model to quantitatively assess the long-term security of an electricity supply system through two potential indicators – expected portfolio cost risk, and SWI. The paper particularly focuses on exploring the role of PV and wind generation in addressing energy security concerns.

The modelling tool was applied to the Australian National Electricity Market (NEM) case study by comparing different RE penetration scenarios in 2030. The modelling results show that PV and wind demonstrate potential in mitigating energy security risks in both cost and physical aspects by means of reducing cost risk and increasing the fuel diversity of electricity generation portfolios. This is in addition to their contributions in reducing CO_2 emissions and reducing overall industry generation cost.

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[2] The locations of PV and wind plants chosen for this study were based upon the 100% RE modelling study by AEMO [27].

The portfolio based modelling techniques applied here can provide a basis for selecting a set of efficient generation portfolios that enhance long-term security of supply. There are, however, some evident limitations of the model and the indicators used in assessing energy security. In the model, short-term aspects of security of supply are not taken into consideration. This aspect is related to short-term operational implications which can arise from increased variability as a result of high RE penetrations. There are also some clear limitations of the SWI in measuring fuel diversity of generation portfolios. The SWI is a very basic indicator for measuring diversity, and therefore it does not take into account the different risks of disruptions associated with various fuel and resource types. For example, the ready availability of domestic low-cost coal in a range of countries including Australia suggests high energy security value [32]. Therefore, domestic availability of particular energy sources is also a relevant factor, as are potential issues regarding whether there is active or potential export of these fuels as an alternative to the domestic market. It also does not reflect the fact that different technology types possess different economic and technical characteristics. These issues potentially provide opportunities for future work to use extended diversity indices that incorporate these types of issues.

6. Current work applying the modelling tool

In collaboration with Tsinghua University, the modelling tool is being applied to explore future electricity sector investments in China by taking into account key uncertainties such as future carbon prices, fossil fuel prices, electricity demand and plant capital costs. The work will focus on the potential impact of a (highly uncertain) carbon price and potentially the pricing of other externalities such as SOx, NOx and particulate pollutants on optimal future generation mixes in China.

Acknowledgement

This work has received funding from the Australian Renewable Energy Agency (ARENA).

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