Energy Modelling:
Forecasting the 2030 Australian Electricity Mix

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***Abstract* - The objective of this paper is to model the 2030 electricity mix in the National Electricity Market (NEM) in Australia, comparing the outcomes of different scenarios with the 2018 electricity situation. This study aims to analyse whether the Australian commitment to the Paris Agreement in 2016 and national energy policies, will have a visible effect in decreasing the historical dependence of the NEM on fossil fuels by 2030 and consequently decreasing the carbon emissions generated. First, the current electricity situation has been introduced, as well as the energy policies and the challenges associated with the integration of variable renewable energy systems. Next, EnergyPlan, which is the modelling tool adopted for this study, has been described and a reference model has been conceived and calibrated based on the 2018 electricity situation on the NEM. The reference model marked the starting point for the 2030 simulations. The simulations have been implemented considering three different supply scenarios and three potential electricity demands, to evaluate how different variables can influence the NEM electricity mix by 2030. This study concludes that by 2030 wind and solar power (including rooftop-PV systems) will be the major renewable energy contributors in the NEM, as opposed to 2018 where hydropower represented the main renewable energy source. Nonetheless, the electricity system in 2030 will continue to rely on fossil fuels, which will account for more than 50% of the final energy mix in every scenario, depicting that new efforts will still be needed beyond 2030.**

Keywords - ***Renewable energy, Energy system modelling, Australia, EnergyPlan***

1. Introduction

Since human appearance on the globe the temperature has been stable until the 19th century with the beginning of the industrial revolution. Between 1850 and 2012, the near-surface air temperature increased by 0.8 degree Celsius.[1] The main cause of this disconcerting global warming is associated with the quick diffusion and concentration of greenhouse gas emissions in the atmosphere, especially carbon dioxide, produced by various human activities, where the dominant one is represented by fossil fuel combustion. Australia, like the rest of the world, is currently facing the effects generated by the growth of greenhouse gasses in the atmosphere. These are mostly visible in a warmer temperature across the country, in stronger winds over the Southern Ocean and in a southward shift of weather systems over the last twenty years. If new implementations are not considered in the upcoming future, global warming is predicted to increase and provoke damages which would affect not only the ecosystem, but also human health, food security and infrastructures. [1]

Most nations in the world have signed the Paris Agreement, which consists of a series of measures to tackle global warming. The main steps include limiting the increase of temperature by 2050 to 1.5°C, allowing for a maximum 2°C increase compared to pre-industrial temperatures, and developing new pathways to decrease greenhouse emissions [2]. In 2016, Australia became a signatory to the Paris Agreement and as part of their agreement, the country has committed to lowering its emissions by at least 26% below 2005 levels by 2030 [3]. Australia is still far from this achievement mainly due to the high dependence of the energy sector (and in particular the electricity sector) on fossil fuels. The electricity sector represents the main contribution of greenhouse emissions in the country [4]. Due to this reason, new strategies are necessary to tackle climate change. Therefore, an energy transition towards a renewable energy system can substantially decrease the carbon dioxide emissions in the electricity sector in the upcoming years, as well as replace several fossil fuel power stations.

Given this introductory context, the purpose of this paper is to model the 2030 Australian power system to evaluate how different scenarios, from both the generation and the demand side, could impact the 2030 energy mix.

Moreover, this study intends to forecast how the energy generation from each source, carbon dioxide emissions and storage consumption will evolve in 2030 compared to 2018.

It is relevant to note that for the aim of this study only the National Electricity Market (NEM) has been considered. This choice has been undertaken as the NEM represents the biggest grid in Australia and manages 80% of the total electricity consumption.

The modelling of the 2030 NEM power system has been developed with the energy simulation tool EnergyPlan. Firstly, the reference model has been implemented to represent the 2018 electricity system in the NEM.

This step is fundamental to calibrate the model for the 2030 simulations.

The objectives of this study set through the 2030 Electricity Modelling of the NEM are the following:

- Forecasting the 2030 Electricity mix, considering two different contexts, the electricity supply excluding rooftop-PV systems and the electricity supply including rooftop-PV systems.

- Evaluating the renewable energy share, the CO_2 emissions and the storage consumption in 2030.
- Assessing the amount of renewable energy to be curtailed (e.g. wasted renewable energy generated).
- Evaluating the impact of flexible demand on the curtailment of renewable energy generation.

The forecasts of the 2030 Electricity Mix have been assessed for three different supply scenarios, which assess a different development of the power stations in the NEM. Moreover, the modelling has been performed analysing three possible electricity demand growth paths for 2030 (neutral, slow, fast). This choice has been made to assess the possible changes that different electricity demands could bring to the 2030 electricity mix.

This paper is divided in 7 sections. The first chapter begins by explaining the need for an energy transition, followed by the second chapter which describes the current electricity sector in Australia, focusing on the drivers and challenges for a low carbon transition. In the third chapter, a state-of-the-art review regarding previous studies which explored the integration of renewables in the Australian electricity system is presented. The fourth contains the methodology utilized for the creation of the 2030 Australian energy model.

The fifth chapter introduces the scenarios included in the 2030 model, while chapter six depicts the analysis and the results obtained from the simulations. The last chapter highlights the conclusions achieved from the performed research.

2. The Australian electricity context

Since the 1950s, Australia has been enduring an evident electricity transformation, with visible changes occurring at every electricity stage: generation, transmission, distribution and consumption. The reason of this transformation can be attributed mainly to economic, engineering and environmental factors which are driving the Australian energy transition [5].

From its first creation and during further developments which began in the 1950s, the Australian Electricity System was based on centralised coal-fired power stations [5]. Despite the passing of decades, the current electricity situation remains very similar. By the end of 2018, the NEM relied on traditional fossil fuels for approximately 85% of its electricity generation, with more than 75% coming from black or brown coal fired power stations, while the rest was mostly related to gas generation plants [5]. This substantial fossil fuel presence in the actual NEM electricity mix is due to the abundance of fossil fuel resources present in Australia. However, in the last decade and most notably in the last three years, the NEM has been experiencing a quick transition towards a generation mix with an increasing percentage of energy generated by low emission technologies.

From 2012, around 4,000 MW of coal capacity have retired due to power plants reaching their technical lifetime [6]. In contrast, the last five years have seen a substantial development of renewable energy projects, with the installation of around 3,400 MW of large-scale wind capacity and over 1,900 MW of large-scale solar-PV since 2014 to the end of 2018 [6]

Simultaneously, on the consumers' side the electricity dynamics are changing. Year by year the number of households and businesses installing rooftop-PV systems are increasing. This trend is driven by incentives from the government and state side, as well as evident advantageous in terms of reducing the electricity bills. Rooftop-PV systems are not dispatched by the wholesale market, but they decrease the electricity demand required to be met by dispatchable generation [6]. By the end of 2018, there was a total of 6.98 GW of small-scale rooftop PV systems installed in the NEM [7].

The transition towards a low-carbon electricity system in Australia is currently driven and incentivised by two National Government Policies: The Renewable Energy Target (RET) and The Emission Reduction Fund (ERF) [8]. The RET is a National Government scheme which aims to decrease the overall GHG emissions present in the Australian territory by promoting the implementation of renewable energy technologies. This policy is in turn divided into two schemes: the Large-scale Renewable Energy Target (LRET), which has the purpose of generating 33,000 GWh of additional renewable electricity generation by 2020 and the Small-scale Renewable Energy Scheme (SRES), which incentivizes the installation of small-scale renewable energy systems, for instance rooftop-PV[9]. The ERF is a national policy which incentivizes both businesses and individuals to reduce their carbon emissions, through the surrender of Australian Carbon credit Units (ACCUs) [10]. Under this scheme any type of activity, belonging to any type of sector (vegetation, industry, agriculture, energy efficiency, waste) which can lower the national carbon emission can be considered valid. Moreover, the actual generation technology capital cost (referring to the cost of producing 1 kW of power of a specific technology) of wind turbines and solar-PV are rapidly falling. In 2018, the capital cost of wind and solar-PV declined to less than 2,000 [$/kW], while capital costs of coal-fired power stations remained above 4,000 [$/kW] and with high probability this will not drop in the upcoming years [11]. This factor will be a determinant driver for the deployment of these renewable technologies in the future, even after the end of the 2020 RET scheme.

However, the intensive development of mostly wind and solar power plants, across the NEM territory, is increasing the installed capacity of power generation which is characterized by having a variable output which relies on weather conditions. This will create new challenges to maintain a reliable and secure supply generation mix that is capable of always matching the electricity supply with the demand [12]. Therefore, the implementation of flexible energy technologies to tackle the variable and uncertain output from the integration of multiple renewable energy plants, will help to maintain a reliable power system. These technologies consist of peaking gas power plants and storage systems, which are capable of ensuring a quick ramp up of the electricity supply whenever there is a peak electricity demand [13].

Moreover, the recent overtaking of distributed energy resources (DER), mostly identified by rooftop-PV systems, is transforming the operation of the grid, creating a more decentralized system. As a consequence, the grid is accommodating two-way energy flows in the low voltage distribution lines [14]. These developments result in more unpredictable power flow on the distribution lines. For instance, the large quantities of electricity fed into the grid by DER systems can exceed the voltage, capacity and thermal constraints of the distribution lines, causing damages to the network. To tackle this problem a modernisation of the grid will be needed. For instance, forms of monitoring and controlling through new technology devices, such as smart meters, will allow for better communication and coordination between all electricity parties, as well as new accurate forms of forecasting which are capable of predicting more volatile load behaviour and rooftop PV generation. [15] A solution to solve some of the challenges created by the integration of both utility-scale variable renewable plants and DER can be achieved by increasing the flexibility on the demand side, through demand side management (DSM). DSM consists of a feasible alternative to reduce peak electricity generation and network requirements. It achieves this through the reduction or the shift of the electricity demand and by providing frequency services, which translates in less investments required for flexible supply generation, transmission and distribution network. [16]

3. State-of-the-Art

Multiple scientific research papers have been published regarding the investigation of the Australian electricity system. This chapter aims to describe them, including their achievements and conclusions.

In Graham and Williams paper, a simulation to analyse the optimal shares of various energy technologies under a policy of greenhouse gas mitigation is described in order to identify the best investment path for Australia in 2020. This work is carried out with the use of an integrated bottom-up tool OzECCO, which aims to optimize the investment and output for each specific energy technology generator for the time-frame studied in the model. From the results of this simulation wind energy appeared to be the most competitive renewable energy technology. However, biomass showed a high potential, which is mostly limited by resource constraints. [17]

Saddler et al. explores the possibility of achieving 50% reduction in CO2 emissions from stationary energy (heat and electricity sectors) by 2040 in Australia, compared to 2004. The development of the energy supply system is based on small improvements of the existing technologies and considering economic and population growth to forecast the energy demand by 2040. This work highlights that in a scenario with further developments in the existing clean energy technologies (i.e. PV, solar thermal with thermal storage, on-shore and off-shore wind), there is the capacity to achieve more than 80% reduction in CO2 emissions. Therefore, it underlines the importance of fostering and expanding the Research & Development support for clean energy technologies in the future. [18]

Chowdhury and Than Oo’s paper aims to analyse the Australian electricity sector and to propose the new developments of renewable energy technologies which will ensure the government’s renewable energy target of 20% of the total electricity generated in 2020 produced by renewables. In order to achieve this target, this study explores the possibility to install an additional power capacity of 2,235 MW of PV systems and 14,600 MW of wind systems. This new energy generated by renewable sources would decrease the use from coal power plants, helping to reduce the carbon dioxide emissions by 50.5 Mt. [19]

In Huva et al. paper, an optimisation model is developed to study how various combination of wind and solar farms could affect the energy mix in the state of Victoria, Australia. This study elaborates six different scenarios. it concludes that despite different site selections for wind and solar farms for each scenario, there are periods of low renewable energy output for all of them, which need a back-up power capacity from both gas and pump-hydro stations, in order to meet the electricity demand. However, this model considers a timeframe of five days for each season of the year 2009. This factor represents a limit to this study, which would need further investigations considering longer time domains to depict more realistic scenarios. [20]

Nunes et al. focuses on the transition towards high renewable energy penetration in the state of Queensland in Australia. The integration of high variable renewable energy sources in the Queensland power system is achieved through a stochastic multi-stage planning model. The model considers both long-term and short-term uncertainties. Moreover, the model aims to co-optimise generation and transmission investments, which are taken in multiple stages of the planning horizon. This study concludes that the achievement of 50% renewable energy produced will increase the total system costs. However, this work also depicts the importance of the complementarity of photovoltaic and wind systems energy output, for optimum investments in renewable projects. [21]

Elliston et al. investigates the possibility of shifting towards a 100% renewable energy system in the NEM, in Australia in 2010. This study depicts the feasibility to transit to a complete sustainable electricity system, through the utilization of commercially available technologies. In this scenario, solar energy, which includes concentrating solar thermal (CST) power and photovoltaics, is capable of supplying 50% of the total annual electricity demand. Moreover, this paper highlights the reliability of the whole supply system modelled, which is capable of meeting the peak demand during periods of low variable renewable energy production. [22]

Lanzen et al. aimed to simulate a low-carbon electricity supply for the entire territory of Australia. The paper explored how to achieve a 100% renewable electricity mix through the utilization of operating and commercialized technologies. A first investigation was conducted to identify appropriate locations where to invest in the installation of new renewable generators and to determine the quantity of biofuel availability. This study concluded that to achieve a low-carbon supply Australia will need a total of approximately 160 GW of installed capacity. This amount will involve wind farms, concentrating solar plants, photovoltaic utilities and hydro and biofuel plants. [23]

In Blakers et al. study, a 100% renewable energy scenario is evaluated and presented through an hourly energy balance analysis of the Australian National Electricity market. This paper considers the same electricity demand from 2008, assuming it will remain stable during the years. It focuses on the expansion of wind and photovoltaic technologies which will be capable of supplying 90% of the annual energy balance, while the remaining 10% will be met by hydro power and biomass. The form of storage adopted in this study is pumped hydro energy storage, neglecting any contribution of batteries energy systems in the future. The outcome is that the total cost to balance energy demand and supply in a 100% renewable scenario is relatively small. This is due to substantial growth of photovoltaic and wind sources and the omission of new developments of other low emission technology (e.g. solar thermal, geothermal, ocean, biomass) which are, in the authors' opinion, still far from being competitive. [24]

4. Methodology

This section is divided in two sub-paragraphs. Firstly, the energy modelling tool EnergyPlan is introduced. Then, the reference model is created and compared with historical data from the NEM.

4.1 EnergyPlan tool

The modelling of the 2030 Electricity Mix in Australia has been developed with the use of the EnergyPlan tool.

EnergyPlan is a software oriented to assist in the design of national energy system plans, through the modelling of the whole national heat and electricity supplies, as well as the transport and industrial sectors [25].

Energy Plan is a deterministic model, which means with the same input it will always obtain the same output, as opposed to stochastic tools which use for instance Monte Carlo methods [26].

This tool analyses the energy models for the length of one year, in steps of one hour, which provide a detailed overview of the system modelled for daily, weekly and monthly time frames. [25]

The inputs required are essentially energy demands, generation and energy storage capacities, costs and a different range of regulation strategies. The resulting outputs are expressed in the form of annual energy generation by each technology, electricity import/export, fuel consumptions, CO2 emissions and total costs [27].

The demand is divided in multiple inputs which must be provided on a yearly basis and the user has to insert a distribution file of 8784 values in txt format, which specifies the hourly demand required along the year (referring to a leap year). [28]

The supply tab-sheet defines each energy source as a whole, without treating each power station individually. Dispatchable and variable energy sources both require the capacity of each source to be provided in MegaWatt (MW). The efficiency value for every dispatchable technology must be provided into EnergyPlan.

On the other hand, the variable renewable energy sources require as input a distribution file of 8784 values in txt format, specifying the hourly production by each source along the year. [28]

The tool enables two different types of simulations: technical or economic. The first one intends to minimize the fossil fuel consumption, whereas the second one intends to optimize the economic profit for each energy plant. The economic simulation additionally requires a set of input data regarding each investment, fixed and variable costs for each technology included in the model, and a txt file with 8784 values containing the hourly electricity price along the year. [28]

4.2 Reference model

The first step required before the computation of the Energy Plan simulation regarding the 2030 Australian Electricity sector, consists of the modelling of the NEM system from a reference year. This model needs to be calibrated, comparing real data from the reference year with the results obtained through the algorithms applied by the software. It was decided to consider a maximum tolerance of 5%, meaning that the values obtained from EnergyPlan simulation cannot vary more than 5% from the historical energy data.

The energy model from the reference year will be the starting point for the evaluation of future scenarios and it allows the user to better understand the energy operation in a specific country. The chosen reference year was 2018. The main sources used for the creation of the model were provided by the Australian Energy Market Operator (AEMO) [29,30]. This process has been executed by applying the technical simulation in the software, given there was no economical input required for the purpose of comparing the technical performance of each electricity generation source with the software output [31].

The reference model confirmed its reliability by having a variation of less than 5% for every source output from the real 2018 Australian data, as shown by table 1.

Table 1: Comparison between real data and EnergyPlan output

Electricity Generation in 2018			
	Real Data [TWh]	*Energy-Plan Output [TWh]*	*Error*
Wind	14.16	13.56	4.3%
Photovoltaic	1.85	1.79	3.4%
Run of river	0.69	0.69	0.6%
Dam Hydro	15.61	15.60	0.1%
Bioenergy	0.19	0.19	0.4%
Fossil fuel	159.67	160.07	0.3%
Sum	192.17	191.90	0.1%

The final renewable energy share in Australia in 2018 corresponded to 16.8% of the total electricity generated, in accordance with the EnergyPlan output of 16.5%. The most significant mismatch of 4.3% is represented by wind energy, followed by 3.4% from photovoltaic systems. This difference in the final energy generated by these sources is related to the power capacity installed for these technologies. The considered capacity installed used as the input in EnergyPlan was obtained from the average between the capacity installed at the beginning and at the end of 2018, due to the impossibility of inputting in the software different capacities installed for different times along the year. These approximations thus induced the errors compared to the real data.

5. Australian 2030 Scenarios

The Australian electricity projections used as the input for the implementation of the 2030 EnergyPlan simulations, were sourced from the Australian National Electricity Market (NEM), which developed forecasts for both the demand and the supply side.

In order to provide a holistic overlook of the 2030 Australian electricity mix, this chapter considers three potential electricity demand growths: neutral, slow and fast, which are based on three different economic growth rates. The neutral growth is distinguished by a stable economic evolution, which reflects in an electricity consumption rise of approximate 1.3% each year, with a forecasted 2030 electricity demand of 203,405 TWh [32]. The slow growth faces reduced economic investments, which result in a lower electric grid consumption compared to the neutral demand. The forecasted 2030 slow growth electricity demand accounts for 166,425 TWh [32]. Alternatively, the fast growth is distinguished by a strong rise in individual household incomes and a robust economic situation, which leads to 220,490 TWh of 2030 electricity demand [32]. These electricity demands have been implemented to model a sensitivity analysis for each supply scenario. The three generation supply scenarios are: the ESOO (Electricity Statement Of Opportunities) – low RES scenario, the ISP (Integrated System Plan) – high RES scenario and the ISP – high RES with Storage scenario.

The ESOO – low RES scenario contains every existing power plant including those announced to be retired, as well as committed large-scale generation projects which satisfy the following criteria: “acquisition of a site, procurement of the components needed to build the generator, relevant planning approvals, obtaining finance and a final construction date”[13]. This model does not include new generation developments beyond 2021, as the projects planned to be built beyond this year presently remain uncommissioned [33]. The data regarding the ESOO – low RES scenario was sourced from the ESOO report [33].

The ISP – high RES scenario, which information are sourced from the Integrated System Plan Report [34], aims to forecast the most accurate supply electricity scenario for the future Australian Electricity System. This forecast relies on economic and grid-reliability analysis as well as government energy policies, to predict the required energy projects necessary to guarantee a safe long-term supply of electricity and therefore minimise the total resource costs. The ISP – high RES scenario includes a vast quantity of new renewable energy projects, mostly wind and solar, which (unlike the ESOO – low RES scenario) will be implemented beyond 2021. Moreover, it considers the retirement of more coal power stations compared to the ESOO – low RES. This reason is explained since these power stations did not have announced their retirement yet, but they will achieve their maximum technical life utilization within 2030. [34].

The last scenario to be considered is the ISP – high RES with Storage. This scenario is similar to the ISP – high RES scenario in terms of generation capacities installed by each source, but it has been modelled in a separate scenario as it includes the development by 2030 of a remarkable storage project: the Snowy 2.0, which do not yet meet the commitment criteria by the National Electricity Market. This project will be capable of operating like an enormous battery, recycling the same water through the upper and lower reservoir, with a pumping capacity of 2,000 MW and the capability to store around 350 GWh. Snowy 2.0 is forecasted to operate on the market from late 2024-2025. [34]

The installed capacities forecasted by 2030 in the ISP – high RES, ISP – high RES with Storage and ESOO – low RES scenarios are displayed in table 2.

Table 2: Installed capacity by 2030 for each supply scenario

2030 Supply Scenarios [MW]			
	ISP	**ISP-Stor.**	**ESOO**
Thermal Pow. Plants	27723.7	27814	32608.8
Hydro	8021.2	8021.2	8021.2
Wind	10943	10866	8671.5
Utility Solar	9686	9759	4814
Utility storage	4543	5367	1328

6. Simulations Results and Analysis

For the purpose of this work both the technical and the economic simulations have been implemented, to find how the different algorithm utilized by the software could affect the final 2030 electricity mix in the NEM.

The technical simulation aims to minimize the electricity production from fossil fuel power plants. Due to this reason, this type of simulation utilizes the storage capacity only in cases of a renewable energy surplus which exceeds the electricity demand and it does not consider any other kind of energy storage situation which could be beneficial from an economic point of view.

For instance, the technical simulation is not able to store energy from condensing power plants ahead of time in off-peak periods, in case there is not enough supply to meet the demand at the next required moment.

Therefore, the economic simulation was considered more suitable for the aim of this study, despite the fact that the technical simulations provide accurate outputs regarding the amount of renewable energy produced by each source for each scenario and in terms of excess of electricity – which will exceed both the demand and the total storage capacity and will need to be curtailed.

The economic simulation describes a more realistic Australian electricity mix for the 2030 forecasts, where storage systems are used not only for technical purposes (storing the extra power generated from renewable sources), but also for economic reasons. This involves exploiting the most profitable electricity price between off-peak and peak demands and thereby having a more diffused storage consumption.

The economic simulation algorithm applied by EnergyPlan prioritizes the use of the least expensive supply source in order to meet the demand during each moment of the year. This model is based on an energy market composed of plant-operators who pursue maximising their economic profit. [28] The algorithm mainly follows two steps, firstly it calculates the short-term marginal cost of supplying one unit for all the technologies involved in the system considered, then it identifies the least expensive technology to produce an extra electricity unit. [31]

Moreover, two contexts have been modelled in EnergyPlan for the 2030 Australian simulations and the results are described in section 6.A and 6.B.

The first context neglects the electricity generation from rooftop-PV systems and its forecasted households' consumption by 2030, considering that rooftop-PV systems will only be utilised for households' self-consumption, without interacting with the electric grid.

On the other hand, the second context incorporates rooftop-PV systems in the 2030 model, assuming their capability of feeding the electricity into the grid and thus contributing to meet the national electricity demand. This choice has been made given that in 2030 under both the ISP – high RES scenarios, Australia is forecasted to face a remarkable diffusion of Solar rooftop-PV systems which will account for almost 17 GW of new power capacity installed. Therefore, it was decided to evaluate this context to forecast the impact that the substantial installed capacity of rooftop-PV systems will have in the 2030 energy mix. In order to be coherent, the additional electricity consumption of 18,100.25 GWh related to the rooftop PV usage forecasted in 2030 by AEMO, has been summed to the yearly electricity consumption for each potential growth demand (neutral, fast and slow) [32].

A. *Economic simulation: 2030 electricity mix – excluding rooftop-PV systems*

The final 2030 electricity mix percentages obtained in the economic simulations are very similar to the proportions obtained in the technical simulations for each scenario, despite a slight increase in the percentage of the fossil power plants in the final energy mix, which account
for approximately 1%, as shown by table 1.

Table 3: Renewable energy share percentage comparison between technical and economic simulation

	% RES					
	Economic Simuation			*Technical Simulation*		
	Neutr.	*Fast*	*Slow*	*Neutr.*	*Fast*	*Slow*
ESOO	23.2%	21.4%	28.4%	23.3%	21.5%	28.4%
ISP	29.4%	27.1%	35.9%	29.7%	27.4%	36.3%
ISP-Storage	29.2%	26.9%	35.5%	29.6%	27.3%	36.2%

The higher contribution of fossil fuel power plants compared to the technical simulation is related to the higher consumption of the energy storage systems along the year. In the economic simulation, during off-peak hours the system stores electricity generated from base load power plants as the electricity price is low, then the storage systems discharge the stored amount during peak times in order to gain an economic profit. Consequently, the resulting amount of energy produced by fossil fuel power plants increases compared to the technical simulations, since the storage input provided by thermal power plants (E_{input}) is equal to the output (E_{output}) of the storage systems supplied to meet the electricity demand, divided by the charge (η_{charge}) and discharge ($\eta_{discharge}$) efficiencies of the storage, as presented by equation (1)

$$E_{output}[TWh] = \frac{E_{input}[TWh]}{\eta_{charge}\times\eta_{discharge}} \qquad (1)$$

The first analysis regards the electricity mix obtained from the implementation of the economic simulation for all three supply scenarios. The results depict that the NEM, despite a still high dependence on fossil fuel electricity generation, will have a sharp increase of the renewable energy contribution, as noticeable from figure 1, 2 and 3. This outcome is particularly evident in the ISP – high RES and ISP – high RES with Storage scenarios, which will account respectively for 60.35 and 60.23 TWh of energy generated from renewable energy sources, in contrast to the only 47.32 TWh relate to the ESOO – low RES scenario. These results highlight the fast overtaking of solar and wind sources in the energy mix in 2030 compared to the 2018.

On the other hand, hydro generation will remain relatively constant from 2018 to 2030, due to the lack of new developments and the projection of a relatively stable water supply every year. The sensitivity analysis adopted emphasises that different demographic and economic growths will play a relevant role on the electricity share. The fast electricity demand growth, for instance, will require more electricity supply, which translates to more dispatchable production from fossil fuel thermal plants, and consequently more carbon dioxide emissions.

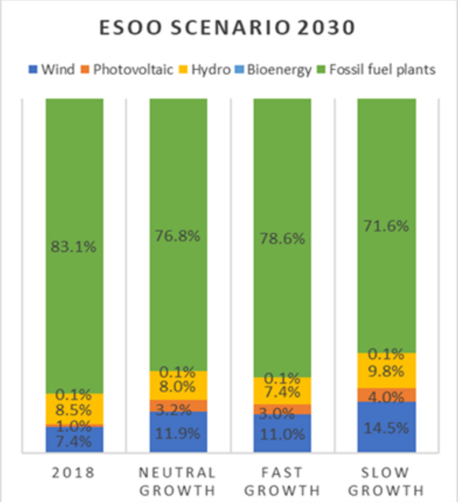

Figure 1: 2030 electricity mix for the ESOO – low RES scenario under the economic simulation

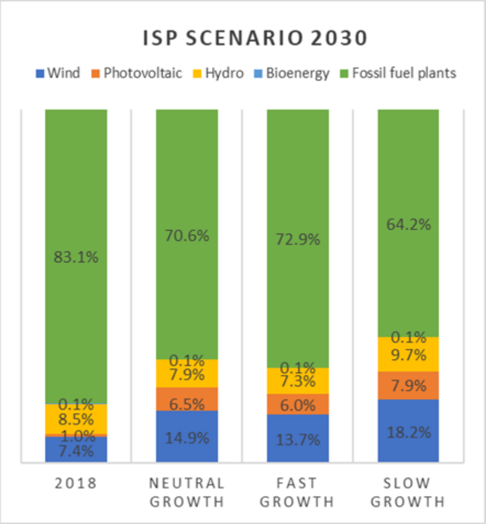

Figure 2: 2030 Electricity mix for the ISP – high RES scenario under the economic simulation

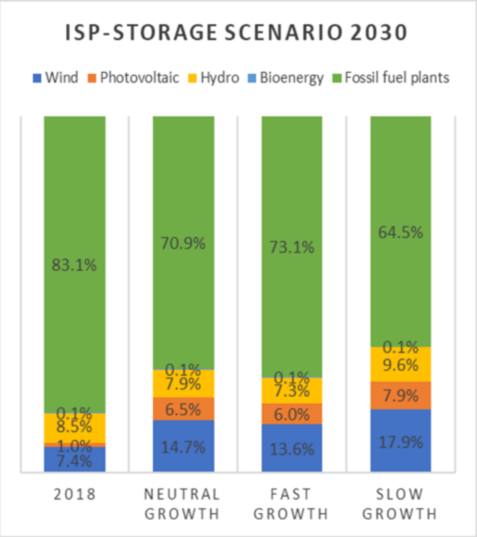

Figure 3: 2030 Electricity mix for the ISP – high RES with Storage scenario under the economic simulation

The lower fossil fuel percentage in the 2030 energy mix reflects in lower carbon dioxide emissions for each scenario compared to the 2018 emissions, except for the fast growth considering the ESOO – low RES scenario, which overcome the 148.6 Mt related to 2018 carbon dioxide emissions, as it is displayed by table 3. However, considering the Neutral Growth for each Scenario is noticeable the net CO_2 decrease in 2030 in the ISP – high RES and ISP – high RES with Storage scenarios, which account respectively to 131 Mt compared to the ESOO – low RES scenario, in which the emissions will be over 143 Mt. These environmental benefits, in terms of CO_2 reduction, are the consequences of the higher number of renewable projects considered under the two ISP scenarios.

Table 4: Carbon dioxide emissions by 2030

CO_2 [Mt]			
	Neutral	*Fast*	*Slow*
ESOO	143.8	158.1	110.2
ISP	130.8	142.3	99.4
ISP-Storage	131.0	142.5	100.7

Despite, very similar results in terms of 2030 energy mix and CO_2 emissions, the ISP - high RES with Storage scenario depicts a higher yearly higher energy consumption from energy storage systems, as represented in table 3.

Table 5: 2030 Energy storage consumptions

Pump/Battery- 2030 yearly storage consumption			
	ESOO	*ISP*	*ISP-Storage*
Fast [TWh]	2.45	9.62	16.77
Neutral [TWh]	2.45	9.71	16.99
Slow [TWh]	2.46	9.95	17.63

The remarkably higher utilization of the storage systems in the ISP – high RES with Storage scenario is due to the presence of the Snowy Hydro 2.0 Scheme, which increases substantially the storage capacity included in this scenario compared to the ISP – high RES and ESOO – low RES. The higher storage consumption translates into greater flexibility and reliability for the Australian electricity system, which is able to provide electricity from the discharge of the storage systems to meet the demand during peak times.

B. Economic simulation: 2030 electricity mix – including rooftop-PV systems

The simulations show the significant increase of the solar percentage in the 2030 final energy mix, compared to the ISP – high RES and ISP – high RES with Storage scenarios excluding the contribution of rooftop-PV systems. For instance, in the neutral growth, the solar percentage grew by almost 10% considering the integration of solar rooftop-PV systems. Figure 4 and 5 clearly show how the integration of solar rooftop-PV systems in the 2030 Australian electricity mix for both the ISP – high RES Scenarios shifts the energy production proportions, resulting in a reduced dependence on fossil fuel power plants. Consequently, the results from the economic simulations depict that in the context including rooftop-PV systems there is a further reduction of carbon emissions, from 148.6 Mt in 2018 to 127.4 Mt in the ISP – high RES scenario and to 126.3 Mt in the ISP – high RES with Storage scenario, considering the neutral electricity demand.

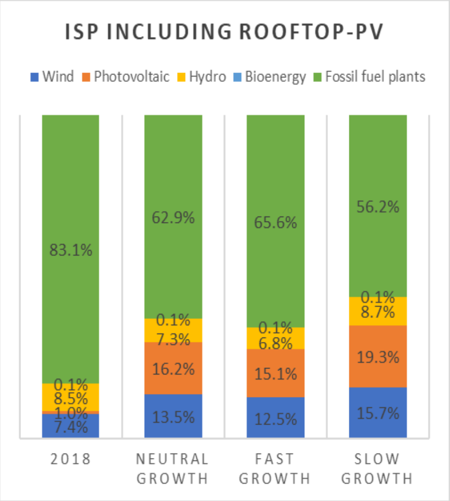

Figure 4: 2030 Electricity mix for the ISP – high RES including rooftop-PV systems under the economical simulation

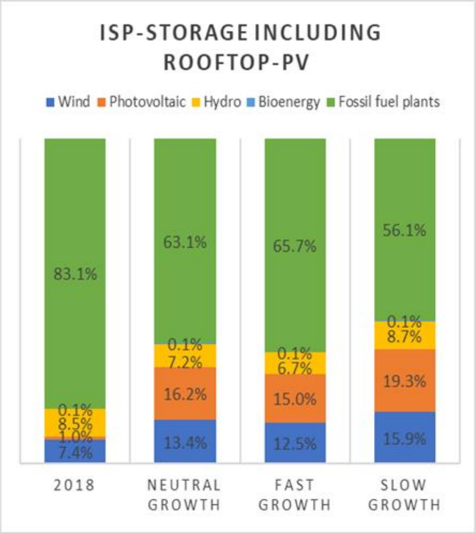

Figure 5: 2030 Electricity mix for the ISP – high RES with Storage including rooftop-PV systems under the economical simulation

C. *Renewable Energy Curtailment*

With the introduction of rooftop-PV systems in this analysis, it is forecasted a significant photovoltaic power production during the middle of the day. This event is expected to shift the daily dynamics of when the electricity storage systems will be charged. Therefore, most of the energy storage consumption is concentrated during that time of the day, when it is forecasted to be economically profitable to store electricity, due to the substantial renewable energy production, which make the electricity price decline.

Despite the higher energy production from renewable source including rooftop-PV capacity under the ISP – high RES and ISP – high RES with Storage scenarios, there will be the necessity to curtail some extra power generated from renewables which will exceed both the demand and storage capacity, as shown by figure 6. This occurs during certain peak generation moments along the year, concentrated mostly in the hours of the day with highest solar irradiation. Due to its greater storage capacity, the ISP – high RES with Storage scenario is capable to reduce more of the amount of energy which needs to be curtailed. Moreover, during the slow electricity demand for both scenarios, the lower electricity consumption over the year results in the need for a greater amount of renewable energy to be curtailed.

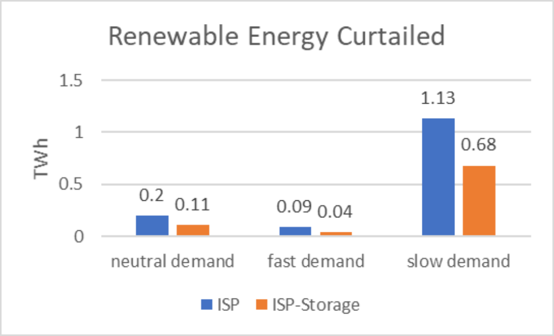

Figure 6: Renewable energy curtailed

D. *Flexible Demand Sensitivity Analysis*

A last sensitivity analysis has been computed to evaluate how the impact of making electricity demand flexible could change the amount of energy curtailed, ensuring a better management of the demand–response over the year of 2030. The flexible demand option in EnergyPlan consists of freely distributing a certain percentage of the total yearly demand over the day according to the actual electricity balance, decreasing the peak demand periods and concentrating the power consumption in the peak hours of renewable energy production. [28].

This is a reasonable assumption, given there will likely be more policies oriented to change the consumers' behaviour in the future, towards a higher use of electricity from renewables (e.g. a higher use of electricity from photovoltaic systems during day-time), as well as new mechanisms such as Demand Side Management which promotes methods of facilitating the integration of renewable energy, by matching the renewable energy output with the electricity demand. Currently, there are government institutions, such as the South Australian Government, are investing in projects which seek to incentivise behavioural changes, shifting the consumers' power consumption towards the use of electricity provided by new technologies, such as renewable sources. This intends to decrease the energy consumption during peak demand times. The model evaluated therefore shows that an hourly shift in the power consumption can reduce the curtailment of renewable energy by 2030. [35]

Figures 7 and 8 show, for both the ISP – high RES and ISP – high RES with Storage scenarios, what impact the different flexible demand percentages can cause. The decision was made to analyse the effect caused by a maximum of 10% of flexible demand out of the total yearly consumption, in order to evaluate a realistic scenario in which a portion of electricity consumers will be able to shift their power consumption throughout the day.

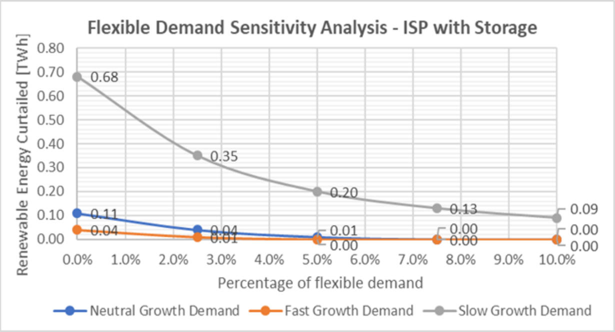

Figure 7: Flexible demand sensitivity analysis for the ISP – high RES scenario including rooftop-PV

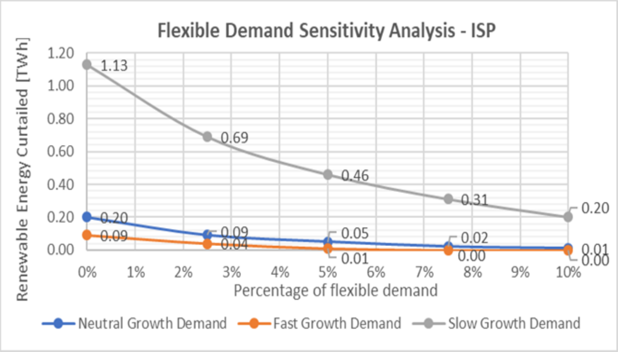

Figure 8: Flexible demand sensitivity analysis for the ISP – high RES with Storage scenario including rooftop-PV

Observing the trends projected above, it is evident how making just 5% of the total consumption flexible will already consistently decrease the amount of renewable energy curtailed, consequently reducing the consumption from fossil power plants by the same amount. This percentage of flexible demand will be used by the consumers to exploit the significant solar production, which will appear during mid-day. Except for the slow growth demand, 5% of flexible demand will already be sufficient enough to drop the curtailment of renewable energy to almost zero TWh for both Scenarios.

The flexible sensitivity analysis confirms that even shifting a slight percentage of the total yearly electricity consumption to periods of high-peak renewable energy production, can significantly reduce the amount of electricity in excess.
Moreover, this analysis shows the consumer's potential in taking a step towards shifting their energy consumption throughout the day. This has the collective impact of igniting change for a more sustainable future.

7. Conclusion

This paper investigated the transformation of the electricity system in the Australian National Electricity Market, considering a horizon of 2030. The results obtained through the modelling of the electricity system in Australia by 2030, outlined that the country is on the right path to shift towards a clean renewable electricity system as a consequence of their commitment to the Paris Agreement. This is particularly noticeable given the history of Australia's high dependence on fossil fuel resources.

The modelling of the 2030 Electricity mix in the NEM has been performed with both the technical and economic simulation, considering three different supply scenarios: the ESOO – low RES, the ISP – high RES and the ISP – high RES with Storage. Moreover, a sensitivity analysis considering three potential electricity demand growths (neutral, slow and fast) have been computed for each 2030 supply scenario. The results have been analysed for both the technical and the economic simulation.

The economic simulation turned out to be more appropriate for the purpose of this work. This type of simulation was capable of illustrating a more realistic picture of the NEM electricity system, due to its ability to make greater utilization of storage energy systems compared to the technical simulation.

Evaluating the neutral electricity demand growth, the ESOO – low RES scenario depicted a 2030 electricity mix with a RES share of only 23.2%, where wind and hydropower contributed the most with a share of respectively 11.9% and 8%. On the other hand, photovoltaic energy under the ESOO – low RES scenario still represented a minor role in the final energy mix with a share of only 3%. These results indicated the increase of RES share in comparison to the 16.8% in 2018, where hydropower represented the most influential renewable energy source with a share of 8.5%. At the same time the energy mix under the ESOO – low RES highlighted an electricity mix which was still largely dependent on fossil fuel power stations. This dependence is amplified in the fast electricity demand growth, which depicts a RES share of only 21.4%, due to the higher electricity demand forecasted in 2030.

On the contrary, the ISP – high RES and the ISP – high RES with Storage scenarios depicted an energy mix with RES shares of respectively 29.4% and 29.1% by 2030, in the case of a neutral electricity demand. These results are the consequence of the extensive installed power capacity of approximately 11 GW of wind and 10 GW of solar across the NEM territory. In both ISP – high RES scenarios wind and solar contributed for approximately 15% and 6.5% in the final 2030 energy mix. The increase of renewable energy percentage in the ISP – high RES and ISP – high RES with Storage scenarios translated in a production of respectively 130.8 Mt and 131 Mt of carbon dioxide emissions, which denotes a reduction compared to the 148 Mt generated in 2018.
Despite very similar results in terms of the 2030 electricity mix for both the ISP – high RES and ISP – high RES with Storage scenarios, the economic simulation highlighted the benefits of a higher storage capacity included in the ISP – high RES with Storage Scenario. The simulation output showed a storage consumption of 17 TWh for the ISP – high RES with Storage scenario in 2030, as opposed to the ISP – high RES scenario where storage consumption accounted for less than 10 TWh. The higher storage consumption under the ISP-Storage scenario reflected in a higher flexibility of the entire NEM electricity system, since energy storage systems are capable of quickly regulating their output.

Moreover, the ISP – high RES and ISP – high RES with Storage scenarios have also been modelled with the inclusion of the forecasted rooftop-PV capacity installed by 2030 in the NEM. This addition resulted in a final RES share of approximately 37% for both scenarios, when considering a neutral electricity demand.
However, the integration of rooftop solar PV systems in the 2030 ISP and ISP scenarios, (which have been forecasted at a total of 16.8 GW installed capacity), would have resulted in excess production of renewable energy which would have surpassed the electricity demand and the available storage capacity. This excess translated in a need for the curtailment of the extra RES generation. Therefore, a new analysis was performed to evaluate the impact of flexible demand on the curtailment of renewable energy. This last study was executed for each potential electricity demand, considering a maximum 10% of flexible energy demand. The results showed that the flexible demand was capable of completely avoiding all the renewable energy which would have been curtailed for the neutral and fast growth of electricity demand, while significantly reducing the amount of curtailed RES generation in the slow growth of electricity demand, for both ISP – high RES and ISP – high RES with Storage scenarios.
The results obtained in this work present a complete overview of the future changes that will occur in the NEM electricity system; however, they need to be considered with prudence. EnergyPlan is an energy tool created to model future energy systems, due to this reason this software

clearly simplifies the complexity of a real national electricity system.

This method neglects, for instance, the geographical location of each power plant, as well as the internal electric network system, in which congestions could occur. Moreover, it would be interesting to forecast a future electricity system where there could be the possibility for separately modelling of rooftop-PV systems from large-scale solar PV farms, as well as considering small-scale households' batteries, the internal electricity network and households' electricity consumption. This would facilitate an evaluation of a more authentic scenario, taking into consideration the more diffused role of rooftop-PV systems. However, these changes would substantially increase the complexity of the model.

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