Energy Modelling:

Forecasting the Australian Electricity Mix by 2030

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Energy Engineering and Management

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Abstract

The objective of this thesis 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 analyze 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 NEM and the current electricity mix have 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 thesis, 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 systems modelling, Australia, EnergyPlan

Resumo

O objetivo desta tese é modelar o mix de eletricidade em 2030 no National Electricity Market (NEM) na Austrália. Além disso, este estudo examina se o compromisso australiano com o Acordo de Paris de 2016 e as políticas nacionais de energia terá um efeito visível na redução da dependência de combustíveis fósseis do NEM e na redução de emissões de carbono geradas até 2030. Primeiro, é introduzida a atual mistura de eletricidade no NEM, bem como políticas energéticas em andamento e os desafios associados à integração de sistemas de energia renovável. O EnergyPlan, que é a ferramenta de modelagem adotada, é então descrito ao projetar e calibrar um modelo de referência com base na situação do NEM de 2018. O modelo de referência é o ponto de partida para as simulações de 2030. As simulações são implementadas considerando três cenários possíveis de geração e três diferentes crescimentos na demanda de eletricidade para avaliar sua influência no mix final de eletricidade no NEM até 2030. Este estudo conclui que até 2030 NEM, energia eólica e solar (incluindo sistemas de telhado fotovoltaicos) serão os principais contribuintes para as energias renováveis, em comparação com 2018, onde a energia hidrelétrica representou a principal fonte de energia renovável. No entanto, o sistema elétrico em 2030 continuará a depender fortemente de combustíveis fósseis, que serão responsáveis por mais de 50% do mix final de energia em todos os cenários, mostrando que serão necessários esforços adicionais além de 2030.

Palavras-chave

Energia renovável, modelação de sistemas energéticos, Australia, EnergyPlan

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List of Acronyms

ACCU	Australian Carbon credit Unit
AEMC	Australian Energy Market Commission
AEMO	Australian Electricity Market Operator
AER	Australian Energy Regulator
AMI	Advanced Metering Infrastructure
CCGT	Combined Cycle Gas Turbines
CEEP	Critical Excess Electricity Production
CHP	Combined Heat and Power
CO2	Carbon Dioxide
COAG	Council of Australian Governments
DL	Dispatchable Loads
DLM	Direct Load Control
DSM	Demand Side Management
DR	Demand Response
DUID	Data Unit Identifier
EE	Energy Efficiency
EC	Energy Conservation
ERF	Emission Reduction Fund
ESOO	Electricity Statement Of Opportunities
ISP	Integrated System Plan
LRET	Large-scale Renewable Energy Target
MGSS	Minimum Grid Stabilization Share
NEM	National Electricity Market
NER	National Electricity Rules
NSW	New South Wales
NTEM	Northern Territory Electricity Market
OCGT	Open Cycle Gas Turbine
QLD	Queensland
RES	Renewable Energy Source
RES1	Wind Energy
RES2	Photovoltaic
RES3	Run-of-river
RES4	Offshore Wind Energy
RET	Renewable Energy Target

RTP	Real Time Pricing
SA	South Australia
SRES	Small-scale Renewable Energy Scheme
TAS	Tasmania
TSO	Transmission System Operator
VIC	Victoria
WEM	Wholesale Electricity Market

List of Software

EnergyPlan Version 14	Energy system analysis modelling software
Microsoft Excel 2017	Calculation and graphical chart software
Microsoft Word 2017	Text editor software

Chapter 1

Introduction

This chapter introduces the topics evaluated in the thesis, as well as the motivation to conduct an energy modelling on the future electricity mix in Australia. Moreover, Chapter 1 defines the objectives and the structure of the work.

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1.1 Motivation

The Earth has always gone through cycles of climate change since its birth. Multiple studies have proven that the Earth has experienced 10 major ice age cycles over the last millions of years, which reflected in a temperature variation of approximately five degrees Celsius for every ice age cycle. These changes were the consequences of several natural causes, such as the variation of the orbit of the Earth, volcanic eruptions and changes in the Sun's intensity.

However, since human appearance on the globe the temperature has been stable until the 19^{th} century with the beginning of the industrial revolution. Since 1850 until 2012, the near-surface air temperature increased by 0.8 degree Celsius. 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. Figure 1.1 displays the influence of carbon dioxide emissions on the temperature variation in the last 2000 years. These gasses create a greenhouse effect in the atmosphere, limiting the radiant heat flow from the Earth to the space, trapping the heat on the Earth's surface and the Earth's atmosphere. [1]

The effects of Global Warming are already visible in many parts of the ecosystems, for instance glaciers are shrinking, sea levels are rising, and significant animals and plants species are changing their locations or lifecycles to face the variation of the temperature.

It is expected that without any rapid intervention to tackle this situation, the temperature is expected to globally rise by 4°C by 2100, since the industrial revolution which began in the 1850's. [1]

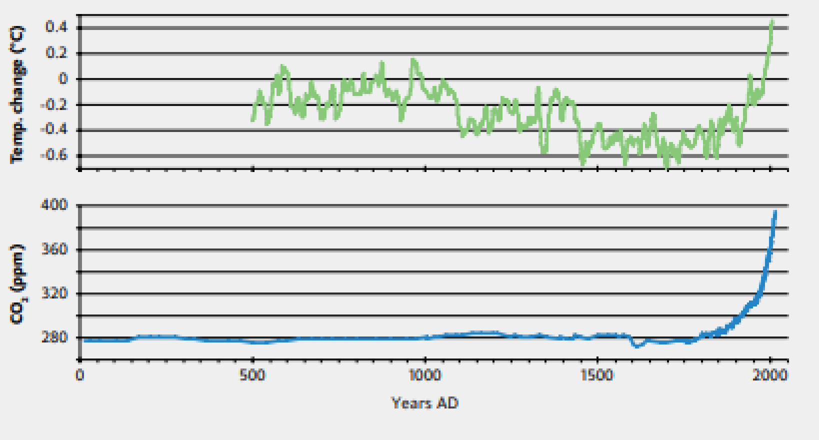


Figure 1.1: Temperature and CO2 changes in the last 2000 years [1]

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. 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 [2] [3]. Nevertheless, 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 as depicted by figure 1.2 [4].

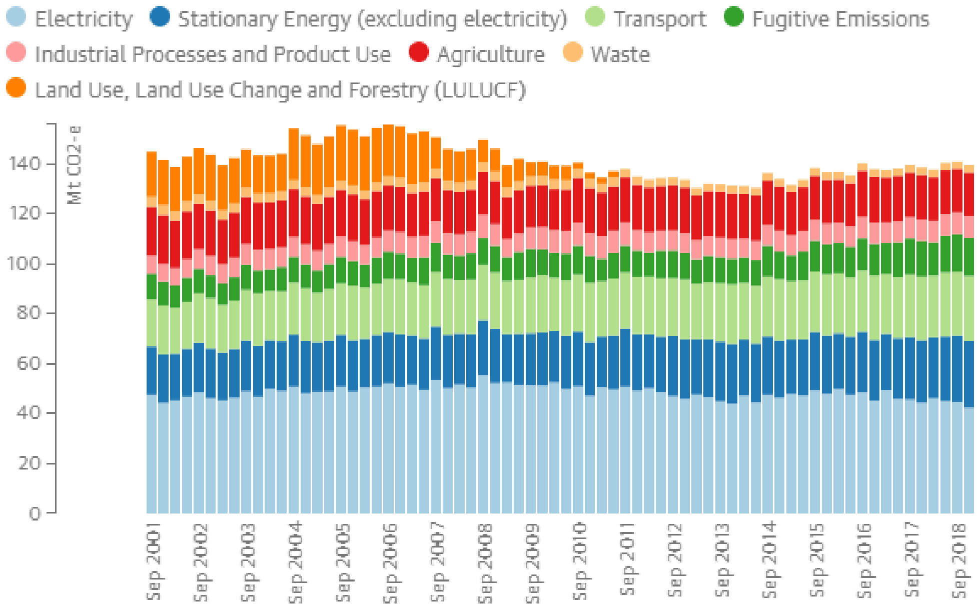


Figure 1.2: Australian emissions by sector [5]

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. This would assist in achieving the temperature target defined by the Paris Agreement by 2050.

This transition will not only involve the construction of renewable energy plants, but also new pathways to combine the variable energy output with storage flexible systems which are capable of always supplying the required electricity demand, without depending on fossil fuel dispatchable (i.e. controllable) sources.

1.2 Objectives

The purpose of this thesis 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.

2030 has been chosen as it is a time-frame which allows for a realistic analysis of the evolution of the electricity sector in Australia. Beyond this year, it becomes difficult to evaluate the changes which will occur within the Australian electricity market.

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, for both contexts mentioned in the point above.
- Assessing the amount of renewable energy to be curtailed (e.g. wasted renewable energy generated), considering different storage capacities available in the NEM.
- 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.

1.3 Thesis outline

This thesis is structured in six chapters and one annex. The first chapter introduces the topic evaluated in this work, as well as the motivation to conduct an energy modelling on the future electricity mix in Australia. Moreover, Chapter 1 defines the objectives and the structure of the work.

Chapter 2 aims to help the reader to familiarize with the context of the Electricity Sector in the NEM, describing its history, structure and current situation. The most recent achievements in terms of renewable energy integrations are described, as well as the existent energy policies and the future challenges to transit towards a clean electricity system.

Chapter 3 is divided in two main sections. The first one explains the methodology of the work, describing the structure of the energy tool utilized. The second part instead is dedicated to the State-of-the-art review, which presents relevant works performed by other authors related to the topic of this thesis.

Chapter 4 describes the modelling of the reference year: the 2018 electricity system in the NEM. It displays all the steps and the parameters required by the software for the modelling of the electricity system, as well as the validation of the model with the real 2018 historical data of the NEM.

Chapter 5 describes the changes that will occur between the reference year and 2030, for both the demand and the supply side. It evaluates different potential electricity demand growths, as well as three different supply scenarios which will be simulated in the 2030 modelling.

Chapter 6 consists of the analysis of the results obtained with the technical and economic simulation for each possible electricity demand growth and each supply scenario, for the 2030 energy modelling of the NEM. Moreover, it explains the pros and cons encountered with both the technical and the economic simulation.

Chapter 7 represents the conclusion of the thesis. It provides a summary of the most relevant points elaborated through this work. Moreover, this chapter suggests new improvements and areas of research that can be evaluated more in depth in further studies concerning the modelling of the electricity system in the NEM.

Annex 1 consists of the 2030 cost database provided by the EnergyPlan software developers. It regards the investment, fixed and variable O&M costs for each technology modelled in the system.

Chapter 2

The Australian Electricity Context

Chapter 2 aims to give an overview of the electricity sector in the Australian National Electricity Market. It firstly describes the structure and the origin of the electricity sector in the country. Following, the next section has the purpose of illustrating a frame of the actual electricity situation, including a description of the electricity mix for each state and the energy policies adopted in the country. Lastly, this chapter explains the challenges which will occur in the electricity sector, in relation to the significant deployment of renewable energy technologies.

2.1 The Australian energy context and the NEM – National Electricity Market

Australia is the sixth largest country on the Earth, counting for slightly above 25 million people concentrated mostly in the urban areas along the coast, with most of the country being uninhabited, as a consequence of being the driest country in the world. This geographical territory is split into seven federal states: Australian Capital Territory, New South Wales, Victoria, Tasmania, Queensland, South Australia, Western Australia and Northern Territory.

Australia can rely on a significant variety of energy resources which contribute to both the national domestic consumption and fossil fuel and uranium exports. In particular, Australia benefits from possessing the world's largest uranium resources and the fourth largest coal resources, as well as remarkable conventional and unconventional gas reservoirs [6]. Furthermore, Australia has an enormous potential in terms of renewable energy generation. It has the highest concentration of solar radiation per square meter on the Earth, absorbing an average of 58 million picojoules of solar energy per year (around 10 000 times more than the total Australian energy consumption), together with advantageous wind conditions in terms of average wind speed and topography. These factors make wind and solar the favourite renewable sources for upcoming national investments and project developments. [7]

The purpose of this study focuses on the electricity sector in the country, which is the largest contributor of emissions, currently accounting for approximately one third of the total green-house gas emissions. This is due to the traditional centralised electricity system being predominantly based on coal fired power stations. [7] As a consequence of the remarkable size of the country (which faces evident obstacles for the implementation of a single electricity network due to the large distances to cover), Australia has multiple electricity networks, in which the NEM and the WEM are the main players. The NEM (National Electricity Market) allocates over 80% of the total electricity consumed in Australia and interconnects the eastern states: Victoria, Queensland, New South Wales, Tasmania, Australian Capital Territory and South Australia. On the other hand, the WEM (Wholesale Electricity Market) is responsible for the electricity delivery in Western Australia, while the Northern Territory has recently announced the development of the Northern Territory Electricity Market (NTEM) by 2020 [8]. The WEM and the NTEM have not been considered in the scope of this thesis, playing a secondary role compared to the NEM contribution to the Australian electricity sector.

2.1.1 NEM history

At the beginning of the 20th century, only Tasmania and Victoria identified their state electricity resources, developing respectively the first dam-hydro power plant, with a capacity of 6.8 MW in Tasmania in 1916, and the brown-coal power station in Victoria in 1921, with an installed capacity of 50 MW. After World War II, Australia saw a significant economic growth which drove the rapid construction of multiple coal power stations and the subsequent shift from an electrical system run by local authorities, to a centralized system, which extended not only to cities but also to rural areas. This rapid expansion of coal power stations which marked the decades from the 1950's to 1990's, was mainly driven by the discovery of an enormous quantity of black coal fields in the New South Wales and

Queensland territories. Alongside coal-fired power plants, the same period began the implementation for new hydro power stations (Snowy Hydro Electric Scheme), which lasted from 1949 to 1972, consisting in 16 major dams between New South Wales and Victoria, with a total installed capacity of 3756 MW.

Figure 2.1 shows the trend of the remarkable implementation of the installed power capacity in the post War World period to 1997, with the creation of the National Electricity Market.

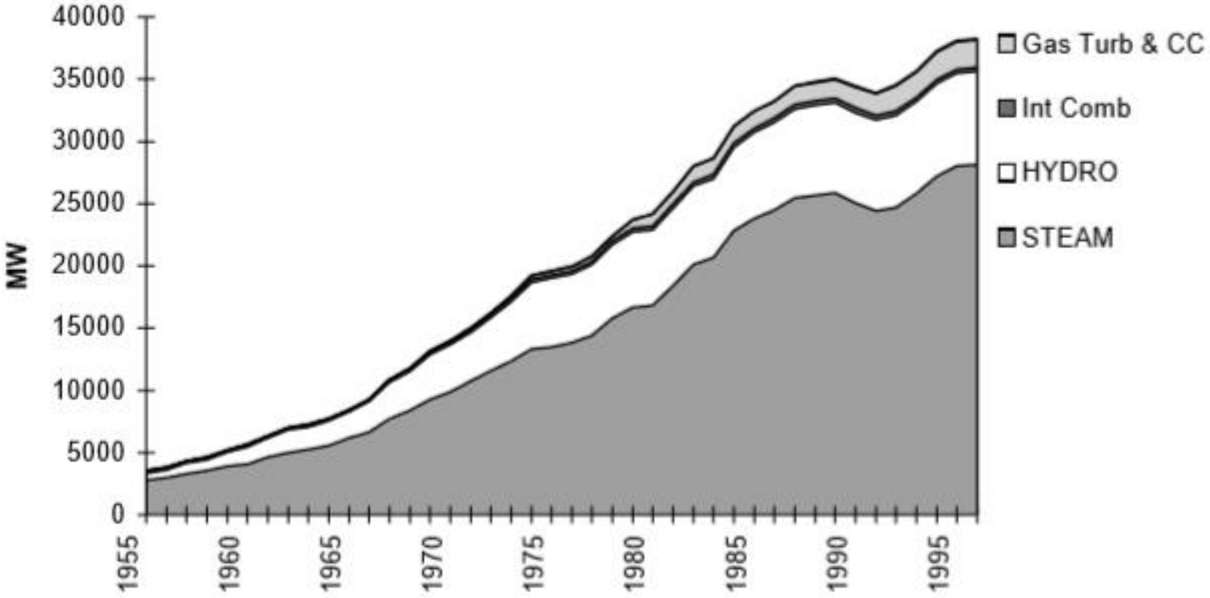


Figure 2.1: Installed electricity capacity in Australia from 1955 to 1997. [9]

In addition to the developments of numerous power stations across the country, from the 1950s there was an increase in the need for high voltage transmission lines which were able to connect remote areas with low-cost energy sources to load centres. Moreover, in 1959 the first interconnection line was built between New South Wales and Victoria as a result of the Snow Hydro Scheme development and in 1990 the next interconnection line was built between South Australia and Victoria, which led to a total capacity between the three systems together of approximately 19,000 MW. [9]

Besides the rapid expansion of the electricity industry in all the Australian states in the second half of the 20th century, all the different stages of the power supply (from generators, to transmission, distribution and retail) were still owned and operated by State Governments. The state electricity monopolies were a barrier to low electricity prices. This reason led to the gradual development from 1991, of the privatisation and disaggregation of the electricity sector [9]. Following, the last objective was the transition towards a single market in eastern and southern Australia to establish a cost-efficient and competitive electricity market, guaranteeing low electricity supply costs and energy security. This process started in 1997, when the New South Wales State and Australian Capital Territory Market joined the Victorian Market. By 1998 with the addition of South Australia the National Electricity Market was created. In the next years, with the conclusion of the construction of interconnectors between New South Wales and Queensland in 2001 and between Tasmania and Victoria in 2005 also Tasmania and Queensland entered the NEM. [10]

2.1.2 NEM structure

The NEM includes 40,000 km of transmissions lines and cables and consists of the longest interconnected power system in the world, covering a distance of around 5,000 km, from the north of Queensland (Port Douglas), to the very south Bass Strait in Tasmania, as shown by figure 2.2.

The NEM carries electricity through transmission networks, from power generators to industrial energy users and local distributors to the six states. In the National Electricity Market there is a total of over 300 participants, which comprise of market generators, transmission network service providers, distribution network service providers, and market customers.

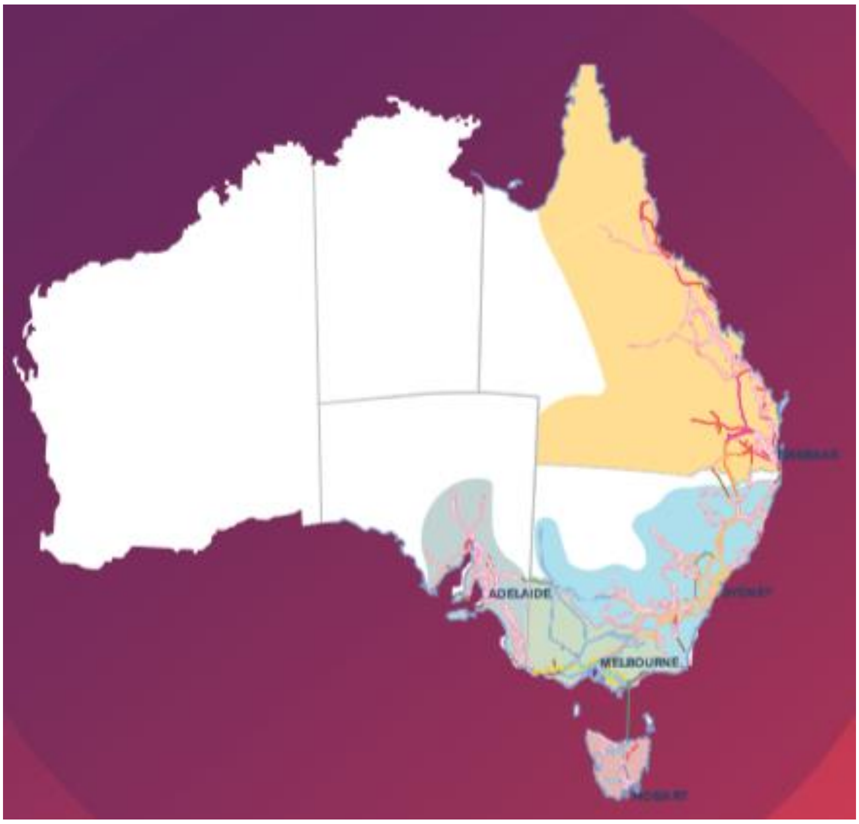


Figure 2.2: The NEM interconnected power system [8]

TRANSPORT OF ELECTRICITY

The Australian national electricity market is based on centralized generation, which means that power stations are distant from the end-consumers and the electricity generated is transported through a connection of high voltage transmission lines. The electricity produced from generators is converted from low to high voltage in generator transformers, to be carried for long distances through transmission lines. Then it reaches the distribution transformers which reconvert the electricity from high voltage to low voltage, to be adequate for the distribution lines to finally reach the end-consumers in houses, offices and industries for any electricity need. Each phase, from the electricity production to the final consumption can be observed in figure 2.3.

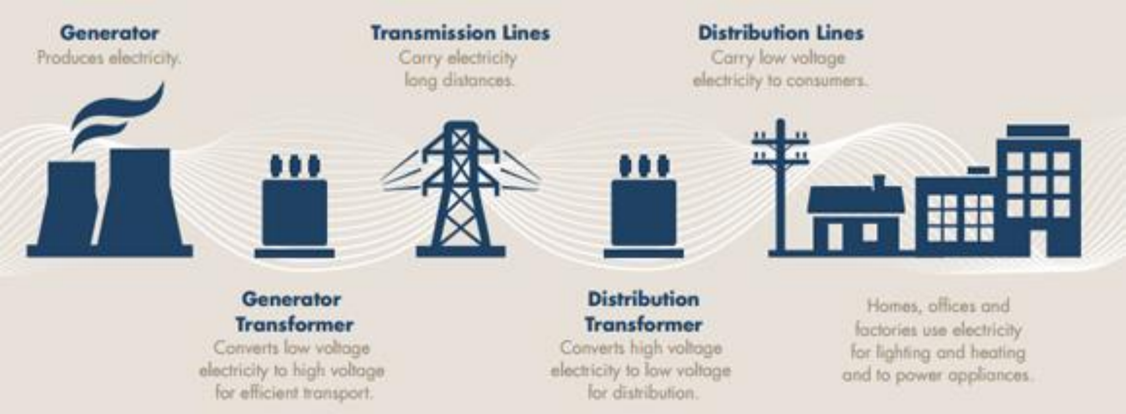


Figure 2.3: Transportation of the Electricity in the NEM [8]

ACTORS IN THE NEM

NEM operations are regulated and managed by several players, first of which is the Australian Energy Market Operator (AEMO). It was founded in 2009 by the Council of Australian Governments, to manage the electricity and gas markets services and the national transmission planning. AEMO is responsible for multiple functions. Uppermost, it controls the system operations of the retail electricity markets in the entire NEM, monitoring the electricity consumption and energy and financial flows, as well as electricity voltage and frequency to guarantee a reliable and secure electricity network. Moreover, AEMO is responsible for electricity system planning, electricity load forecasting, power systems information, security advice and services to all regulators, generators and network operators. For instance, AEMO is empowered to commission service providers to cut-off the electricity supply to customers (typically large industrial customers), in case of excess of electricity demand which exceeds the supply. [10]

Besides AEMO, there are three other institutions involved in the Australian Electricity Market who are in charge of the economic and law regulations: 1) The Australian Energy Regulator (AER), which monitors and regulates the wholesale and retail energy markets, and energy networks, 2) The Australian Energy Market Commission (AEMC), which creates and rectifies the National Electricity Rules (NER), and 3) the Council of Australian Governments (COAG) Energy Council, which controls and supervises the norms and policies concerned with the Australian electricity market. [7]

SPOT MARKET

The trade of electricity in the NEM works as a wholesale electricity market where the electricity is sold by generators and bought by retailers who then distribute it to their customers for their own electricity consumption. Adopting this mechanism, consumers do not have to purchase electricity directly from the whole sale market and moreover do not have to interact with a complex market. The wholesale electricity market is highly competitive, having more than 100 participants among generators and retailers, guaranteeing an efficient operation of the market.

Every five minutes each electricity generator proposes the amount of electricity they will produce, together with their bid for the electricity price. Then AEMO, which is responsible for the NEM spot market operation, ranks each generator offer, from the cheapest to the most expensive, ensuring the most cost-efficient electricity mix to meet the demand, as shown in the example by figure 2.4. Moreover, the market operator ensures that the transmission lines are not overloaded by applying transmission constraints. The electricity demand, which is forecasted by AEMO at the end of each five-minute dispatch interval, is then met by the supply according to the scheduled order of production, from the cheapest generator to the most expensive one. The latter defines the dispatch price for the five-minute interval. The prices of the six five-minute intervals are then averaged over 30 minute trading periods, which sets the settlement price. [11] The gap between the dispatch price and the settlement price is due to technological limitations from when the price system was established in the late 1990s. However, the spot market is under a transformation process, setting the goal to define settlement electricity prices every five minute from 2021. This change will be possible due to the technological advancement experienced in the country in the last years, which will provide a much better synchrony between the physical electricity flows and the electricity prices, as explained in detail under paragraph 2.3 regarding the “Challenges associated with Renewable Energy Integration”.

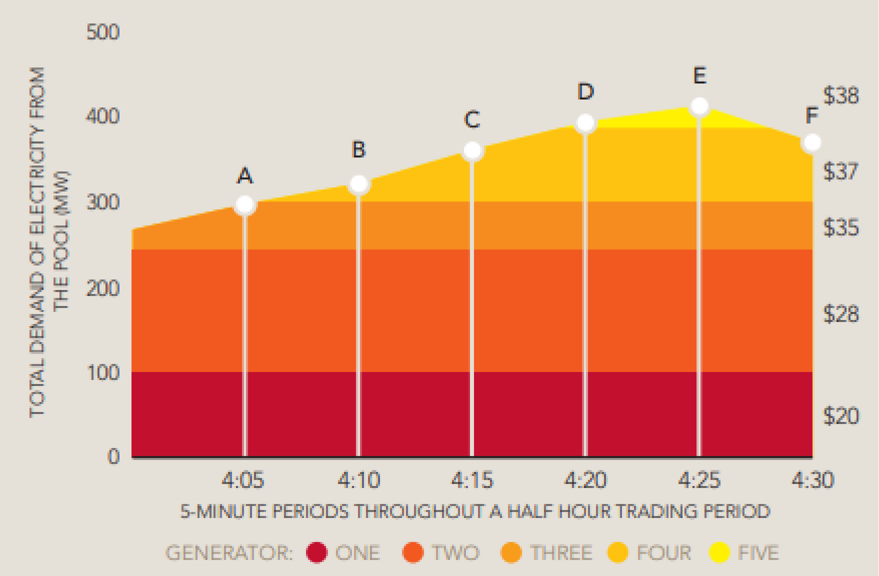


Figure 2.4: The spot price definition [12]

After the electricity demand is met by the supply through the Spot Market, AEMO pays the spot price defined by each 30 minute period to the generators, while the retailers pay back to AEMO the costs associated to the electricity consumption of their customers based on the spot price defined. [11] Figure 2.5 provides an overview of the physical energy flows and the monetary transactions among the participants involved in the spot market.

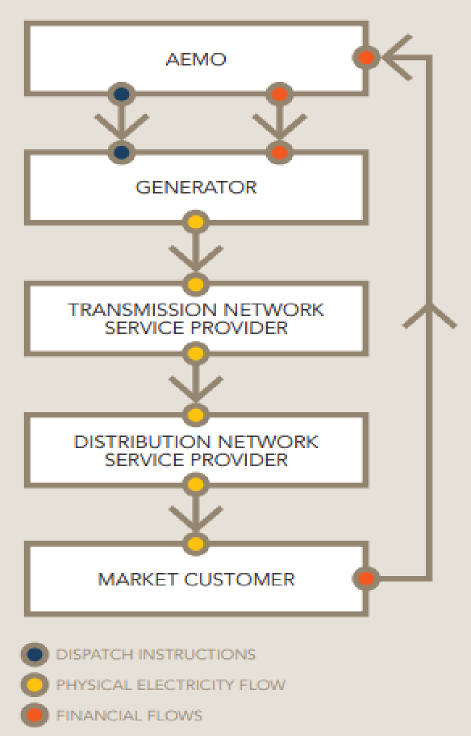


Figure 2.5: Physical and financial flows in the spot market [12]

Beside the wholesale spot market mechanism, generators and retailers often set hedging strategies such as contracts and vertical integration, in order to protect themselves from the risks associated with price fluctuations under the electricity spot market. The contracts between generators and retailers are agreements which set the electricity price in advanced before the actual electricity trade, and agrees on a defined amount of electricity traded between the two participants for a fixed period of time. [13] Conversely, vertical integration refers to a business which owns different stages in the same sector, for instance a company who operates both generation and retail activities. [14]

2.2 Current electricity situation in the NEM

Since the 1950s, Australia is enduring an evident electricity transformation, with visible changes happening for 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 [15]. From its first creation and further during developments which began in the 1950s, the Australian Electricity System was based on centralised coal-fired power stations. Despite the passing of decades, currently the electricity situation is still 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, which refer to combine cycle gas turbines or open cycle gas turbines [15]. This substantial fossil fuel presence in the actual NEM electricity mix is due to the abundance of fossil fuel resources present in the Australian territory. However, in the last decade and most notably in the last three years, the NEM is experiencing a quick transition towards a generation mix with an increasing percentage of energy generated by low emission technologies. This outcome is the consequence of multiple reasons, first of which is the implementations of National Energy Policies and the fall of wind and solar investments costs, which provide a good incentive for numerous companies to invest in renewable energy projects.

Despite having approximately the same amount of total large-scale generation capacity installed as 2013, about 50,000 MW, the NEM is gradually changing its generation capacity mix. From 2012, around 4,000 MW of coal capacity have retired due to the reaching of the power plants' technical lifetime [16]. Moreover, the age of these plants plus their obsolete technology and their high emission production, renders it inefficient to implement any type of Carbon Capture Technology (CCS) to be able to still operate these plants. On the other hand, 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 1900 MW of large-scale solar-PV since 2014 to the end of 2018 [16]. These developments decreased the gap in terms of NEM installed capacity after the exit of the consistent coal capacity from the market. However, in order to rely on its electricity system, the NEM cannot replace this withdrawn coal capacity with only variable sources, such as wind and solar-PV, due to their uncertain output and the impossibility to regulate their output whenever there is a need for it. Other technologies are starting to have a primary role in the generation mix, due to their capability to guarantee flexibility and reliability to electricity systems. These consists in energy storage systems, in particular large-scale batteries, which are facing a significant deployment in the last two years, with a total installed capacity of 190 MW [17]. The diffusion of this technology in the NEM will be discussed more in detail in paragraph 2.2.2.

The fossil fuel generation capacity installed is still the predominant part, as can be observed in figure 2.6, accounting for slightly over 23,000 MW of coal installed capacity, and over 11,200 MW of natural gas and oil plants installed capacity. Hydro-power plays a relevant role in the NEM, having over 8,000 MW installed in several hydro stations mainly across New South Wales and Tasmania. Moreover, it is the first renewable energy source in terms of electricity generation since the creation of the NEM. However, no recent developments under this technology have been realized in the last six years and it is forecasted that wind and solar will overtake hydro power in the electricity mix in the upcoming years.[16-26]

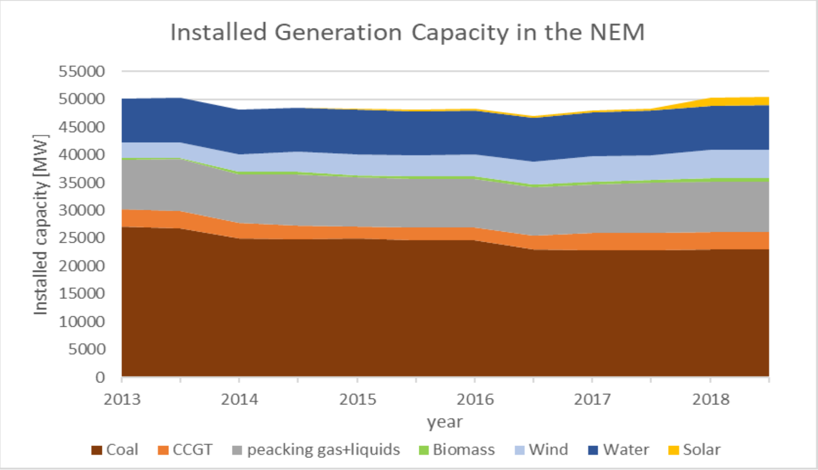


Figure 2.6: Installed generation capacity in the NEM from November 2013 to January 2019 (rooftop solar PV systems have not been considered under this graphic)

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 due to the clear advantageous in terms of reducing the electricity bills, especially in recent years where the NEM experienced a net increase in terms of electricity prices. Rooftop-PV systems are not dispatched by the wholesale market, but they decrease the electricity demand required to be met by dispatchable generation. [16]

By the end of 2018, there was a total of 6.98 GW of small-scale rooftop PV systems installed in the NEM, (referring to rooftop solar systems with a total capacity of maximum 100 KW) indicating the addition of a total of 3 GW from December 2015, as displayed in figure 2.7. The continuous installation of thousands of rooftop systems during the last years is evident across the entire NEM, which is facing a substantial increase in rooftop PV systems in each state. It is important to note that the rooftop capacity regarding ACT has been included in the NSW capacity.[27-29]

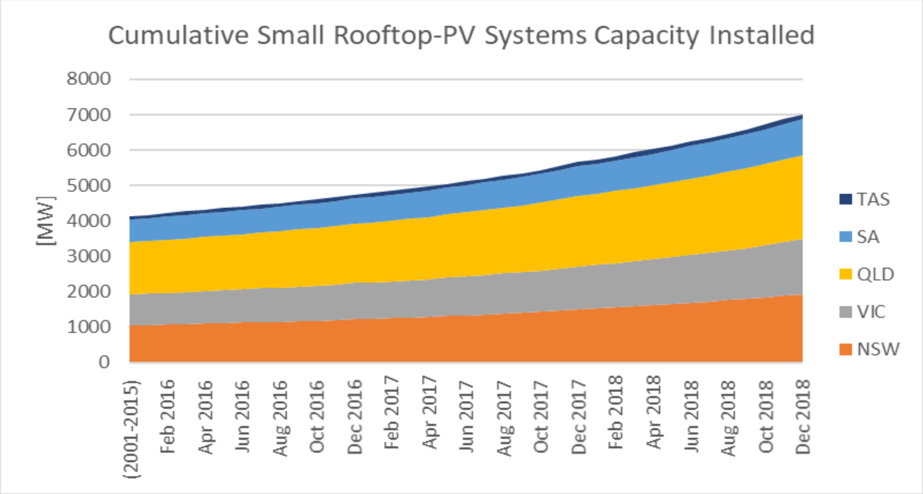


Figure 2.7: Cumulative small rooftop-PV systems capacity in the NEM

2.2.1 National energy policies and cost of technologies

The transition towards a renewable electricity system in Australia is currently driven and incentivised by two National Government Policies, which are directly related to the electricity sector: The Renewable Energy Target (RET) and The Emission Reduction Fund (ERF). [32]

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 [33] [34]. The mechanism of operation for both the LRET and the SRES consists of the creation of tradable certificates to be given to the owners of renewable energy generators for every megawatt hour of power produced. The certificates are generated through an online platform managed by the Clean Energy Regulator, and once they have been issued, they are sold to electricity retailers, who have to collect a certain number of certificates to meet their renewable energy obligation. Then the certificates are proportionally handed to the Clean Energy Regulator, depending on the energy consumed by the energy retailers' customers, as displayed in figure 2.8. [33] [7]

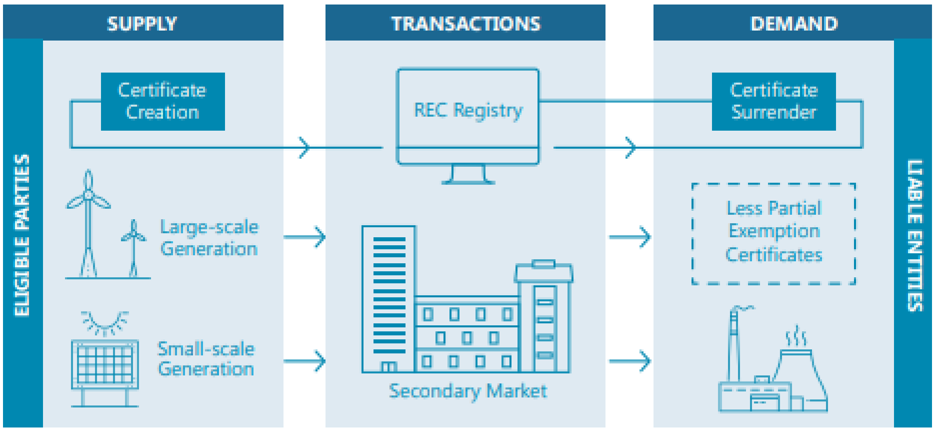


Figure 2.8: LRET and SRES schemes [7]

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). 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. For instance, the use of more energy-efficient appliances, reducing land clearing and planting new vegetation, reducing emissions in high-intensive industrial processes. Every ACCU is earned by a registered participant for every ton of carbon emission reduced and then can be sold to the Australian Government, more specifically to the Clean Energy Regulator. Moreover, the progress obtained by the ERF scheme is guaranteed by the safeguard mechanism, which will force the largest source of emissions to maintain their emission levels within the baseline threshold. The safeguard mechanism is a mechanism created by the Australian Government to ensure that the achievements obtained through the ACCU credits/purchased are not contrasted by net increase in emissions from other actors in the market, who are not involved in the ERF. [35] [36]

The schemes provided by the Australian Government constitute a substantial incentive to assist in the diffusion and development of renewable energy technologies in the Australian states and territories in the last few years. However, 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. 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. A confirmation of this argument is provided by a study conducted in 2018 by Commonwealth Scientific and Industrial Research Organization (CSIRO), which undertook a comparison between the capital cost of the different sources of power generation. In 2018, the capital cost of wind and solar-PV declined to less than 2,000 [$/kW], as shown by figure 2.9, while capital costs of coal-fired power stations remained above 4,000 [$/kW] and with high probability this will not drop in the upcoming years. [37]

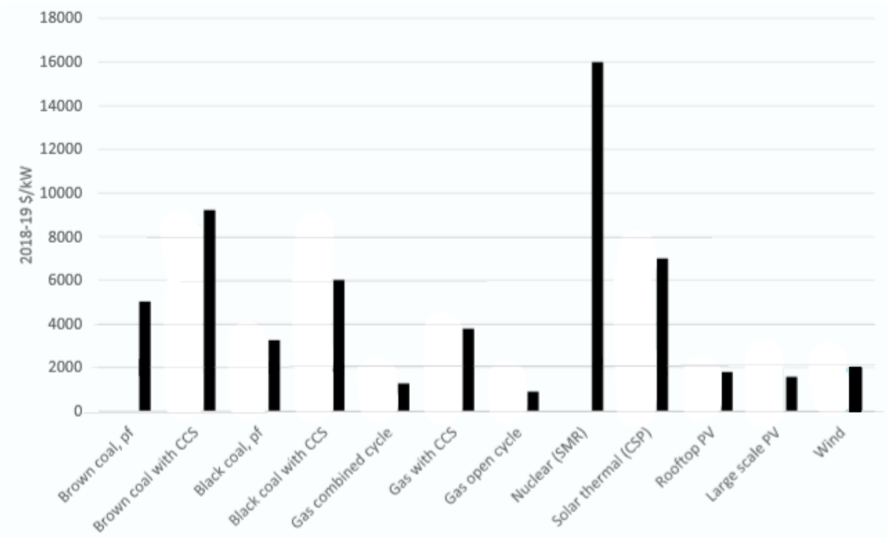


Figure 2.9: Generation technology capital costs [37]

2.2.2 Main achievements towards a renewable electricity transition

The national energy policies as well as the decrease in renewable energy capital costs are driving a fast transition towards a cleaner electricity generation in the National Electricity Market. In the last decade, the statistics show a significant increase of the total percentage of energy generation attributed to solar and wind technologies, as shown in figure 2.10. By the 2017-2018 financial year, wind energy accounted for above 6% of the total energy generated in the NEM, more than six times the percentage of wind energy ten years before. Moreover, the complementary contribution of solar and wind accounted for over 10% of the total electricity mix in the National Electricity Market. It is clear how solar is gaining more relevance year by year in the NEM electricity mix, also due to the fall of its capital investment costs, which make this technology one of the main “actors” in the electricity sector in the following years.

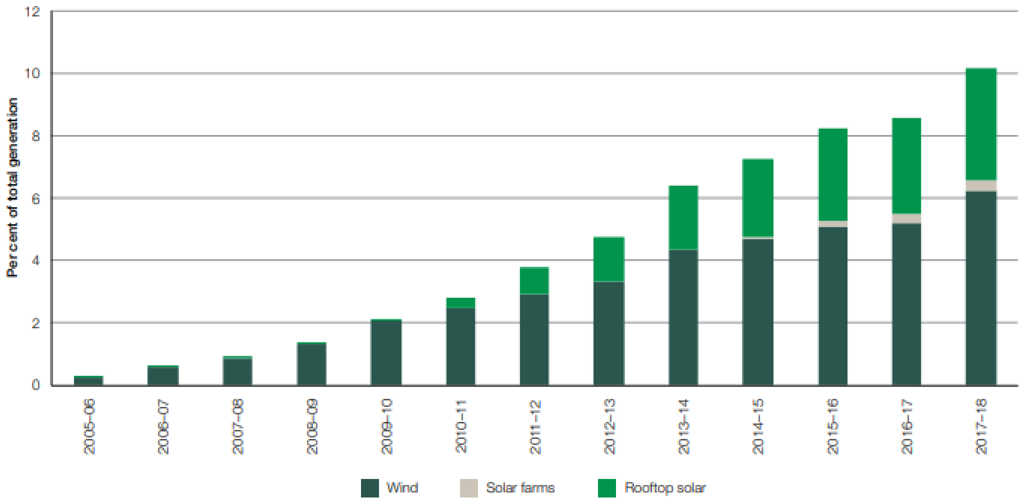


Figure 2.10: Solar and wind generation percentage in the NEM [16]

2018 was an extremely important year for the deployment of renewable energy projects in Australia and particularly in the NEM. By the end of the year, 36 large-scale renewable energy projects were completed in the NEM, respectively 26 large-scale solar farms and 10 wind farms, with a total investment of over $20 billion, which doubled the investment committed for 2017. These developments accounted for an entry in the National Electricity Market of more than 850 MW of wind installed capacity and 1,412 MW of large solar PV installed capacity. This trend is continuing to grow in the upcoming years, as a matter of fact, by the beginning of 2019 there were 85 large-scale renewable energy projects under construction or financially committed. [38]

However, a smooth transition towards a renewable energy generation mix in the NEM requires the implementation of flexible sources, which can deliver electricity quickly whenever it is needed. For this purpose, storage technologies are playing a fundamental role due to their ability to provide frequency control ancillary services and regulate the electricity output generated by variable and unpredictable wind and solar farms. Between 2017 and 2018 the NEM installed four large-scale battery systems, including the largest battery in the world in South Australia, with an installed capacity of 100 MW and a storage volume of 129 MWh. The benefits from the development of batteries were evident from both a technical and economical point of view, reducing ancillary service costs by up to $50 million dollars. [38]

Alongside the rapid expansion and development of large-scale renewable energy projects, the NEM is reaching new records every year in terms of rooftop-PV installations. By the end of 2018, 182,542 small-scale rooftop-PV systems were installed in the NEM, which accounted for 41,284 more installations compared to the year before. The statistics indicated that in the NEM states there were 2 million households owning a small-scale rooftop PV system, which accounts for one in every five households. This data translates to an entry in the market of more than 1,325 MW installed capacity of small-scale rooftop PVs, as displayed in figure 2.11, showing that the highest capacity installed was achieved in 2018, with an installation record in every state except Tasmania. [38]

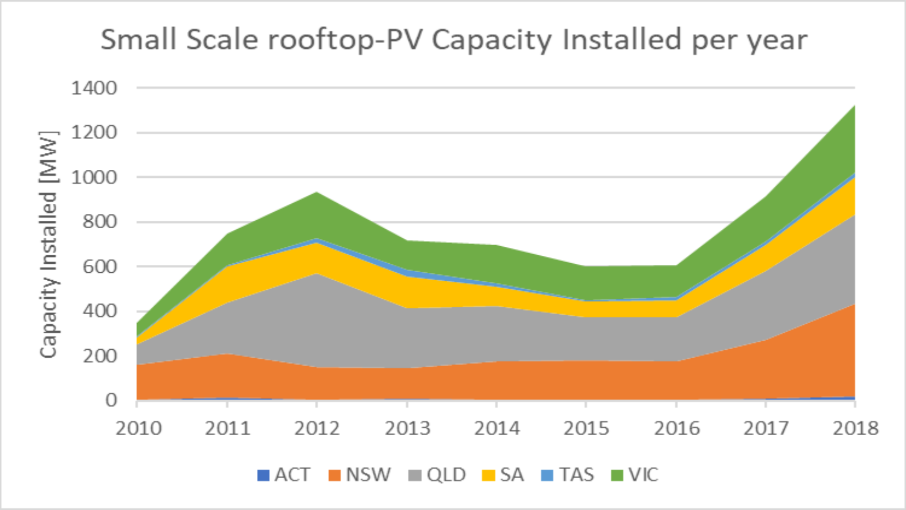


Figure 2.11: Small scale rooftop-PV capacity installed per year

Aligned with this “technology booming trend” there is the recent expansion of medium-scale rooftop solar PV systems. These systems are classified to have a generation capacity among 100 kW and 5 MW and have been installed in buildings with a large surface availability, such as shopping centres, hospitals, commercial buildings and schools. This type of technology is still not extensively diffused in Australia and its installed capacity grew rapidly from 2012, with less than 20 MW installed to 2018 with a total capacity installed of 230 MW. [38]

Despite the electricity generation in the NEM still being predominantly composed of fossil fuels, the Australian Government’s Clean Energy Regulator stated in the “Acceleration in Renewables Investment 2018” Report that Australia is the first country in the world in terms of renewable energy capacity installed per capital. [39]

2.2.3 Electricity situation and energy targets by state

Australia and more precisely the states within the National Electricity Market cover a very broad geographical area, benefitting from very different resources according to each location. This paragraph, indeed, has the purpose of providing a better understanding of the role of every energy source, evaluating their impact in the electricity sector in each state of the NEM.

Figure 2.12 indicates the generation installed capacity by source, dated to January 2019, for each state in the NEM, and excludes rooftop-PV systems [17]. The ACT has been included in the installed capacity of NSW, due to its geographical collocation and its dimension. Each state is characterized by a different generation capacity mix, which reflects the local resources available and the requirements of each state in terms of electricity demand. For instance, New South Wales has a larger installed power capacity than Tasmania and South Australia, due to its greater population and consequently its greater average electricity consumption.

Besides the recent developments in wind and solar energy projects, the figure highlights how the largest generation capacity for each state is still provided by dispatchable sources. For instance, New South Wales and Queensland still rely mostly on black coal, accounting respectively for 10,160 MW and 8,860 MW installed power capacity, while Victoria has 4,660 MW of installed brown coal capacity. On the other hand, Tasmania is heavily dependent on dam-hydro power stations with 2,287 MW installed, while South Australia rely mostly on gas power plants with 3,192 MW installed.

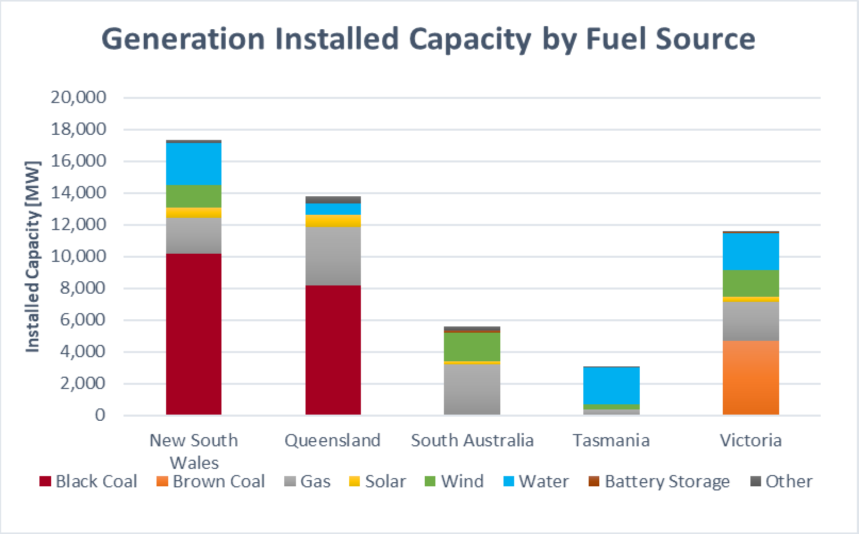


Figure 2.12: Generation installed capacity by fuel source per state [17]

In the following section it will be described an overview of the electricity sector in each state, including the main achievements and the future energy targets.

ACT – Australian Capital Territory

ACT is the smallest and least populated state among the states in the NEM and as a consequence it has also the lowest electricity consumption. Currently, it has a total installed capacity of 56 MW within the state boundaries, consisting of four large-scale solar power plants. By the end of 2018, 78% of its total electricity consumption was generated by renewable sources, improving its record from the 46% of 2017 These achievements are in line with the ACT 100% renewable energy target to be pursued by 2020. The next ambitious objective of the state is to reach zero-net greenhouse gas emissions by 2045. [38].

However, most of the renewable generation percentage in ACT doesn't come exclusively from the solar farms located in the state, but also from various solar and wind farms located in NSW, VIC and SA. These power plants signed contracts agreeing that ACT would pay a fixed tariff for every MWh of electricity produced and in return the state would collect the Large-scale Generation Certificates, emitted by the RET scheme. This mechanism justifies the ACT claim of 100% renewable generation by 2020 and the 2018 level of renewable energy production. [40]

NSW – New South wales

NSW has a variety of generation technologies contributing its electricity mix. Black coal, which fuels five power stations located in the surrounding of Sydney, represents the dominant source of electricity, accounting in 2017 for 63% of the state generation capacity and for 88% of the total electricity produced [14]. Despite coal, NSW benefits from one of the largest hydropower schemes in the country: the Snowy Hydro Scheme, that shares together with Victoria, with a total capacity of 4,200 MW, producing an average of 4.5 TWh per year [41]. Moreover in 2018, 383 MW of large-scale wind power and 347 MW of large-scale solar PV power have been installed contributing for a total of 15% renewable energy generation in the state.

In order to improve the state “green energy transition”, NSW set the target of Zero Net Emission by 2050, as well as the Climate Change Fund Strategic Plan which has the purpose to increase the Renewable energy capacity to more than 10,000 MW by 2021. Other strategies have been planned as the Transmission Infrastructure Strategy to develop new transmission lines for a better integration of the new amount of renewable energy capacity [38].

VIC – Victoria

Victoria has traditionally been dependent on brown coal for electricity generation, due to the significant amount of brown coal mines in this region. However, in the last four year, two large coal-fired power stations have retired, with a total of 1,720 MW exiting the market, which provided over 20% of the total state electricity consumption [42]. On the other hand, Victoria offset the withdrawn coal power stations capacity with a significant development of renewable projects. In 2018 four large-scale solar farms and five wind farms for a total of 558 MW were built in the state, which contributed to achieve the record of 20.6% of the total generation supplied by renewable energy technologies.

The state is driving a clear energy transformation, defining two ambitious renewable energy targets: the achievement of respectively 40% by 2025 which has been extended to 50% by 2030 of total electricity supplied by renewables, with new investments provided by the VIC Government and the achievement of zero net emissions by 2050. Moreover, a new policy called “The Solar Home Program” has been undertaken to promote the diffusion of small-scale energy systems, with the government investment of $1.3 billion to assist over 720,000 households in the next 10 years to install solar panels, or household storage. [38]

QLD – Queensland

Queensland electricity generation industry has always relied upon fossil fuel sources, having currently 80% of its total generation capacity installed coming from black coal fired stations and gas stations. However, energy policies in this state are driving a quick shift towards renewable technologies. Despite only 9.5% of generation from renewable sources in 2018, Queensland is leading the Australian renewable energy “boom”, with the development of 17 renewable energy projects by the end of 2018, reflecting in an addition of approximately 1000 MW to the state generation installed capacity. [38]

The state aims to achieve ”50% renewable energy target” by 2030, thanks to the $1.16 billion investment under the “Powering Queensland Plan” launched by its government in 2018. This plan consist of short-term and long-term strategies to overcome the current challenges to ensure the security of the electricity supply with the upcoming closure of ageing coal and gas thermal plants and the implementation of solar and wind farms as well as storage systems. [43]

TAS – Tasmania

The electricity generation mix is composed mostly by hydro power stations, accounting for more 85% of the total installed capacity, which guarantees the base-load for the state electricity consumption. The rest of the state electricity mix is formed by a gas-fired station and wind farms.

Tasmania was the Australian state with the highest renewable energy share in 2018, resulting in 95.9% of the total electricity production. The state government defined an energy target which aims to reach 100% renewable generation by 2022. This objective will be supported by the development of two new wind farms in 2019 and the feasibility study of the “Battery of the Nation Plan”, consisting of a potential introduction of 2,500 MW of pumped-hydro storage, which would beneficial to create flexibility to the state electricity system as well as to the NEM market, supporting the transition towards a renewable electricity mix. This last project would involve further upgrades and investments to increase the capacity of the interconnector between Tasmania and Victoria. Tasmania was the first state in Australia to achieve net zero emissions in 2015-16, due to its high hydro power generation and its vast forests resources, as well as small energy demand and population. [38] [44]

SA – South Australia

After the retirement of two coal-fired power stations in 2015-2016, the power generation mix of South Australia relies mostly on gas power plants and the vast capacity of wind turbines installed. In 2018 the state achieved 53% of total generation from renewable energy, thanks mostly to the 1,809 MW of wind generation capacity installed which provided 43.5% of the state electricity generation and to 1,009 MW of rooftop PV installed [38] [45]. Currently SA is the Australian state with the highest installed capacity of wind power, which contributes for 35% of the total wind capacity in the NEM [46]. This substantial renewable energy generation, in combination with the poor electricity transmission connection to the other states of the NEM (only two interconnectors with Victoria, for a total of 870 MW in both directions) drove the state government to invest $200 million in the construction of a new interconnector with NSW [38].

The state government, without having any renewable energy targets to look forward, is still participating on new energy policy actions, investing a total of $200 million for “the home battery scheme” and “the grid storage funds” to support the transition towards renewable energy. The first program consists in grants to 40,000 households to install home battery systems, while the second policy intends to incentivise the development of utility scale storage in the state [47].

2.3 Challenges associated with renewable energy integration

The fast deployment of renewable energy technologies in the Australian National Electricity Market is reflecting in an overall decrease of carbon emissions. However, the integration of these technologies is bringing numerous challenges to maintain a secure and reliable national electricity system.

Despite biomass generation, whose energy is stored chemically, and hydropower generation, which can store the gravitational potential energy of the water through the presence of a dam, the rest of the renewable sources consist of non-storable energy fluxes. These sources, such as wind and solar insolation, are characterized by having a variable output which relies on weather conditions.

Currently, the most diffused renewable energy technology in Australia consist of hydro-power generation, wind turbines and solar photovoltaic. Most of the hydropower generation in the country is built as dam-hydro power stations, which possess the advantage of being a dispatchable source of electricity, as the plant operator can regulate the electricity output according to the needed electricity demand.

On the other hand, the intensive development of mostly wind and solar power plants is increasing the installed capacity of variable power generation across the NEM territory, consequently raising the amount of electricity generation output from uncertain and variable technologies. This will create new challenges to maintain a reliable supply generation mix that is capable of matching the electricity demand [48] [49].

The entry of several intermittent renewable power plants will also affect the balance and stability of the electric grid. The electric grid must always have a frequency at 50 Hz to be balanced, this occurs when the electricity generated is equal to the one consumed. A variation in the frequency translates into grid instability, which is induced from an electric demand which overcomes the supply or the reverse situation. In order to avoid grid instability and to balance the grid, AEMO uses frequency control ancillary services (FCAS) from generator suppliers or big electricity users. Generator suppliers have the capability of rapidly increasing the electricity production, while big electricity users have the capability of quickly reducing the consumption. Thermal and hydro power stations have traditionally provided FCAS services. However, with the rapid entry of several wind and solar farms injecting variable electricity output into the grid, the need for further FCAS will be crucial to ensure the security of the grid. [50]

Moreover, the recent overtaking of distributed energy resources (DER) is transforming the operation of the grid, creating a more decentralized system. DER systems are divided into passive and active systems. Passive systems for instances are identified by rooftop-PV, while active systems include the presence of a battery or a storage solution connected to a rooftop-PV system or other home management systems which can be controllable and can regulate their output according to network signals. [51]

The grid has historically been designed to transport electricity from high voltage to low voltage. However, with the integration of rooftop-PV systems owned by households and businesses, the consumers are becoming the electricity producers, selling the electricity generated from rooftop-PV into the grid. As a consequence, the grid is accommodating two-way energy flows in the low voltage distribution lines [52]. These developments result in more unpredictable power flow on the distribution lines, which creates new challenges of guaranteeing the correct technical operation of the network. 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. [53]

Moreover, the rapid transformation of the Australian electricity mix, including the retirement of several coal-fired power stations, has recently caused a net increase of the wholesale electricity prices. The need of electricity generation from gas-fired power stations to meet peak demands, and the high cost of natural gas have played a role in the growing electricity price. This is due to a lower supply capacity from dispatchable generators, especially coal plants. On the other hand, the rise of non-dispatchable wind and solar farms, which are characterized by low operational costs, did not contribute to offset this spike in the electricity price. [14]

Given this context, new approaches are required to overcome both these technical and economic challenges, through the development of technologies on the generation, transmission and distribution side which will be able to modernize the grid for its optimal and efficient operation.

2.3.1 Pathways to overcome the challenges

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. [54]

The DSM consists of multiple methods which are capable of monitoring and controlling consumer loads, through the large diffusion of advanced metering infrastructures (AMI) such as smart meters and digital technologies, which will encourage the integration of renewable technologies.

The main mechanism of DSM is represented by energy efficiency measures (EE), behaviour-based energy conservation (EC) and demand response measures (DR) involving time-shifting of loads.

Energy efficiency and energy conservation actions have a limited contribution to the integration of renewables technologies and contribute mostly to reshape the load curve, through the shift in the use of energy efficiency appliances or through a behavioural change during a period of low renewable output.

On the other hand, demand-response refers to the reduction or shift of electricity consumption from consumers, in response to a signal sent by the system operator. [55]

Three forms of DR are considered applicable to the NEM situation and can ease the integration of renewable energy systems: Direct load Control (DLC), Dispatchable Loads (DL) and Non-dispatchable Real Time Pricing based DR (RTP). [54]

DLC involves the system operator exercising direct control over certain types of loads, such as air conditioning, heating water or swimming pool systems. This method requires the installation of smart control devices, but it can bring extensive advantages to renewables integrations, as it can shut down or shift a load whenever there is a low renewable energy production. [54]

On the other hand, dispatchable loads is a market-based DR method based on either bids from loads purchased by the system operator to decrease their electricity consumption, or bids from loads to sell their electricity consumption to the market. Both these mechanisms offer a solution to match renewable energy output with the loads, resulting in increased consumption during high production of renewable energy and the decreased consumption during low production. [54]

RTP involves the response of consumers to the time variation in electricity prices. This electricity price structure necessitates the implementation of advanced meter infrastructure, which is beneficial for the integration of renewables, matching their production with the demand. This method could be suitable for households with a storage battery system which is capable of charging the electricity produced from rooftop-PV during moments of low electricity prices and discharging the electricity during high electricity price periods, thus avoiding the increase in the electricity price.

However, this mechanism would require a coordinated approach to avoid system instability caused by the unpredicted behaviour of multiple customers turning on or off their loads. [54]

On the generation side, there is a need for the implementation of flexible energy technologies to tackle the variable and uncertain output from the integration of multiple renewable energy plants. 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 on the electricity demand side.

While wind and solar power generation is not dispatchable due to the output variability which is dependent on weather conditions, the future development of new peaking gas-fired plants and utility-scale electricity storage systems will provide high flexibility in the electricity system, being able to rapidly generate electricity matching the peak demand. [49]

Moreover, the Australian Government is investing in the economic and technical feasibility of renewable-based FCAS through both utility-scale renewable plants such as wind farms and utility-scale battery storage, and distributed energy sources (DER) such as rooftop-PV with battery storage systems. This is to ensure grid stabilization with the upcoming retirement of multiple coal power plants, which have traditionally provided ancillary services. [50]

The new entry of solar and wind power plants will also require new changes on the Australian electricity grid. As wind and solar sources are often located far from the load centres, this will necessitate the creation of new transmission infrastructure. Moreover, due to the variability of these resources, as the renewable energy generation will become more prevalent in the Australian electricity system new interconnectors will be needed to facilitate the transmission of variable renewable electricity output between different region, e.g. exporting the electricity generated from wind in South Australia or the electricity generated from solar in Queensland to other regions. [52]

A new pathway will also be undertaken on the market side, with a new rule which will establish the new wholesale electricity settlement price every 5 minutes, as opposed to the present 30 minutes settlement. The new price settlement time will commence its operation from July 2021 and will be possible due to the implementation of new metering and data communication technologies. Moreover, it will create multiple benefits such as the decrease in electricity prices and the facilitation of the transit towards a more renewable energy system. Various studies have proven that the 30 minutes settlement procedure, which has been described in paragraph 2.2.1, benefits big generators by allowing them to adjust their bidding price and output, creating scarcity in one of the six dispatch intervals. Consequently, this increases the electricity price in that interval, with an overall high price in the settlement, which in turn maximizes their profits. [56]

The five minutes settlement instead will encourage the new entry of variable renewable energy systems combined with the development of fast response technologies, such as batteries. This will allow a more accurate price signal and more efficient generation and consumption of electricity, thus facilitating the investments for the transition towards a more renewable energy generation mix. [56] [57]

Chapter 3

Methodology and State-of-the-art

Chapter 3 aims to describe the methodology utilised for the modelling of the 2030 Australian Electricity Mix, introducing the tool EnergyPlan. The rest of this chapter is dedicated to the State-of-the-art review, which presents relevant works performed by other authors related to the topic of this thesis.

3.1 Methodology

Nowadays, it is extremely important to simplify existing energy systems through the creation of models. These are needed in order to analyse and provide alternatives to improve the existing systems. For instance, energy models can play a significant role in the transition towards systems with a higher penetration of renewable energy which will substitute the traditional power plants.

The creation of models is developed with the help of energy tools, consisting of software which can perform the analysis of energy models. Currently there are several energy tools available, specialized for different aims.

However, the EnergyPlan tool has been deemed suitable for the purpose of this thesis due to its ability to simulate the yearly operation of an energy system, from both a technical and economic perspective, analysing each different energy technology and providing an accurate hourly energy balance during the year of study.

In the following sections a more detailed description of the tool and its structure has been presented.

3.1.1 Energy Plan tool

The modelling of the 2030 Electricity Mix in Australia has been developed with the use of the EnergyPlan tool. This software was created in 1999 by Henrik Lund and constantly developed, by the research developers at Aalborg University in Denmark [58]. For the purpose of this work the latest version (14th) available was utilized. EnergyPlan has the advantage of being a freeware user-friendly tool designed in a series of tab sheets and based on an analytical programming in Delphi Pascal, which makes the calculations very quick, rendering it an ideal tool to model complex energy systems. [58]

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. However, this tool has been used for both larger and smaller scale objectives, such as European and local municipalities levels. [59]

EnergyPlan is classified as a simulation tool, due to its capability to model a variety of solutions that can be compared to each other, rather than an optimization tool which is able to model "the optimum solution". [60]

The purpose of this software is to model future energy systems, due to this reason it includes detailed future technologies such as renewable sources or synthetic fuels, and approximate modelling of traditional energy sources, for instance thermal power plants.

It emphasizes the interactions between various energy forms such as electricity, gas, district heating and cooling grids, which are likely to happen in future energy systems. For instance, the electricity supplied by renewable energy systems can be converted into other energy forms as heat, hydrogen, synthetic gas and biofuels. [61]

The schematic of EnergyPlan is presented by Figure 3.1, which highlights the capability of the software to simulate a future interconnected energy system.

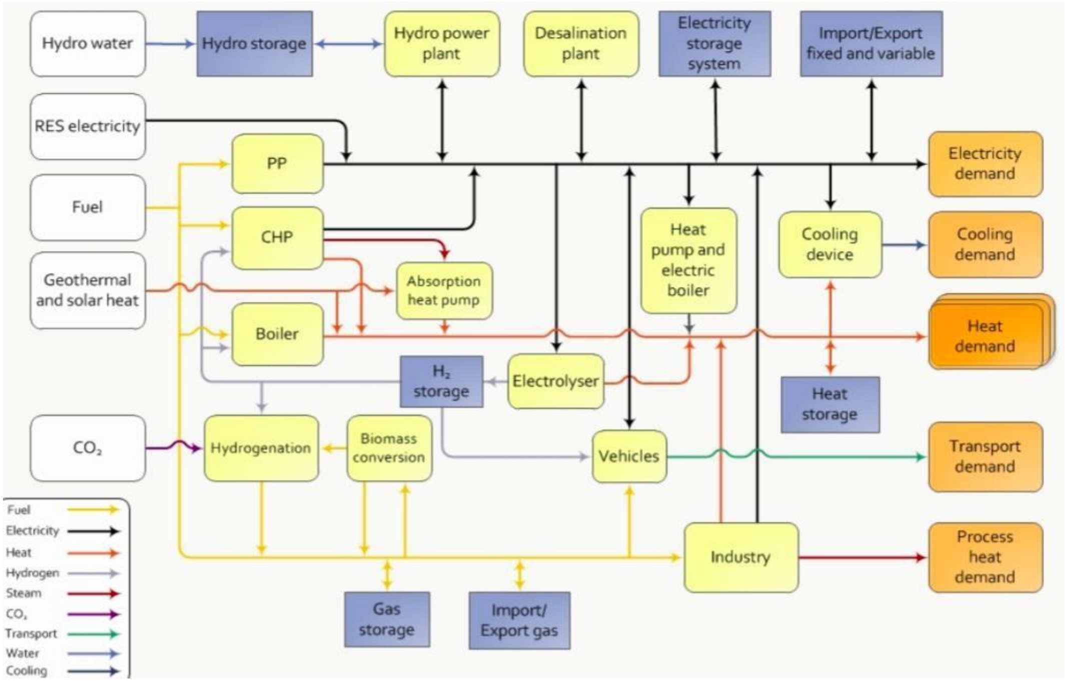


Figure 3.1: EnergyPlan model schematic [62]

3.1.2 Model overview

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 [63].

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. Moreover, the user can combine multiple simulations of individual years, in order to analyse more extensive scenarios. [59]

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, CO_2 emissions and total costs. [58]

The demand is divided in multiple inputs which must be provided on a yearly basis. However, the only inputs required relates to the objective of the work; for instance if the model to be analysed concerns only the power sector, the heat and transportation demand will be neglected. Moreover, 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). [62]

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 (which consist of dam hydro stations and thermal power plants) must be provided into EnergyPlan. [62]

On the other hand, the variable energy sources (in particular, renewable energy systems of a fluctuating nature) require as input a distribution file of 8784 values in txt format, similar to the demand input described previously, specifying the hourly production by each source along the year.
The storage option allows the user to choose the type of energy storage used in the model, specifying the capacity and the volume of the system. [62]

Moreover, nine regulation strategies are provided by EnergyPlan to control the Critical Excess of Electricity Production (CEEP), in order to monitor the surplus of energy generated, which exceeds the aggregate sum of the demand, the energy storage and the interstate transmission capacity.
These nine different regulating options, which can be applied in varying combinations, are:

- 1: Reducing wind (RES1) and photovoltaic (RES2) energy
- 2: Reducing cogeneration production in group 2 (Replacing with boiler)
- 3: Reducing cogeneration production in group 3 (Replacing with boiler)
- 4: Replacing boiler production with electric heating in group 2.
- 5: Replacing boiler production with electric heating in group 3.
- 6: Reducing run of river (RES3) and off-shore wind (RES4) energy
- 7: Reducing thermal power plant production in combination with RES1, RES2, RES3 and RES4
- 8: Increasing CO2 Hydrogenation (See Tab sheet Synthetic Fuel) if available capacity
- 9: Part-loading nuclear (specify partload option in Electricity Only tabsheet) [62]

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.
Unlike the technical simulation, 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. [62]

At last, the output results obtained from the tool have the option to either be displayed on the software screen, be printed in A4 version or be exported in an excel sheet. Furthermore, the outcomes expressed as energy balances can also be visualized by the user in a graphic option, with the choice of respectively a daily, weekly, monthly or yearly time frame. [62]
Figure 3.2 provides a clear overview of the EnergyPlan model.

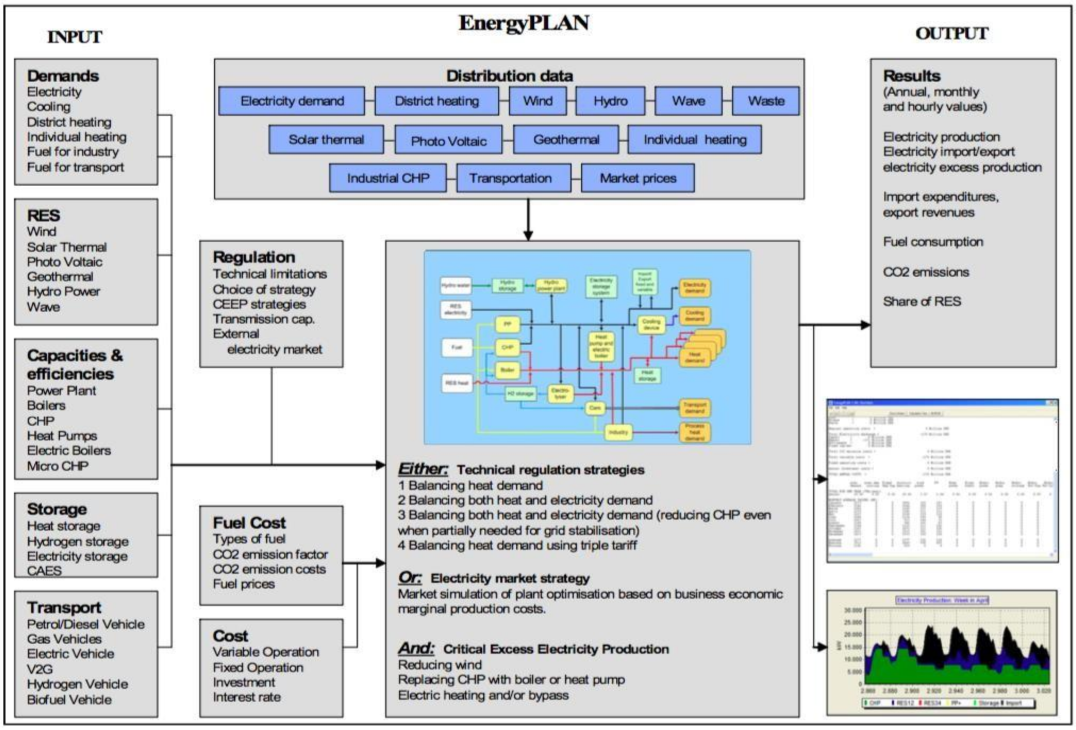


Figure 3.2: EnergyPlan model overview [64]

3.2 State-of-the-Art

Currently, a significant number of research papers regarding future energy planning with a high renewable energy penetration have been implemented through the EnergyPlan Software.

This tool has already been utilised mostly for future national energy plans, e.g. in Austria, Belgium, Croatia, Czech Republic, Denmark, Finland, France, Germany, Greece, Hong Kong, Ireland, and Italy. However, EnergyPlan has also been applied for smaller scale modelling – two examples are the study of “Energy self-sufficient neighbourhoods in the Netherlands” [65] and the study of “A 100% Renewable Energy for Aalborg” [66]. Moreover, EnerglyPlan has also been utilised for continent level modelling such as the study regarding the entire European Union, “Smart Energy Europe: A 100% Renewable Energy Scenario for the EU28” [67]. Further studies regarding other countries and municipalities can be find on [68].

EnergyPlan has been used for multiple purposes due to the vast options that the software offers. Several models have been developed to obtain a 100% Renewable Energy System, e.g. Cosic et al. developed a study to achieve 100% Renewable system in Macedonia by 2050 [69], the Danish Society of Engineers, IDA, regarding “A smart Energy System Strategy for 100% renewable Denmark” [70], and the model for “Zero Carbon energy system in South East Europe in 2050” [71]. These works have the ambition to create a future energy system in which all different energy sectors (electricity, heat and transport) are integrated together.

Other research papers focused on the penetration of a specific technology in the future energy system. For instance, Marczinkowski and Østergaard explored the potential of investing in battery energy storage systems and thermal energy storage systems to allow a better integration of renewable energy sources in the energy supply mix in Samsø and Orkney islands [72]. Lund in [73], analysed the short and long-term potentials of the integration of wind power in different energy systems, evaluating different regulation strategies considering a wind power from 0% to 100% of the total electricity demand.
Another research undertaken by Aalborg University investigated the role of Solar thermal in the future energy mix of four countries: Germany, Austria, Italy and Denmark. It concluded that despite high socio-economic costs, solar thermal will be competing with other technologies in a system with high penetration of renewables and its integration will have the potential of contributing around 3-12% of heat production. [74]

Furthermore, many scientific research papers [74-81] and reports [81,82] have been published regarding the investigation of different aspects of the future electricity system in Australia. Presented below are the most relevant works:

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 shows a high potential, which is mostly limited by resource constraints. [75]

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 (year of the publishing), using the optimisation energy tool Markal. 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 side 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 R & D support for clean energy technologies in the future. [76]

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 energy generated in 2020 produced by renewables. In order to achieve this target, this study explores the possibility to install an additional power capacity of 2235 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. [77]

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 time-frame 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. [78]

Nunes et al. focus 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 depicts also the importance of the complementarity of photovoltaic and wind systems, for the optimum investments in renewable projects. [79]

Elliston et al. investigates the possibility to shift 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 include 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. [80]

Lanzen et al. aimes to simulate a low-carbon electricity supply for the entire territory of Australia. The paper explores how to achieve a 100% renewable electricity mix through the utilization of operating and commercialized technologies. A first investigation is 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 concludes 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. [81]

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. [82]

The 2013 AEMO report aims to achieve 100% renewable energy, focusing only on the electricity sector and it considers two different scenarios for both 2030 and 2050. The first scenario assumes a quick technology transformation, and a moderate economic growth, while the second scenario assumes a high economic growth and a slow technology transformation. The results obtained suggest that Australia will have a diverse range of resources, without having a specific technology which will dominate the future energy mix. However, bioenergy will play a significant role in all four scenarios, which could present future challenges in terms of collecting and processing the needed fuel. In order to achieve a 100% renewable system, it will require greater capacity to be installed than the one needed by traditional thermal plants, approximately more than twice the maximum power demand capacity. This emerges from the higher deployment of intermittent sources (e.g. PV, wind, wave) which operate at lower capacity factors compared to the other technologies in the predicted energy mix. [83]

Alike the previous works, The Institute for Sustainable Futures (ISF) developed an analysis for the achievement of a 100% renewable energy system in Australia. This paper evaluates three different scenarios: a reference scenario based on government forecasts, a renewable scenario which focuses on the full renewable energy transition for only the power sector by 2030, and an advanced renewable scenario which considers a completely clean energy system by 2050. This work emphasizes how a full transition towards a renewable energy system is both technically and economically feasible, but requires the shift towards the management of wind and solar (which will represent the base-load generation) and dispatch power plants, such as storage technologies, concentrating solar power plants, dam hydro power stations and bio-energy plants. Nonetheless, the authors of this paper reiterate the importance of long-term energy policies to be able to realize this energy transition. [84]

Chapter 4

Reference Model and Calibration

Chapter 4 presents an overview of the creation of the reference model on EnergyPlan, describing in detail each section on the software utilised for the modelling. Moreover, its calibration has been analysed in detail under this section. These steps are extremely important for the purpose of creating a model capable of simulating a reliable forecast for 2030.

4.1 Reference model: Australia 2018

In order to obtain a reliable output from the 2030 Energy Plan simulation, the energy system from a reference year needs to be validated, comparing real data from that year with the results obtained through the algorithms applied by the software.

This process is extremely important as 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. Therefore, the reference system to be modelled needs to be able to represent correctly the energy situation of the country and if this does not occur, a further calibration is necessary to approximate the values in order to avoid considerable mistakes during the forecasting of future energy scenarios. 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.

Moreover, it is preferable to collect the reference data from a recent year, to have a reliable starting point for the model of the future energy system.

The chosen reference year was 2018, which had all the detailed and necessary hourly energy data regarding the Australian electricity situation readily available by the Australian Electricity Market Operator (AEMO).

Whilst the achievement of an energy system with high penetration of renewables requires the integration of the three energy sectors (electricity, heat and transport), the purpose of this work is limited to the study of only the electricity sector. This choice was made in accordance to the actual Australian electricity situation, which has always been predominantly ruled by coal power plants. The fast development of renewable projects, especially photovoltaics and wind farms, has evoked in me the interest of further investigating how the electricity mix is likely to change in 2030. Furthermore, the heating sector has been neglected from the aim of this thesis as there are low heating needs in Australia due to weather circumstances. Nevertheless, EnergyPlan has a detailed section for its model on heating, given the software was developed in Denmark and it is important to have an efficient heating sector for reducing fossil fuel consumption.

The last key points concern the structure of the Australian grid.

Being an island, this country does not have any interconnection transmission capacity – in other words, Australia lacks the capacity to import/export any electricity from/to other countries.

Moreover, as mentioned in the 2nd Chapter, the National Electricity Market (NEM) excludes 2 out of the 7 states in the country: Western Australia and Northern Territory, which have their own grid and power suppliers. Due to this reason, these two states have been avoided from the Australian electricity model analysed in this study.

The following sections examine the principal inputs assumed for the creation of the reference model: Electricity Demand, Thermal Power Plants, Renewable Energy, Electricity Storage and Regulation and Balancing Strategies. Lastly, the calibration of the reference model has been verified.

4.1.1 Electricity demand

The energy demand inputs required by EnergyPlan concern the yearly electricity consumption and the hourly electricity demand. All the other demand inputs in the software regarding the heating/cooling and transportation demand have been neglected as it extends beyond the scope of this thesis.

The data regarding the hourly electricity demand for the entire year of 2018 in Australia was available from AEMO. It provides the historical data regarding the electricity demand every 30 minutes cumulated per month, for each state belonging to the NEM: Queensland, New South Wales, Victoria, Tasmania and South Australia. [85]

Consequently, the average hourly electricity demand was calculated, aggregating each state demand for the entire year of 2018 and creating only one distribution file to represent the total Australian demand, as shown in figure 4.1.

This file is composed of 8784 values as EnergyPlan operates on a leap year, and due to this reason the last 24 values of each file have been repeated to guarantee the proper size of the file.

The total electricity consumption in 2018 corresponds to a total of 191.89 TWh.

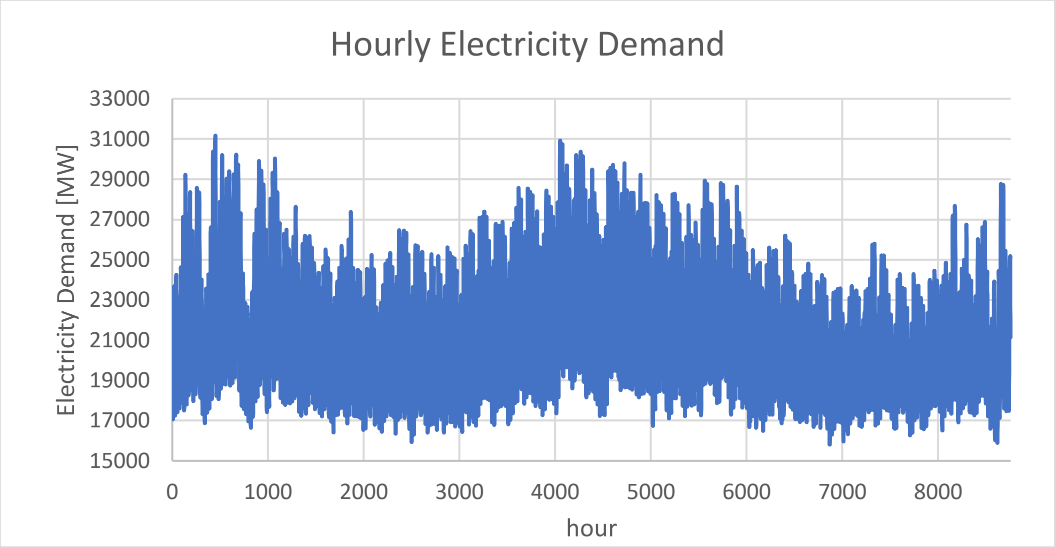


Figure 4.1: Australian electricity demand by hour during 2018

4.1.2 Thermal power plants

As described in the second chapter, Australia remains highly dependent on thermal power plants, particularly on coal stations. For instance, more than 75% of the total electricity generation in 2018 was attributed to coal.

Currently, Australia has an installed capacity of 26,006 MW condensing power plants operating on coal. These types of plants have a continuous utilization due to their low operation costs, but have a very low load flexibility and are generally used for base load consumption. On the other hand, in 2018 Australia counted an installed capacity of over 11 000 MW between OCGT (Open Cycle Gas Turbines), CCGT

(Close Cycle Gas Turbine) and compression reciprocating engines, operating on natural gas and oil. Moreover, biomass also contributes to thermal electricity production, but this generation only accounts for power plants which are limited to industrial consumption. Therefore, these plants do not participate in the central electricity dispatch since their production is utilized locally by industrial consumers.
Table 4.1 represents an overview of the total capacity installed and energy generated in 2018 by each fuel and is available from AEMO archive data documents, which provided the supply generation every five minute from each power station for the entire 2018 [86] [87]. Despite a high flexibility of gas and oil stations consisting mostly of CCGT and OCGT, these thermal plants have greater marginal costs compared to coal power plants, reflecting in a lower utilization rate. Therefore, the yearly energy generated by coal stations is remarkably the highest compared to the other fuels.

Table 4.1: Installed capacity and energy generated by thermal power plants

Thermal Power Plants

Fuel:	**Coal**	**Natural Gas**	**Oil**	**Biomass**
Capacity Installed [MW]	23006	10096	1199	98
Energy Generated [TWh]	146.30	12.31	1.06	0.19

As previously mentioned, EnergyPlan is a software focused on future renewable energy systems and due to this reason its modelling of fossil fuel energy plants is not very detailed.
Regarding the modelling of thermal power stations, it offers to model the system with two condensing mode operation options: PP1 and PP2 – in both cases the only information required are regarding the total capacity installed and the efficiency. The main difference between these two options is that PP1 is prioritized in the energy balance over PP2. Due to this reason, it was decided to model all the capacity related to coal power plants as PP1, as these types of plants are used for the base load and have a continuous operation in the real Australian energy system. All the capacity belonging to oil and natural gas, (OCGT and CCGT and compression reciprocating engine) were instead modelled under the PP2 option. Moreover, thanks to this distinction between the two types of thermal plants, it was possible to insert a different efficiency value for PP1 and PP2. An efficiency of 33% was allocated for the coal power plants, whilst a higher efficiency of 42% was used for PP2. These values have been sourced from the average of the actual efficiency for these types of plants available in [88]. Despite this differentiation, the software is not able to include any consideration regarding a higher flexibility of OCGT and CCGT plants, which are often utilized during peak demand periods, over coal power plants. Given these reasons, for the calibration of the model it was decided to ensure the total energy generated by thermal fossil fuel power plants would match the real Australian value.

The industrial electricity production, related to biomass use, was instead inputted in a separate section available in the software dedicated to Industrial Cogeneration Power Plants. This section requires the total energy generated in the entire year and has the option to model three different groups:

- Group 1 is dedicated to plants which operate only for heat production.
- Group 2 is dedicated to plants which can operate only in cogeneration mode (heat and electricity production).
- Group 3 is dedicated to plants which can work also in a “traditional” way, operating only for electricity production.

Consequently, the total 2018 electricity generation from biomass was inputted under Group 3, for a total of 185 GWh.

4.1.3 Renewable energy

Four renewable energy sources for electricity production have been implemented in the reference model: wind, solar photovoltaic, run of river hydro and dam hydro. For all these sources, the software requires the installed power capacity and a distribution file collecting the hourly loading factor, regarding a leap year: 8,784 values (the last 24 values have been repeated to ensure the proper size of the file). The loading factor consists of the instant power divided by the installed power capacity of the considered technology. Moreover, the user can define for only the fluctuating renewable sources (excluding dam hydro) a stabilization share and a correction factor. The stabilisation share involves choosing a percentage of the total capacity installed which will be used for grid stabilization purposes. A correction factor is capable of changing the hourly distribution generation according to new technology evaluations, which is able to enhance the overall conversion efficiency of the source considered. An example of the correction factor for wind energy is shown in figure 4.2.

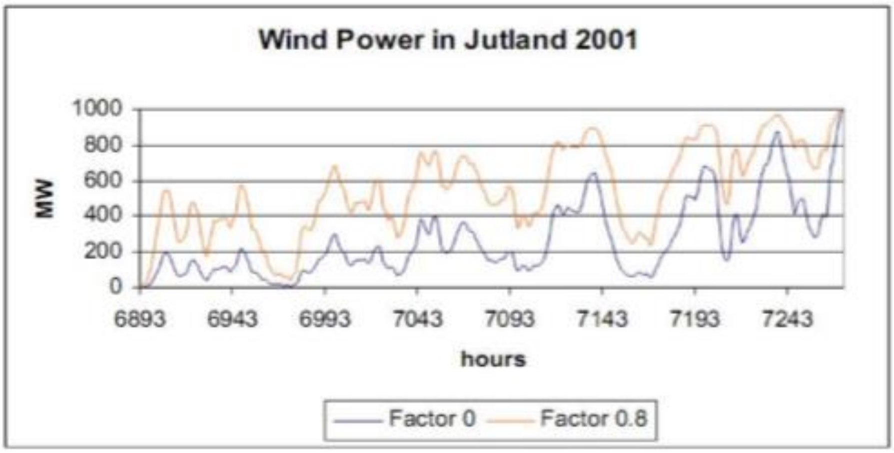
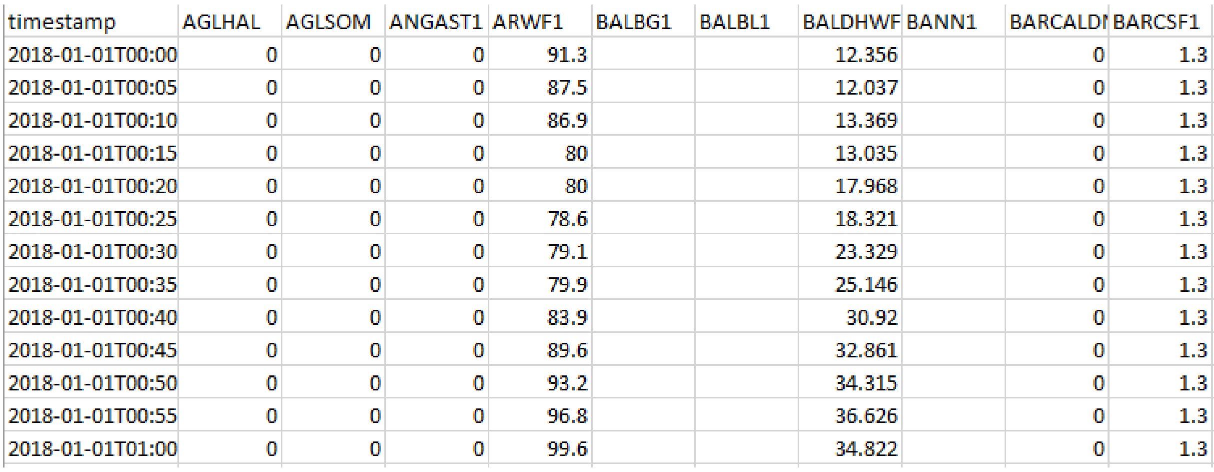


Figure 4.2: Correction factor for wind energy [62]

These last two inputs have been neglected during the implementation of the reference model as renewable sources in the NEM currently do not have grid stabilization properties and the introduction of the correction factor would be out of the scope of the reference model.

The data regarding the hourly power production by each renewable source throughout 2018 in Australia was available from AEMO [86] in a row form, with the power production of each individual power plant (renewable and not) mentioned in the form of DUID – Data Unit Identifier, which is registered every five minutes for the entire year, as shown by figure 4.3. Following, it was necessary to first identify the typology of each power plant (expressed in the form of DUID) from the file with all the registered participants in the National Electricity Market [87], then aggregate all the data belonging to the same energy source, and then calculate the average hourly power produced for the entire year of 2018.



timestamp	AGLHAL	AGLSOM	ANGAST1	ARWF1	BALBG1	BALBL1	BALDHWF	BANN1	BARCALD	BARCSF1
2018-01-01T00:00	0	0	0	91.3			12.356		0	1.3
2018-01-01T00:05	0	0	0	87.5			12.037		0	1.3
2018-01-01T00:10	0	0	0	86.9			13.369		0	1.3
2018-01-01T00:15	0	0	0	80			13.035		0	1.3
2018-01-01T00:20	0	0	0	80			17.968		0	1.3
2018-01-01T00:25	0	0	0	78.6			18.321		0	1.3
2018-01-01T00:30	0	0	0	79.1			23.329		0	1.3
2018-01-01T00:35	0	0	0	79.9			25.146		0	1.3
2018-01-01T00:40	0	0	0	83.9			30.92		0	1.3
2018-01-01T00:45	0	0	0	89.6			32.861		0	1.3
2018-01-01T00:50	0	0	0	93.2			34.315		0	1.3
2018-01-01T00:55	0	0	0	96.8			36.626		0	1.3
2018-01-01T01:00	0	0	0	99.6			34.822		0	1.3

Figure 4.3: Extract of the electricity supplied by each registered participant in the NEM [86]

The following sections will describe the assumptions considered in order to model each renewable source.

Wind

Drawing from [86] (Electricity Supplied file), it was possible to define the hourly power production by wind technology during 2018 in Australia, as shown in figure 4.4.

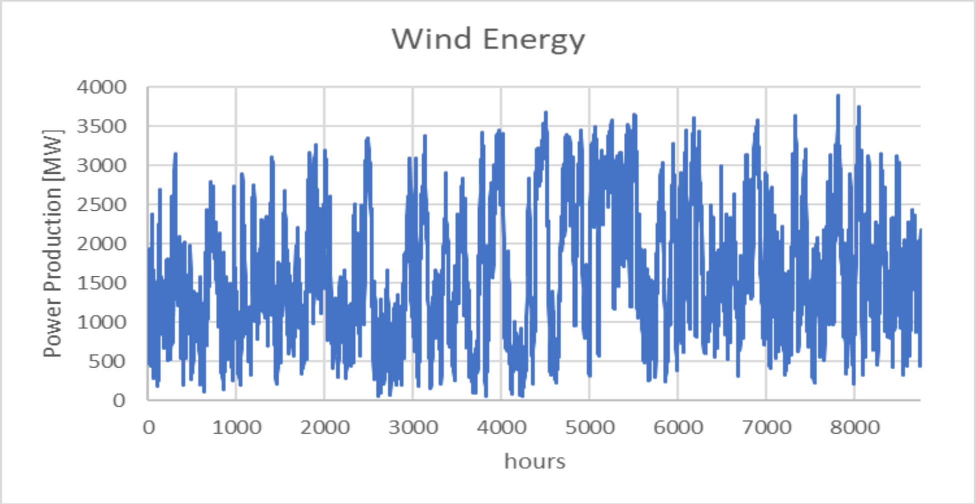


Figure 4.4: Hourly Power production from Wind Energy

However, from the figure above, it is noticeable that the power production increases throughout the year. This event is not due to weather phenomena, but instead due to the installation of new wind farms during 2018.

Owing to the Registered Participants in the NEM file, it was possible to define the total capacity at the beginning of 2018 and the total capacity at the end of 2018, which were 4,165 MW and 5,049 MW respectively. In order to implement the distribution file of the loading factors so that it is valid for future Australian Scenarios, it was necessary to evaluate the hourly loading factors. This has been calculated as the instant power produced by wind energy divided by the total capacity installed at that hour of the year. This operation was possible as [86] provides information regarding the starting operation date for each new wind farm throughout all of 2018. The final hourly distribution for the wind load factors is demonstrated in figure 4.5.

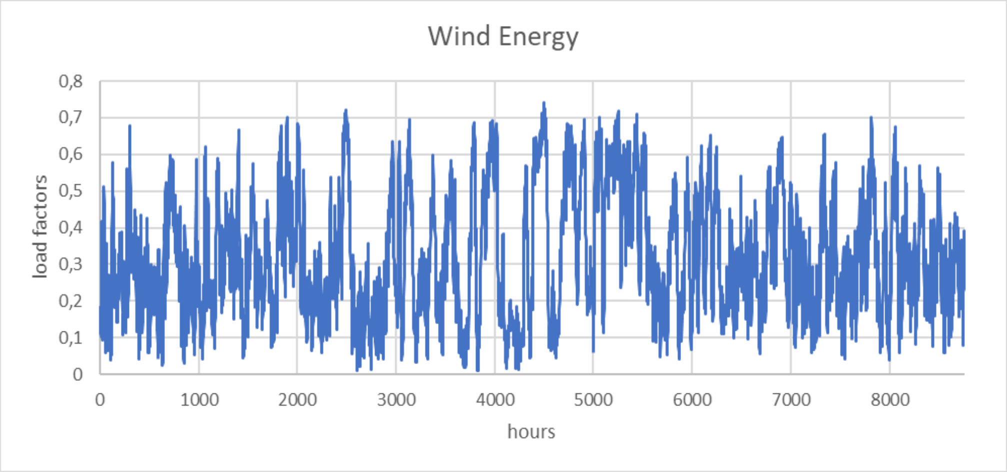


Figure 4.5: Hourly distribution for the wind loading factors

4,607 MW was inputted as the installed capacity; this value was calculated as the average between the installed capacity at the beginning and at the end of 2018.

Photovoltaic

Australia faced a remarkable capacity installation of solar farms throughout 2018, going from 363 to 1,933 MW, which reflects a consistent increase of power generation, as shown by figure 4.6. However, it is relevant to underline that all the Solar PV capacity regarding the residential sector was not considered in the modelling of the reference year, due to lack of data regarding their hourly power distribution.

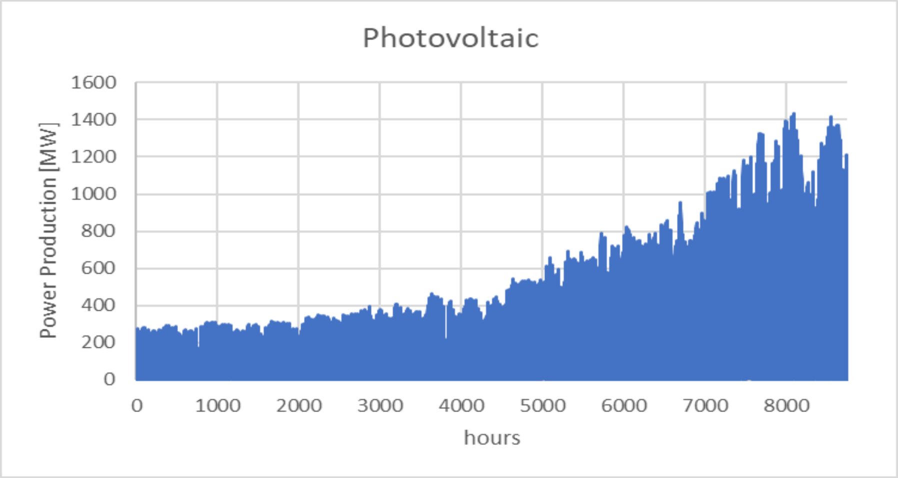


Figure 4.6: Hourly Power production from photovoltaic energy

In order to create a reliable hourly distribution file of the photovoltaic loading factors for the reference model, the same approach utilised for wind energy was applied. Figure 4.7 below, highlights the capability of photovoltaic systems to have higher loading factors during the summer months (November, December and January).

The installed capacity of photovoltaic inputted in EnergyPlan is equal to 1,148 MW, which represents the average between the installed capacity at the beginning and at the end of 2018.

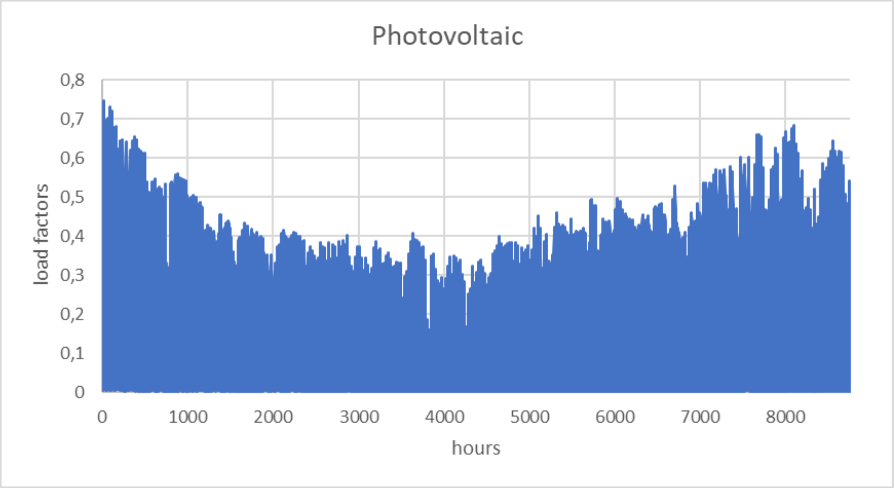


Figure 4.7: Hourly distribution for the photovoltaic loading factors

Run-of-river

This section in EnergyPlan is dedicated to the hydro generator plants with no water storage provided, where the electricity is generated directly from the river flow. These stations operate as variable energy sources, as their electricity production is dependent on weather conditions. Currently Australia has a total run-of-river installed capacity of only 154 MW, which belongs to six hydro stations operating in the Queensland state [86]. As such, Australia remains minimally dependent on this energy source, which accounts for approximately 0.3% of the national installed power capacity.

As there were no new installations of run-of-river hydro plants during 2018, the hourly distribution file of the loading factors was created by dividing each hourly power generation by the total installed capacity. Figure 4.8 depicts how this power production is heavily dependent on the rainy season in the Queensland territory, which occur during Summer (from December to April) [89] .

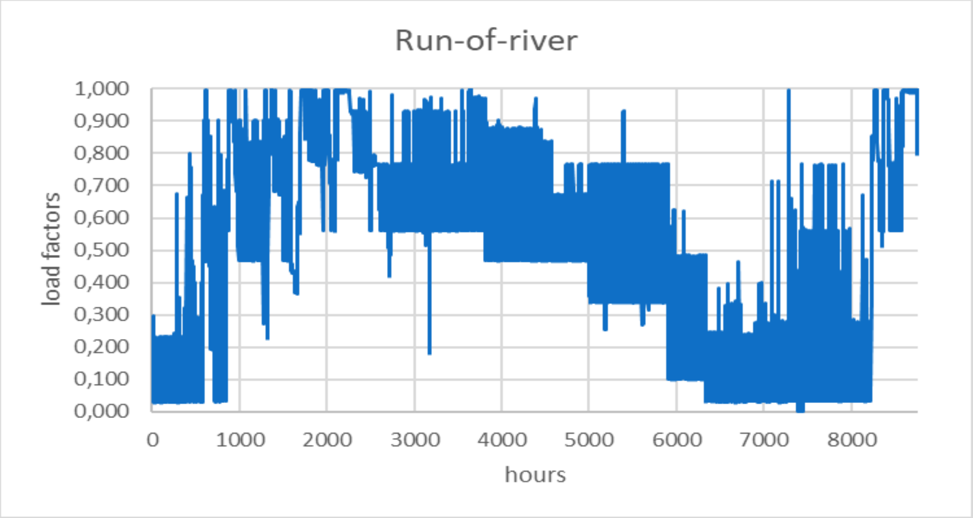


Figure 4.8: Hourly distribution for the run-of-river loading factors

Dam hydro

Dam hydro power stations are capable of storing water in the reservoir created through the dam, thereby having the ability to control their electricity production.

The modelling of this technology in EnergyPlan differs from the fluctuating renewable sources; in addition to the total power capacity installed, it requires the yearly water supply to the reservoirs, the hourly water supply distribution, the efficiency of the turbines and the total storage capacity of the reservoirs in GWh.

The total dam hydro power capacity was obtained from the NEM Registered Participants file [87] , counting 37 hydro stations for a total of 7867 MW capacity. Furthermore, a turbine efficiency of 90% was assumed as indicated by the Australian Hydroelectricity Factsheet [90].

The total storage capacity has been obtained as the sum of each reservoir capacity. Unfortunately, other than the capacity regarding the reservoirs in Tasmania which equal to 4575 GWh (which was already provided in an energy unit [91]), the capacities for all the other stations have been estimated using the formula below. The volume of the reservoir V, the density of the water ρ, the gravity acceleration g and the height of the reservoir h, have been sourced from [92].

$$\mathrm{Ereservoir} = \frac{V \times \rho \times g \times h}{3600} \times 10^{-9} \ [\mathrm{GWh}]$$

The total energy storage capacity obtained was 6973 GWh.

Due to the unavailability of information regarding the yearly water supply, this value was estimated as the total electricity generated in 2018 (15.61 TWh), which was calculated from the AEMO electricity supply file [86], divided by the turbine efficiency. The resulting value of the yearly water supply was 17.33 TWh. Furthermore, the distribution file of the hourly water supply required by EnergyPlan was approximated by dividing the hourly electricity generated by the efficiency, then normalizing the values between 0 and 1. This last step is due to the software requirement of a file with normalized values between 0 and 1. Figure 4.9 reports the hourly electricity generated by dam hydro power stations throughout 2018.

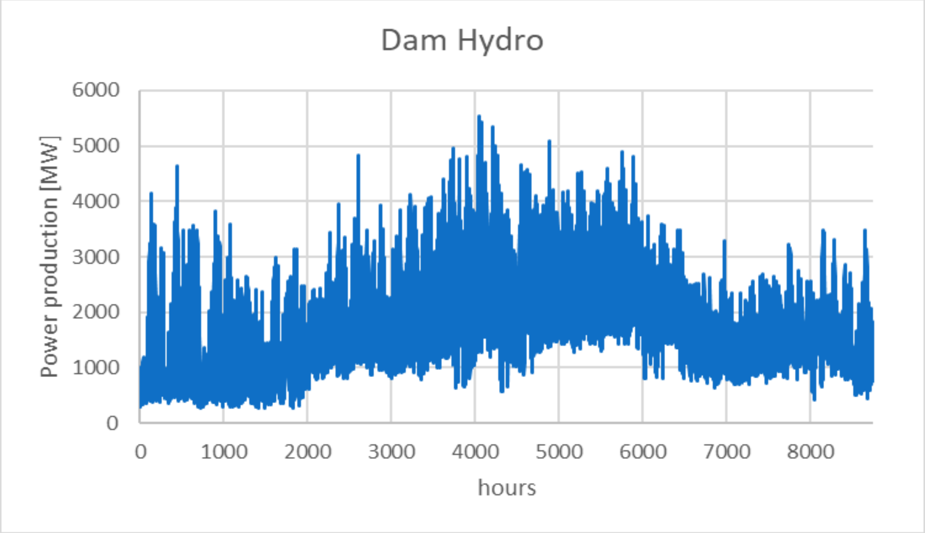


Figure 4.9: Hourly power production by dam hydro power plant

Furthermore, it is important to specify that hydro production is fairly constant in Australia, without having a significant variation year by year. Referring to the statistics available from the International Energy Agency (IEA), the water supply is relatively steady over the years with a maximum variation of 10%, which reflects a variability of approximately 1% of the total energy produced. This illustrates the modest influence of the water supply variability on the final electricity mix. [93]

Therefore, the hourly distribution files implemented for the reference model, regarding both run-of-river and dam hydro sources, are also considered reliable for the implementation of future scenarios, without the need of differentiating between dry, wet or normal year.

4.1.4 Electricity storage

Energy Plan has two different options to model electricity storage systems, one refers to a pure reversibility cycle and the other corresponds to pump-back capacity in a river flow dam.

The first type can be applied to model different kinds of storage systems, including batteries and pump-hydro reservoirs systems. It consists of a closed cycle, which can be described as two reservoirs at different heights. The software requires as input, the charge and discharge capacity and efficiencies (pump and turbine capacity in the case of a pump-hydro system) and the total energy storage capacity. Currently, Australia has a total of six large scale “pure reversibility cycle” energy storage systems, which are a combination of pump-hydro systems and battery storage, with a total of 5.92 GWh storage capacity, 651 MW of charge capacity and 691 MW discharge capacity, as depicted in table 4.2. This value will soon increase due to the vast amount of projects presently under commission. The efficiencies considered are respectively 90% for the discharge and 85% for the charge, obtained from averaging the batteries and pump-hydro systems efficiencies [88].

Table 4.2: “Pure reversible cycle” energy storage systems

Station Name:	**Technology**	**Charge Capacity [MW]**	**Discharge Capacity [MW]**
Wivenhoe Power Station	Hydro-pump Storage	240.0	250.0
Wivenhoe Power Station	Hydro-pump Storage	240.0	250.0
Ballarat Battery Energy Storage System	Battery storage	30.0	30.0
Gannawarra Energy Storage System	Battery storage	30.9	30.9
Dalrymple North Battery Energy Storage System	Battery storage	30.0	30.0
Hornsdale Power Reserve	Battery storage	80.0	102.4

Pump-back storage systems instead are capable of pumping back the energy into the river flow, which is connected to the reservoir. The input required by the software is the pump capacity plus its efficiency. At present in Australia, there is only one operating pump-back storage system which is Tumut 3 Hydro Pumps, which has the installed capacity of 600 MW and an efficiency of 75% [94].

4.1.5 Regulation and balancing strategies

The electricity grid is always required to be balanced, through the electricity demand constantly matching the electricity generation. This aim can be achieved through stabilization services provided by part of the electricity generation sources, which are identified by EnergyPlan as thermal and dam hydro power plants (excluding industrial thermal plants) [62]. These sources have the advantage of being controlled and regulated for any grid and demand purpose, thus capable of being adjusted with a relatively fast response.

The software requires as input the minimum grid stabilization share (MGSS), which guarantees during each moment of the year an assured minimum percentage of electricity supplied by dispatchable sources (thermal and dam hydro plants) that can contribute to grid stabilization. As per the EnergyPlan developers’ advice, a MGSS of 30% is considered reasonable for most countries.

This value was negligible for the model of the reference year. Drawing from [86], it was calculated that the electricity production share from dispatchable sources during any hour in 2018 never fell below 75% of the total power generated. This value reflects the actual Australian electricity scheme, where the energy generation from variable renewables never exceeded 25% of the power produced. However, a

MGSS of 30% was still adopted for the 2030 scenarios simulations due to the projected development of wind and solar technologies together with the retirement of coal power plants.

Furthermore, the software gives the option to insert the minimum Thermal Power Plant (PP) generation throughout the year, which referred to 12,480 MW from coal power plants in Australia in 2018. Thus, coal thermal plants are usually operated for base load supply, always maintaining a minimum level of electricity production. Halting and restarting the operation of these plants would induce high costs and long starting periods.

For the modelling of the 2018 Australian Electricity System there was no need of setting any CEEP Strategy, since there was no excess of electricity generation during 2018 due to the contained renewable energy production. However, for the implementation of the future scenarios, Strategy 7 (reducing thermal power plant production in combination with RES1, RES2, RES3 and RES4) was adopted which guarantees the minimum curtailment of renewable energy, ensuring always at least 30% of MGSS from dispatchable sources.

4.2 Calibration results

The calibration has the aim of validating the model created with Energy Plan, in order to guarantee that the software has the correct structure for the analysis of future scenarios.

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 [95]. The Economic simulation would indeed be needed to evaluate the optimum performance of the energy system from a business point of view.

Table 4.3 shows the results obtained and the comparison between each generation source, in order to validate the software calibration.

Table 4.3: Comparison between real data and EnergyPlan output

Electricity Generation in 2018			
	Real Data [TWh]	*Energy-Plan Output [TWh]*	*Variation*
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 Power Plants	159.67	160.07	0.3%
Sum	192.17	191.90	0.1%

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

The most significant mismatch of 4.26% is represented by wind energy, followed by 3.35% from photovoltaic systems. This difference in the final energy generated by these sources is related to the power capacity installed for these technologies.

As previously explained, the considered capacity installed 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.

On the other hand, all the other output comparisons reflected a variation of less than 1%, validating the model.

The final renewable energy share in Australia in 2018 corresponded to 16.83% of the total electricity generated, in accordance with the EnergyPlan output of 16.52%.

However, from the technical simulation of the reference model there was no energy storage consumption, in contrast to the actual energy storage consumption of 0.47 TWh. This EnergyPlan outcome is the consequence of the technical simulation algorithm applied by the software, which operates the energy storage systems only in cases of an abundancy of power production from variable sources which exceed the current demand. In a real system, the energy storage technologies are operated also during off-peak hours, storing the cheap electricity generated by base load plants and selling it later during peak periods to obtain an economic profit. Therefore, this reason explains the amount of storage consumption in Australia during 2018.

Therefore, for the implementation of the 2030 electricity mix scenarios in Australia, the economic simulation will also be applied in order to evaluate the most probable future energy storage consumption in a real case scenario, where each supplier tries to maximize their profit.

Chapter 5

Australian 2030 Scenarios

Chapter 5 aims to evaluate the electricity projections in Australia by 2030, in order to have all the necessary inputs for the modelling of the 2030 Australian electricity mix through the EnergyPlan software. It analyses three potential electricity demand growths, as well as three different generation supply Scenarios.

5.1 Scenarios forecast

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) website, 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. These electricity demands have been implemented to model a sensitivity analysis for each supply scenario.

The three generation supply scenarios which will be described in detail in the following paragraphs, are:

1. The ESOO (Electricity Statement Of Opportunities) – low RES scenario, which describes the changes which will occur due to the committed opening of power plants and retirement of power plants. [96]
2. The ISP (Integrated System Plan) – high RES scenario, which refers to a longer-term vision, forecasting the shift towards a situation in which the renewables energy resources would reach a deeper penetration. [97]
3. The ISP – high RES with Storage scenario, which has the same purpose as the ISP, but further includes the Snowy 2.0 hydro pump storage facility. [97]

5.2 2030 Electricity demand

The Australian population is projected to grow at a yearly rate of 1% - 1.3%, in parallel with an increase use of electrical appliances in the residential sector and a higher need of heating and cooling, manufacturing capacity and computer hardware in the business sector. This reflects a strong correlation between economic and demographic growth with the electricity consumption. [96]

Nevertheless, the higher dependency on electricity does not necessarily translate in a higher grid consumption, given the projected substantial diffusion of rooftop PV and improvements on energy efficiency.

As mentioned in the paragraph above, the plausible economic growth paths in Australia until 2030 define three potential electricity demand growths: neutral, slow and fast.

The neutral growth follows a stable economic evolution, with a moderate spread of distributed energy resources, such as rooftop PVs and distributed batteries. This projection faces a slow electricity consumption rise of approximately 1.3% each year for the next 20 years.

On the other hand, the slow path faces reduced economic investments, which result in a lower electric grid consumption compared to the neutral demand.

Alternatively, the fast growth is distinguished by a strong rise in individual household incomes and a robust economic situation, which leads to a higher electricity demand, supported by the implementation of new sustainable and low emission policies.

Ultimately, the main difference between the three demand projections manifests in the disparity of the diffusion of electric vehicles, whilst the diffusion of battery storage systems and rooftop PVs will follow the same growth. [96]

Table 4.1 highlights the main differences between the three different electricity demand Scenarios.

Table 5.1: changes regarding according to different electricity growing paths [96].

	Neutral Growth	**Slow Growth**	**Fast Growth**
Economic Growth & Population Outlook	Neutral	Weak	Strong
Rooftop & Non-scheduled PV	Neutral	Neutral	Neutral
Electric Vehicle uptake	Neutral	Weak	Strong
Battery Storage Installed Capacity	Neutral	Neutral	Neutral

The three electricity demands have been considered in two different contexts for the purpose of the 2030 simulations analysed in Chapter 6.

The first context classifies these as native consumptions by AEMO, as they refer to the national demand met by scheduled, semi-scheduled and non-scheduled generation delivered to the consumers by the electric grid (excluding the demand met by solar rooftop generation).

The scheduled generator has an aggregate capacity of 30 MW or more. The semi-scheduled generator has an intermittent output, as wind or solar sources, with a capacity of 30 MW or more. The non-scheduled generator has a capacity lower than 30 MW. [87] [98]

The different electricity native consumption trends are presented in the figure 4.1 below.

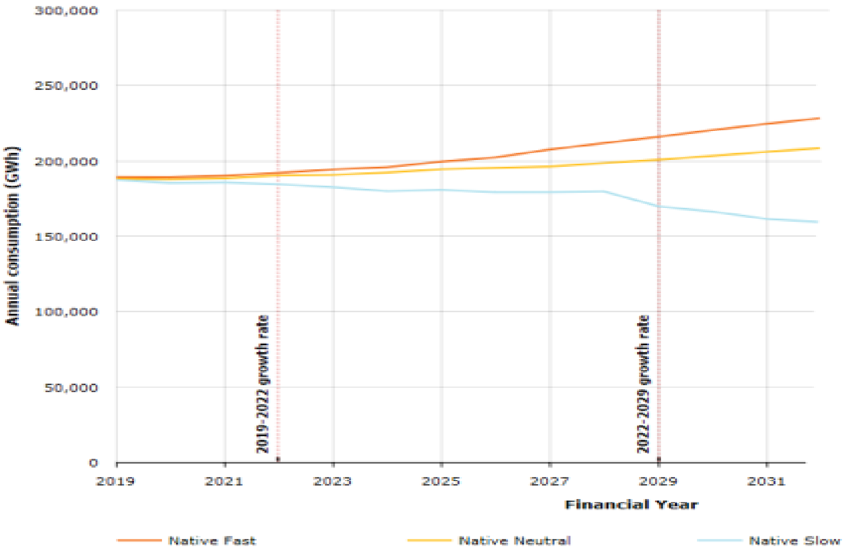


Figure 5.1: Australian electricity native consumption by each growth [99]

In contrast, the second context assumes that by 2030 rooftop-PV systems will be capable of feeding electricity into the grid, significantly contributing to meet the electricity demand. Therefore, the energy forecast related to rooftop-PV consumption has been added to all three 2030 native electricity demand projections.

Table 4.2 below depicts the yearly electricity consumption for each Demand Scenario, considering the case with and without rooftop PV consumption.

Table 5.2: 2030 Australian electricity consumption projections [99]

	Slow	**Neutral**	**Fast**
Grid Cosumption [GWh]	166425.27	203404.8	220490.34
Grid+Rooftop PV Consumption [GWh]	184525.52	221505	238590.59

5.3 Three supply scenarios

In the 2030 projections, each forecasted supply scenario is required to ensure reliability in meeting the electricity demand during each moment of the year. As mentioned in paragraph 5.1, three different future supply scenarios are evaluated by the AEMO: ESOO – low RES, ISP – high RES and ISP – high RES with Storage.

The ESOO – low RES scenario considers 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” [49]. This model does not include new generation developments beyond 2021, as the projects planned to be built beyond this year presently remain uncommissioned [96].

On the other hand, the ISP – high RES scenario and the ISP – high RES with Storage scenario have the purpose of meeting the projected electricity demand at low costs, incorporating the implementation of a rich portfolio of intermittent energy projects and transmission developments beyond 2021. [97]

5.3.1 ESOO – low RES scenario

The 2018 ESOO report aims to inform the industry about the energy market, assessing if the projects existing, committed or currently under construction across the NEM are capable of guaranteeing supply reliability.

The ESOO – low RES highlights the future upcoming changes particularly regarding the withdrawal of fossil fuel power plants which have traditionally played a significant role in the Australian Energy sector, but are soon to be replaced largely by the development of Wind and PV-solar farms.

Table 5.3 shows the announced retirement of four thermal power plants, with a total of 2700 MW being removed from the total dispatchable Australian supply capacity.

Table 5.3 :Committed retirement of fossil fuel power stations [100], [101], [96]

	FUEL	REGION	YEAR OF RETIREMENT	CAPACITY WITHDRAWN
LIDDEL POWER STATION	Coal	New South Wales	2022	2000 MW
MACKAY GAS TURBINE	Oil	Queensland	2021	34 MW
TORRENS POWER STATION	Natural Gas	South Australia	2021	480 MW
TAMAR VALLEY CCGT	Natural Gas	Tasmania	2019	208 MW

Torrens A Power Station, however, will be partially replaced in 2019 by the Barker Inlet Power Station (gas powered plant) which will provide a total capacity of 210 MW [101].

This substantial fossil fuel power capacity, which played a notable role in guaranteeing stability and reliability to the Australian Electricity grid, will retire due to the gradual deterioration and the conclusion of the power plants expected technical lifetime. The ESOO – low RES scenario will replace these dispatchable sources with the commitment of 6.3 GW capacity installation of variable power sources (wind and solar farms), along with the commission of 77 MW capacity of utility scale storage. This has the capability of providing flexibility and reliability to the new Australian supply electricity scheme. [96]

Figure 5.2 depicts an overview of the changes which will be accomplished by the ESOO – low RES scenario.

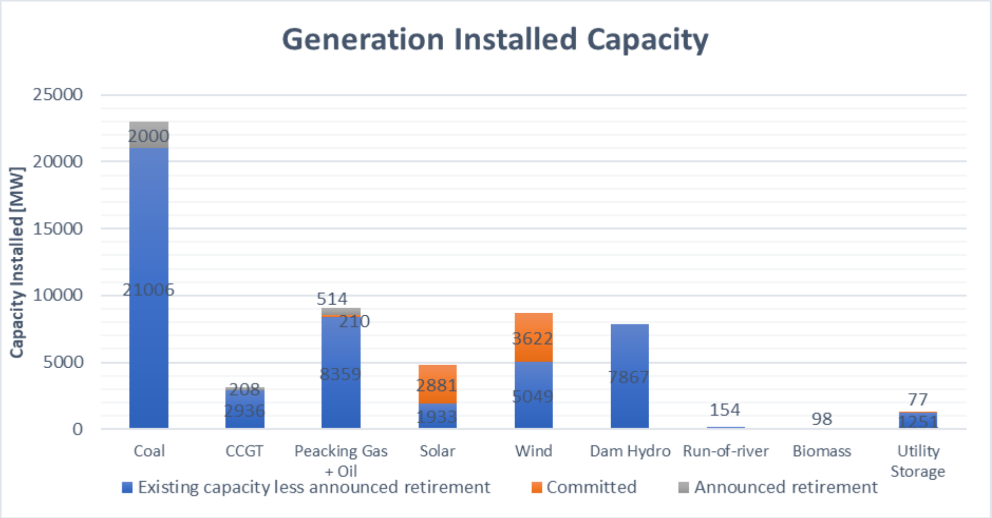


Figure 5.2: Total generation installed capacity by source in the ESOO – low RES scenario

This figure underlines how such a significant development of renewable energy systems is being installed in a very short time. The shift towards a national electricity system with a significant electricity capacity provided by renewable sources is the consequence of the Large-Scale generation certificates (LGCs), which consist of financial incentives provided by the Australian Government in the form of tradable certificates which act as an electronic form of currencies, as explained in paragraph 2.2.1.

Queensland, the closest state to the Capricorn Tropic, will face a remarkable implementation of large-scale PV-Solar farms due to its advantageous location which provides a constant amount of solar irradiation throughout the year. On the other hand, the southern regions, in particular Victoria, will focus on the construction of several wind farm projects.

Due to the massive investments in renewable energy projects, with part of the commissioned capacity already under construction, Australia is likely to reach by 2020 the legislated national Large-Scale Renewable Energy Target of producing 33 TWh from renewable sources [33]. However, as previously mentioned, the ESOO – low RES Scenario includes the development of a gas-powered plant (Barker Inlet) which will support to provide a higher flexibility for the electricity supply in the national territory. This will operate as a back up to the renewable variable energy sources whenever they are unable to meet the electricity demand.

5.3.2 ISP – high RES scenario

The Integrated System Plan (ISP) is a cost-based engineering optimisation which aims to model the most accurate supply and transmission 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 power projects necessary to guarantee a safe long-term supply of electricity and therefore minimise the total resource costs. [97]

The ISP – high RES scenario includes a vast quantity of new renewable energy projects which (unlike the ESOO – low RES scenario) will be implemented beyond 2021, as well as the retirement of several thermal power plants. [97].

The new supply energy mix in the ISP model will experience a substantial retirement of traditional coal power plants. This event will drastically impact the ISP – high RES scenario more than the ESOO – low RES, due to the higher withdrawn capacity predicted to be shut down by 2030. This is the result of two additional power plants achieving their maximum technical life utilization, Vales Point and Gladstone, as displayed in figure 5.3, with the retirement of 1320 MW and 1680 MW [97].

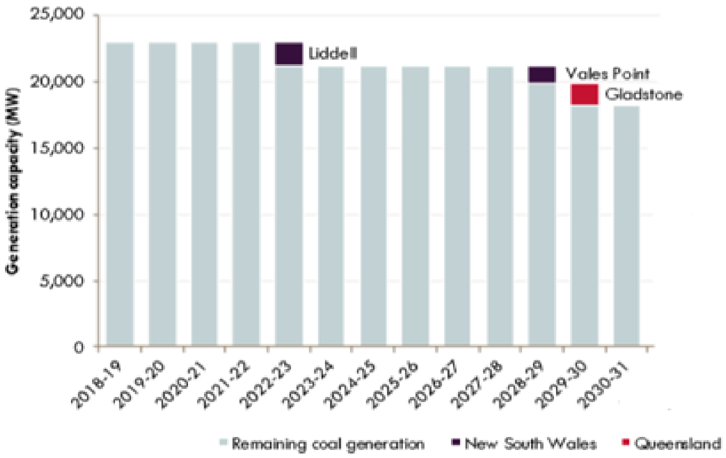


Figure 5.3: Forecasted coal power plants retirement in the next 20 years by the ISP – high RES [97].

The consequences derived from the closure of these thermal power plants will not only reflect on the dispatchable supply capacity, which will be clearly reduced, but also in terms of grid stability. The latter consists in the ability of coal power generators to provide grid security services, as inertia and frequency control.

The ISP – high RES scenario evaluated an economically profitable replacement of the retiring coal power plants by a mixed portfolio of renewable generation, storage systems and flexible thermal capacity, which will be able to guarantee the security and stability of the electricity grid. The planned supply capacity to be installed by 2030 will strongly be linked to further implementations on the electricity transmission side. This latter upgrade will be needed to ensure a secure national electricity system which requires a strong interconnected network in order to provide an easy electricity access to the new RES supply developments across the entire NEM (National Electricity Market). [97]

As described above, the ISP – high RES model bases its projections on the strong drop of renewable energy generation costs, which will be a relevant driver for their expansion in the Australian electricity market. These new forecasted developments along with improvements in the transportation, heating and industry sectors, aim to meet the Australian Emission Reduction Targets of producing between 440 and 452 Mt of Carbon Dioxide by 2030, about 26-28% below the 2005 level. [102]

By 2030 the ISP – high RES projects a consistent implementation of PV-solar and wind farms (with approximately 10 GW of installed capacity respectively) after locating 34 renewable energy zones with an easy access to pre-existing transmission capacity across the entire national electricity market territory, as shown in the figure 5.4 below. [103]

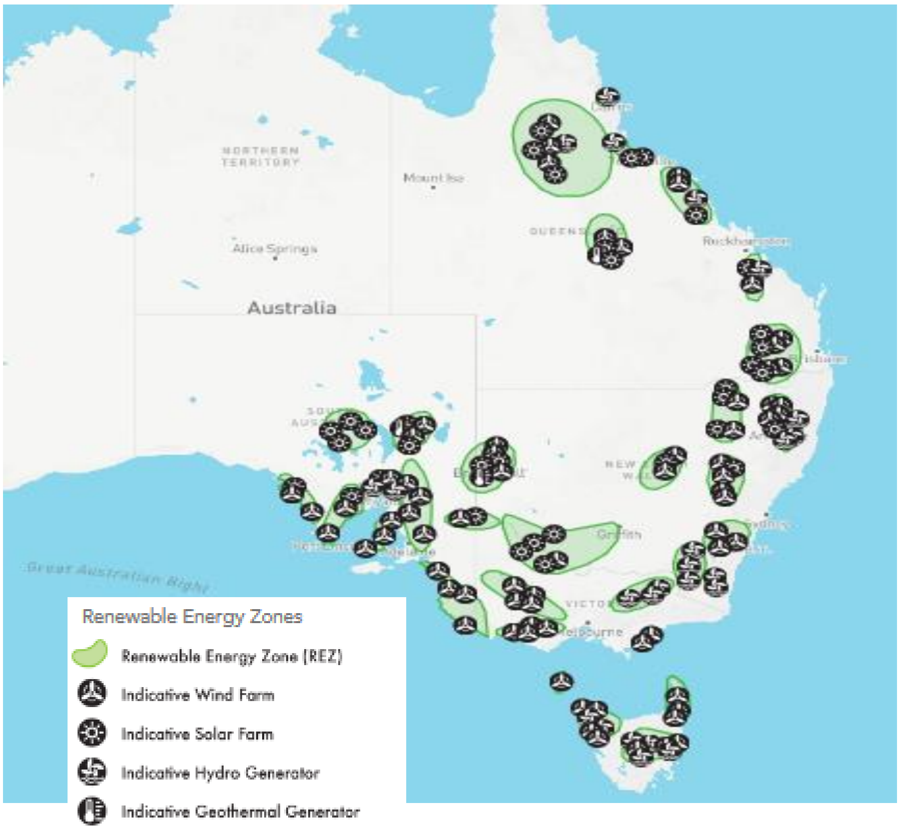


Figure 5.4: Renewable energy zones forecasted for future project implementations [103].

This will require the growth of utility storage systems by a projected implementation of 4,543 MW across the country, to guarantee flexibility to the grid and to enable a smooth shift of the electricity produced by solar farms during the day towards the evening when peak electricity demand occurs. Furthermore, after the closure of the Liddell Power Station in 2022, and the Vales Point and Gladstone coal power plants by 2030, with a total reduction of 5,000 MW in the national capacity, the introduction of 300 MW of gas power generation will smooth the transition towards renewables energy, providing fast-responding electricity generation. [104]

In addition to the significant diffusion of large-scale renewable projects, the ISP – high RES model included the forecasted installed capacity of rooftop-PV and distributed batteries. These sources will face a fast growth by 2030, with an installed capacity of 16,765.5 MW regarding rooftop-PV and 3,851.5 MW regarding distributed storage. [104].

It is projected that the significant rooftop-PV capacity installed in the next years will highly contribute to meeting the future electricity demand by feeding electricity into the grid. On the other hand, only a minor part of the entire distributed batteries will play a role in the grid-load distribution management and the rest will operate in conjunction with rooftop-PV systems, without having any interaction with the grid. [97]

The figure 5.5 shows the future power system installations in Australia till the year 2030-2031.

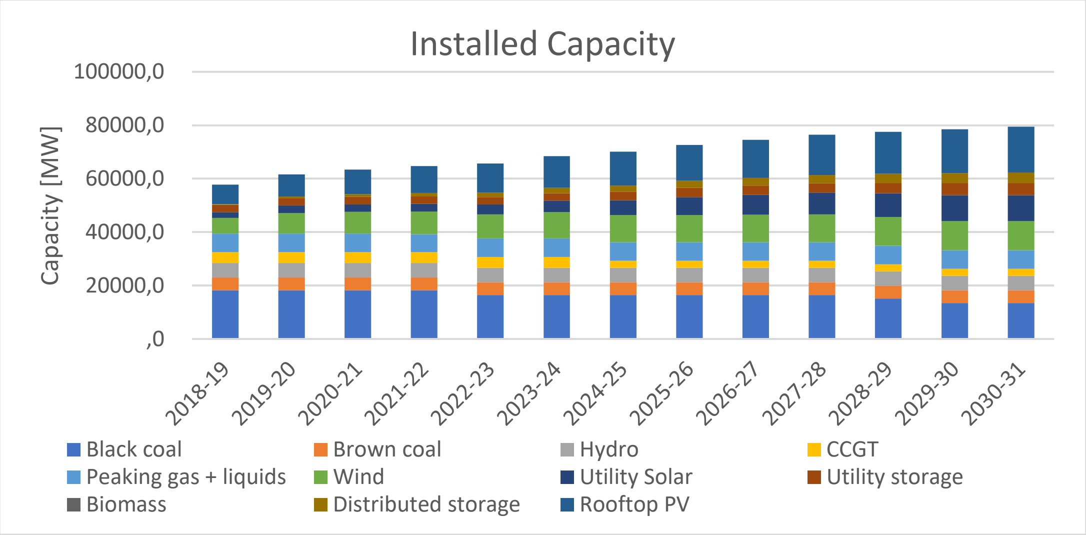


Figure 5.5: Installed capacity by source in ISP – high RES scenario [104]

The ISP – high RES model is based on the prediction related to each financial year. In order to have a more accurate data set input for the implementation of the EnergyPlan simulations for the 2030 electricity scenarios, the average between the capacity installed by each power source in 2029-30 and 2030-31 has been computed.

5.3.3 ISP – high RES with Storage scenario

The last scenario included in the 2030 simulations with the EnergyPlan software is the ISP – high RES with Storage scenario. While this is similar to the ISP – high RES scenario in terms of generation capacities installed by each source, it has been considered in a separate scenario as it includes two remarkable storage projects: the Snowy 2.0 and the Tasmania Battery of the Nation, which do not currently meet the commitment criteria by the National Electricity Market. [97]

Under this model, the 2030 dispatchable generation capacity will remain constant to the actual value of approximately 40 GW. However, this quantity will be largely provided by the new storage facilities.

The Snowy 2.0 is a closed pump storage energy system, which will connect two already existing hydro power schemes (Tantangara and Talbingo) in the New South Wales territory through underground tunnels and power stations with pumping facilities. 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. [105]

On the other hand, the Battery of the Nation still requires the investigation and further development of pump hydro schemes in the Tasmanian island territory. This project has recently reduced the number of potential sites for the implementation of pumping stations from 2000 to 14. The number of sites will be decreased through further technical and economic feasibility studies, to meet the fixed targeted pump capacity of 2,500 MW. [106]

The Battery of the Nation is still far from its final implementation and it is forecasted to start its operation between 2034-2035; due to this reason it has not been included for the purpose of this thesis (which accounts for the modelling of the Australian electricity mix up until 2030).

This scenario benefits both in terms of a slightly higher power capacity by 2030, from 4,543 MW in the ISP – high RES scenario to 5,367 MW in the ISP – high RES with Storage forecast, and of utility storage volume capacity, shifting from 27 GWh in the ISP – high RES scenario to approximately 350 GWh in the ISP – high RES with Storage model, as shown in figure 5.6. [104]

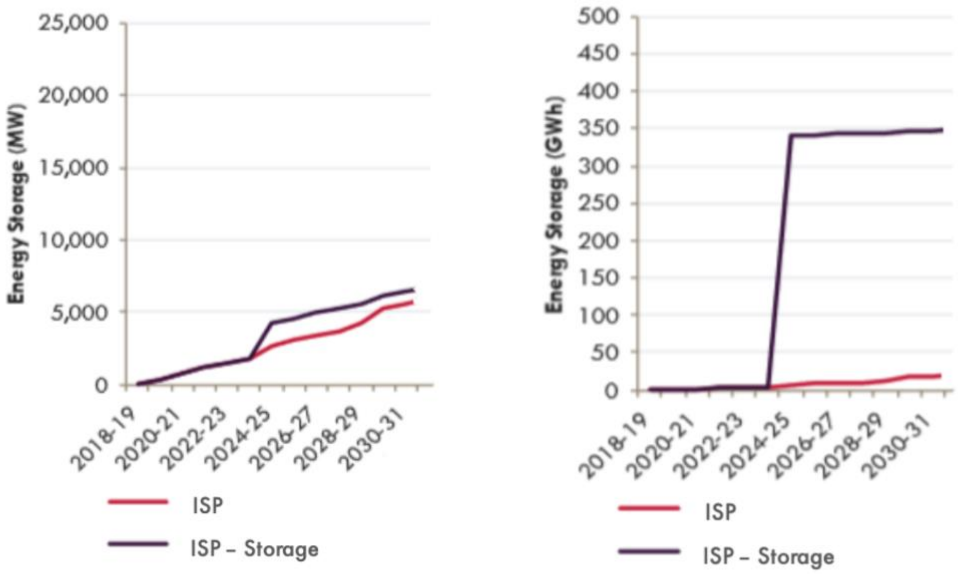


Figure 5.6: Energy storage capacity comparison between ISP – high RES and ISP – high RES with Storage scenario [97]

This massive volume of energy storage available through the implementation of the Snowy 2.0 scheme will ensure reduced short-term risks compared to the ISP – high RES scenario. This is due to the great potential energy that can be stored in the reservoir which affords high flexibility in meeting the required electricity demand when needed [97].

Nevertheless, the ISP – high RES and ISP – high RES with Storage scenarios are very similar in terms of installed capacity by 2030 regarding large-scale wind and solar farms and gas generation plants, in contrast to the ESOO – low RES scenario.

Table 5.4 provides a summary of the total installed capacity by 2030 for every energy source for the three scenarios analysed. It emphasizes a greater implementation of wind, solar and energy storage projects for both the ISP – high RES scenarios compared to the ESOO – low RES. These developments will assist in replacing the energy provided by the thermal power plants which will be closed due to the reaching of their technical life.

Table 5.4: Capacity installed for each source for the ESOO - low RES, ISP – high RES and ISP – high RES with Storage scenarios in 2030 [104] [17] [107].

	2030 Supply Scenarios		
	ISP [MW]	**ISP with Storage [MW]**	**ESOO [MW]**
Black coal	13198	13198	16198
Brown coal	4808	4808	4808
Hydro	8021.2	8021.2	8021.2
CCGT	2649	2649	2728
Peaking gas + Oil	6970.7	7061	8055
Wind	10943	10866	8671.5
Utility Solar	9686	9759	4814
Utility storage	4543	5367	1328
Biomass	98	98	98

Chapter 6

Simulations Results and Analysis

Chapter 6 aims to analyse the results obtained from both the technical and economic simulations evaluated for the ESOO – low RES, ISP – high RES and ISP – high RES with Storage scenarios for the modelling of the 2030 Electricity Mix in Australia. Moreover, it includes an explanation of the pros and cons between the two types of simulations for the purpose of this thesis and the limitations faced during the computations.

6.1 Technical simulation

The technical simulation by EnergyPlan applies an algorithm which maximizes the use of renewable energy sources, with the purpose of minimizing the electricity production from fossil fuel power plants. [62]

It is relevant to note that during the implementation of the technical simulation, the software 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.

After having examined the 2030 Australian electricity scenarios, a technical simulation for each model was conducted.

6.1.1 ESOO – low RES simulation

The simulation for the ESOO – low RES scenario is the first one to be analysed, as shown in figure 6.1. The analysis depicts the different electricity mix over 2030 in Australia obtained from the sensitivity analysis regarding the neutral, fast and slow growth electricity demand projections.

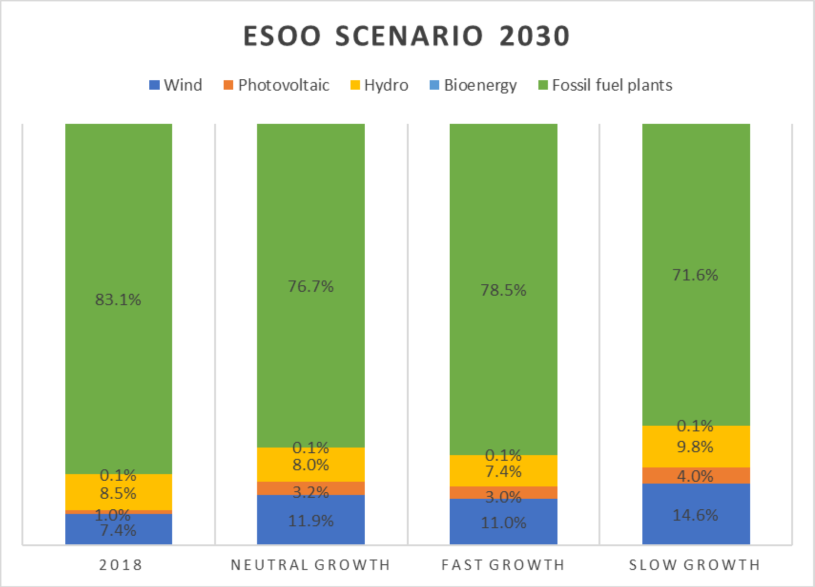


Figure 6.1: 2030 Electricity mix for the ESOO – low RES under different electricity demands

In the ESOO – low RES scenario, it is evident how fossil fuel generation will still play a fundamental role in the electricity mix, regardless of what the electricity demand will be by 2030.

Moreover, EnergyPlan is a software oriented to model future renewable energy systems and is not able to clearly differentiate between condensing power plants which are used as a base load, and gas turbines which are mostly used for peak demand due to their high flexibility. Due to this reason the whole yearly energy generation output from fossil fuel power plants has been combined.

The dam-hydro and run-of-river hydro generation will remain relatively constant from 2018 to 2030, with a production of approximately 15.6 TWh and 0.7 TWh, due to the lack of new developments committed and the projection of a stable water supply every year, as mentioned in Chapter 3. The contribution from these sources has been aggregated under “Hydro” in the electricity mix in figure 6.1, since run-of-river hydro accounted for less than 1% of the total energy generated.

According to the ESOO – low RES scenario, the energy supplied in 2030 will experience an increase in the renewable energy share compared to 2018, with a generation of 24.22 TWh from wind energy and 6.60 TWh from photovoltaic. This is due to the development of committed large-scale renewable projects, which obtained significant incentives from the government to facilitate the transition towards green energy.

On the other hand, the electricity generation from bioenergy, constituted by biogas, will be irrelevant due to the lack of new developments by 2030, with a projected production of less than 0.2 TWh which translates to 0.1% of the electricity generation mix.

Table 6.1 provides the different RES (Renewable Energy Source) share and carbon dioxide emissions according to the different possible electricity demand growths in 2030.

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. Under the ESOO – low RES scenario the power generated by the renewable sources, during each moment of the year, will never be sufficient to satisfy the electricity demand, therefore there will never be the necessity to store energy, due to the lack of surplus supplied by renewable sources.

Table 6.1: RES share and CO2 emissions by 2030 in the ESOO – low RES under different electricity demands

	2018	**Neutral**	**Fast**	**Slow**
% RES	16.8%	23.3%	21.5%	28.4%
CO_2 *emissions [Mt]*	148.6	142.6	156.1	109.7

The RES share in 2030 will not sharply vary from the current situation as shown in table 6.1, despite a significant number of photovoltaic and wind developments already commissioned, as described in the ESOO – low RES scenario. Therefore, in order to have an electricity mix less dependent on fossil fuels and to reduce the overall carbon dioxide emissions, further renewable projects will need to be implemented by 2030, as considered under the two ISP scenarios.

6.1.2 ISP – high RES & ISP – high RES with Storage simulations without rooftop-PV electricity generation

Having described the ISP – high RES and ISP – high RES with Storage scenarios in the previous chapter, the 2030 technical simulation has been computed in order to describe how the energy mix is likely to change under these new developments.

The first simulations for both scenarios were computed neglecting the rooftop-PV systems capacity. This choice has been undertaken to evaluate a future supply scenario in which the rooftop solar systems will be utilized solely for self-consumption, without feeding the electricity produced into the grid. Figure

6.2 below clearly shows how under these scenarios the electricity mix relies more upon the generation from wind and solar farms.

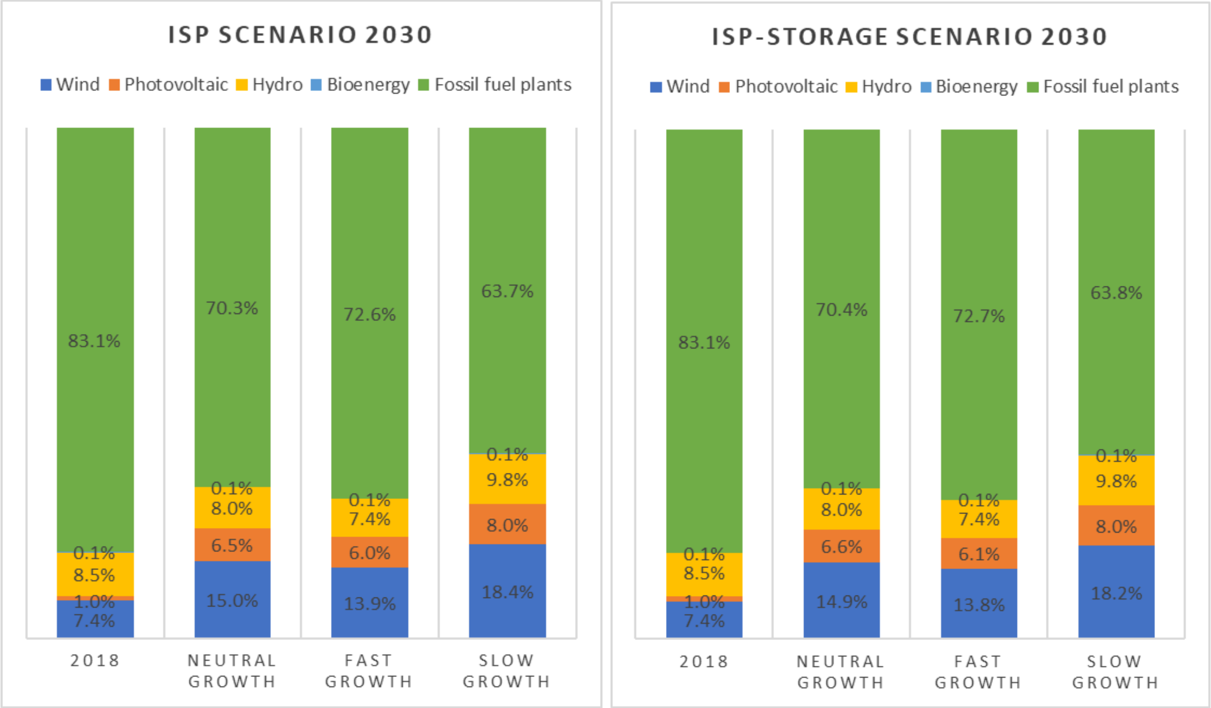


Figure 6.2: Electricity mix for the ISP – high RES and ISP – high RES with Storage scenarios in 2030

Furthermore, as was the case for the ESOO – low RES scenario, the hydro power generation does not face effective generation changes in 2030, due to the lack of further investments for both dam hydro and run-of-river and the steady water supply throughout the year.

The energy mix for the ISP – high RES and the ISP – high RES with Storage scenarios are almost identical, due to a very similar capacity installed by each technology. Table 6.2 depicts how the different large-scale wind and solar capacity developed in each scenario will influence the final yearly electricity production.

Table 6.2: 2030 Power capacity installed and annual electricity generation for wind & solar technologies, for each scenario.

	2030 Capacity Installed [MW]		**2030 Electricity Generated [TWh]**	
	Wind	*Solar-PV*	*Wind*	*Solar-PV*
ESOO	8671.5	4814	24.22	6.60
ISP	10943	9686	30.57	13.28
ISP-Storage	10866	9759	30.35	13.38

In both the ISP – high RES scenarios, wind and especially solar face a greater increase of power capacity installed compared to the ESOO – low RES scenario, as shown in table 6.2. Therefore, it confirms the benefits of “green” energy generated by the additional wind and solar farms (not included in the ESOO – low RES) on the final electricity mix.

The ISP – high RES scenario has an additional installed capacity of respectively 20% for wind and 50% for solar-PV compared to the ESOO – low RES scenario, which reflects a rise of 20% and 50% of respectively wind and solar electricity generation. Between the ISP – high RES and the ISP – high RES with Storage scenarios, there is a variation of only 77 MW of wind energy and 73 MW of solar-PV capacity installed, which results in a difference of less than 1% for both technologies in the 2030 energy generated.

However, wind and solar are fluctuating energy sources which do not have the same capability as thermal power plants of producing electricity whenever it is needed. The unitless measure to indicate the level of productivity of variable energy sources is defined by the capacity factor, as shown by the following formula:

$$c_{factor} = \frac{E_{produced}}{P_{rated} * hours} = \frac{[MWh]}{[MW] * [h]}$$

The numerator indicates the total energy produced (normally in a year), while the denominator expresses the maximum energy that the source could harness as the rated power of the source multiplied by the total period of operation (8776 hours in the case of one year). In Australia, wind and solar-PV have a capacity factor of approximately 0.43 and 0.21. These values have been obtained from Energyplan, after having inserted the data regarding solar and wind loading factors in 2018, from [86].
As a consequence, the total wind and solar-PV capacity forecasted to be installed under the three scenarios is significantly greater than the capacity of the retiring coal power plants, which had a continuous operation running as a base load, as represented by table 6.3.

Table 6.3: Capacity of retiring coal plants and new wind & solar installation for each scenario by 2030.

	Capacity of retiring coal plants [MW]	**Capacity of new wind and solar farms [MW]**
ESOO	2000	6503
ISP	5000	13646.5
ISP - Storage	5000	13642.5

Table 6.4 depicts how despite a significant rise from wind and solar energy generated in both the ISP – high RES scenarios compared to the ESOO – low RES, the forecasted energy storage consumption will be very limited. The power generation from variable sources exceeding the electricity demand is null in the neutral and fast scenarios, and low in the slow scenario – resulting in a yearly energy storage consumption of only 10 GWh.
Therefore, there is no need for the curtailment of electricity in excess, and thus no CEEP strategy has been applied.

Table 6.4: 2030 Storage consumption and lack of electricity under both ISP – high RES scenarios for each electricity demand.

	2030 ISP-Storage SCENARIO			**2030 ISP SCENARIO**		
	Neutral	*Fast*	*Slow*	*Neutral*	*Fast*	*Slow*
Storage consumption [GWh]	0	0	10	0	0	10
Extra electricity supplied needed [GWh]	20	180	0	20	190	0

The second row of the table highlights the limits of the EnergyPlan technical simulation; the electricity supplied will not always be sufficient to meet the electricity demand. For instance, in the fast electricity demand projection which has a yearly energy consumption of almost 240 TWh, there will be a lack of 180 GWh for the ISP – high RES Storage scenario and 190 GWh for the ISP – high RES scenario in 2030.

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. Due to this reason, the software gives as output the amount of electricity that the system lacks in order to meet the yearly demand, which translates into possible blackouts throughout the year. The economic simulation will give a more reasonable output, instead showing that the chances of blackouts are completely avoidable.

6.1.3 ISP – high RES & ISP – high RES with Storage simulation including rooftop-PV generation

As described in Chapter 5, in 2030 under the ISP – high RES scenario, 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. Currently, there are few incentives for ‘feed-in tariffs’ which incentivize selling the excess energy generated by rooftop-PV to the retailers. New challenges will arise in the future to allow bi-directional power flows in the network, in order to feed the electricity from rooftop-PV systems into the grid. [51]

Due to this reason, another simulation has been evaluated to analyse the effect of these developments, taking into consideration that by 2030 the rooftop-PV solar systems will be capable of feeding the electricity into the grid, contributing to meet the national energy demand. In order to be coherent, the additional electricity consumption related to the rooftop PV usage forecasted by 2030 has been summed to the yearly electricity consumption for each potential growth demand (neutral, fast and slow). Figure 6.3 clearly shows 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.

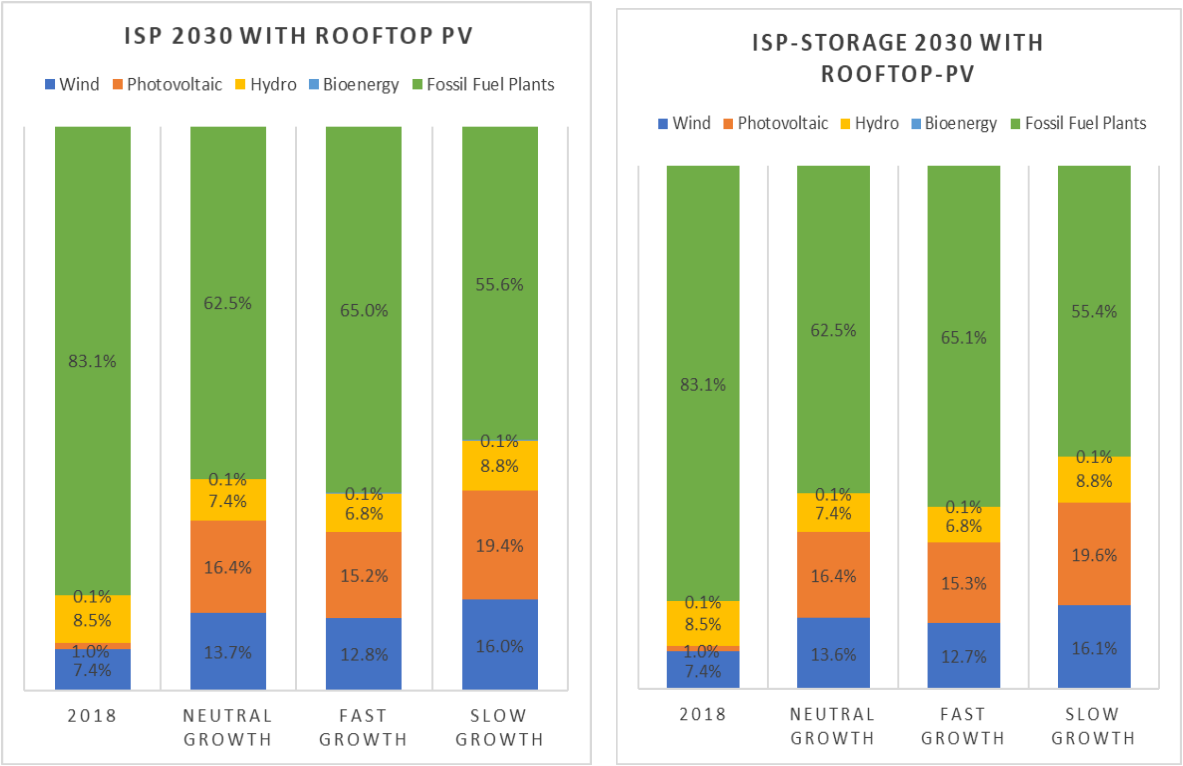


Figure 6.3: 2030 Electricity mix for ISP – high RES & ISP – high RES with Storage scenarios including rooftop-PV systems

The graphs demonstrate that in both slow electricity demand growths, the fossil fuel generation accounts for slightly above 55% of the total yearly electricity generation.

Under these two scenarios, there is a higher utilisation of energy storage due to the remarkable electricity production from solar during the middle of the day. Moreover, the benefits of the ISP – high RES with Storage scenario are highlighted in table 6.5, showing a net increase in the yearly energy storage consumption for each electricity demand growth, compared to the ISP – high RES. In these technical simulations, however, the lack of electricity supply to meet the demand is consistent, due to the same reasons explained in paragraph 6.1.2.

Table 6.5: Storage consumption and extra electricity needed to meet the demand under ISP – high RES scenarios including rooftop-PV

	2030 ISP including Rooftop-PV			**2030 ISP-Storage including Rooftop-PV**		
	Neutral	*Fast*	*Slow*	*Neutral*	*Fast*	*Slow*
Storage consumption [GWh]	1010	520	3140	1110	560	3600
Extra electricity supplied needed [GWh]	180	670	0	170	650	0

Table 6.6 represents a comparison of the total renewable energy share and the carbon dioxide production of the two ISP – high RES scenarios, including and excluding the rooftop-PV systems. The CO_2 emission values obtained for each scenario are lower than the 2018 emissions (148.6 Mt),

confirming that even if the electricity consumption will significantly grow in 2030, the “clean” energy generated will play a fundamental role in preventing the rise of CO_2 emissions. Consequently, the ISP – high RES shows an important step towards the achievement of the 2030 low emission Australian Target, which will need to be supported by improvements in the transportation sector, heat sectors and industry processes.

Table 6.6: RES share and CO_2 emissions by 2030 in ISP – high RES & ISP – high RES with Storage scenarios

		%RES			**CO_2 EMISSIONS [MT]**		
		Neutral	*Fast*	*Slow*	*Neutral*	*Fast*	*Slow*
EXCLUDING ROOFTOP PV	*ISP*	29.7%	27.4%	36.3%	128.2	139.7	97.4
	ISP-Storage	29.6%	27.3%	36.2%	128.3	140.0	97.5
INCLUDING ROOFTOP PV	*ISP*	37.5%	35.0%	44.4%	121.8	132.8	93.7
	ISP-Storage	37.5%	34.9%	44.6%	121.8	133.0	93.6

The introduction of the rooftop-PV systems for the ISP – high RES and ISP – high RES with Storage models have made significant contributions to the total energy production from renewable sources, projecting respectively 82.18 and 82.51 TWh for the slow demand, 83.14 and 83.10 TWh for the neutral demand and 83.24 and 83.17 TWh for the fast demand. These values are evidently greater than the 60.35 and 60.23 TWh belonging to the ISP – high RES and ISP – high RES with Storage models excluding the Solar PV rooftop capacity.

The installation of this consistent amount of new solar capacity caused different values of renewable energy generation, according to the different electricity demand. When considering rooftop-PV systems under the slow electricity demand, the ISP – high RES with Storage scenario reflects a slightly higher RES share compared to the ISP – high RES, which is in contrast to the RES shares excluding Rooftop-PV systems (where ISP – high RES is greater than ISP – high RES with Storage). This effect is the consequence of a higher storage volume and capacity in the ISP-Storage scenario, which enables the curtailment of a lower amount of energy in excess, that exceeds both the demand and the storage capacity.

In order to evaluate the size of the renewable energy curtailed, a further analysis has been evaluated comparing the excess of renewable energy produced under the 2030 ISP – high RES and ISP – high RES with Storage scenarios with rooftop-PV systems (see Figure 6.4). Furthermore, a case which includes the storage capacity of distributed batteries, which relates largely to home batteries has been considered.

This implementation has been computed in order to evaluate how much the power curtailment would diminish if the distributed storage systems would be able to behave like utility scale storage facilities, storing electricity from the grid, even if in 2030 distributed batteries are likely to have a limited interaction with the grid according to the ISP – high RES model [104]

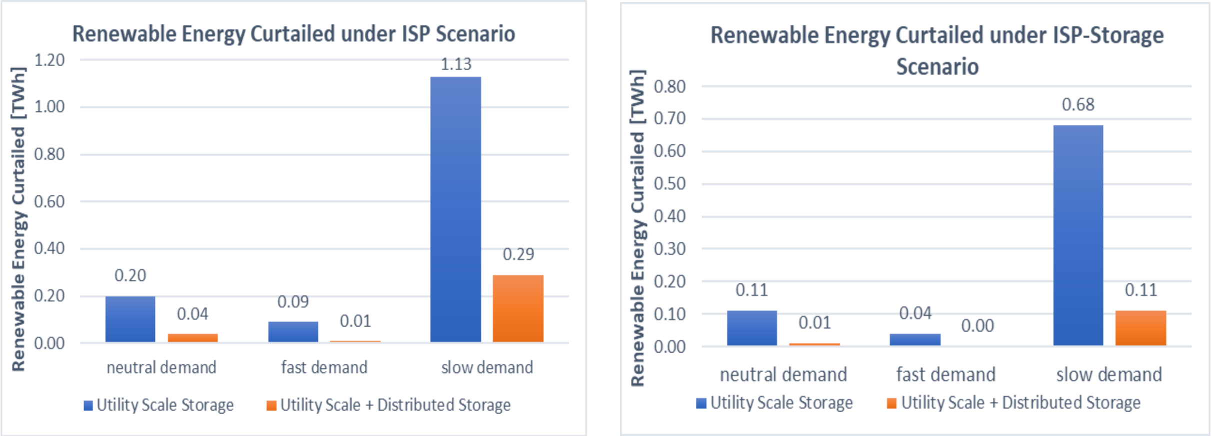


Figure 6.4: Renewable energy curtailed under ISP – high RES & ISP - high RES with Storage scenario

Every electricity demand will have a necessity to curtail different amounts of power generation since under a higher demand, more electricity will be needed and as a consequence, the electricity excess will decrease. The ISP – high RES with Storage scenario is capable of reducing the excess energy supplied by renewable power plants, due to the greater amount of storage and volume capacity available from its facilities, especially the Snowy 2.0 pump hydro scheme, which will fundamentally contribute to energy storage capacity. However, the introduction of the distributed batteries (assuming their capability to interact with the grid) will lower the energy curtailment by more than double in both scenarios, compared to the case with only utility scale storage involved.

Thus, 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.

Nevertheless, the economic simulation analysed in the following paragraph will describe a more realistic Australian electricity mix for 2030, 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 avoiding the black-outs faced in the technical simulation.

6.2 Economical simulation

In this paragraph, the analysis of the economic simulations for the modelling of the 2030 Australian electricity mix for each scenario has been conducted.

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. [62]

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. [95]

To model an appropriate energy system, the economic simulation requires multiple inputs related to the fixed, variable and investment costs for each energy technology. This data was provided by the EnergyPlan cost database which forecasted the costs projected respectively for 2020, 2030 and 2050 [108]. The appendix shows the economic data utilized to implement this simulation.

EnergyPlan also requires the external market price distribution file, which lists the hourly electricity price in Australia during each hour of the year. This input was extremely important for the aim of this work, since according to the hourly electricity price, the software was able to analyse which period during the year was economically advantageous to firstly store then discharge the energy, simulating a real-life electricity market scenario.

The external market price distribution file utilised for the 2030 simulations was obtained from the 2018 Australian hourly electricity price provided by the Australian Electricity Market Operator (AEMO) [85] and the hourly renewable energy share in 2018 and 2030, respectively.

The price formula below intends to find a correlation between the 2030 hourly electricity price and the forecasted hourly percentage of electricity supplied by non-renewable sources in 2030, with the actual 2018 hourly electricity price and the 2018 hourly percentage of electricity supplied by non-renewable sources.

The 2018 hourly electricity price reveals that a higher price is linked to hours with a high non-renewable energy share, inducing the same effect for the projected 2030 hourly electricity price.

"RES" refers to the sum of the hourly energy generated from wind, solar and hydro technologies, and has been calculated for both 2018 and 2030. Moreover, "Demand 2030" indicates the electricity demand during any hour of 2030. This has been obtained as the product of the 2018 hourly electricity demand (provided by AEMO [19]), multiplied by the ratio of the 2030 yearly electricity consumption divided by the 2018 yearly electricity consumption, as shown in the equation below.

$$Price_{2030} = \{Price_{2018} * (1 - \frac{RES_{2030}}{Demand_{2030}})/(1 - \frac{RES_{2018}}{Demand_{2018}})\} \left[\frac{\$}{MWh}\right]$$

Where:

$$RES = Wind_{Energy} + Solar_{Energy} + Hydro_{Energy} \quad \left[\frac{MWh}{hour}\right]$$

$$Demand_{2030} = Demand_{2018} * \left(\frac{Tot_{Consumption_{2030}}}{Tot_{Consumption_{2018}}}\right) \left[\frac{MWh}{hour}\right]$$

The 2030 electricity price distribution file has been computed for the ESOO – low RES, ISP – high RES and ISP – high RES with Storage scenario for each yearly electricity demand (neutral, fast and slow), in order to provide accurate simulations for the future electricity mix.

6.2.1 ESOO – low RES, ISP – high RES and ISP – high RES with Storage scenarios

The economic simulation for all three 2030 scenarios has been analysed (excluding rooftop-PV systems in the ISP – high RES and ISP – high RES with Storage Scenarios).

As indicated by Figure 6.5, despite a slight increase in the percentage of the fossil power plants in the final energy mix, the rest of the energy proportions remain very similar to the results obtained in the technical simulations for each electricity demand growth.

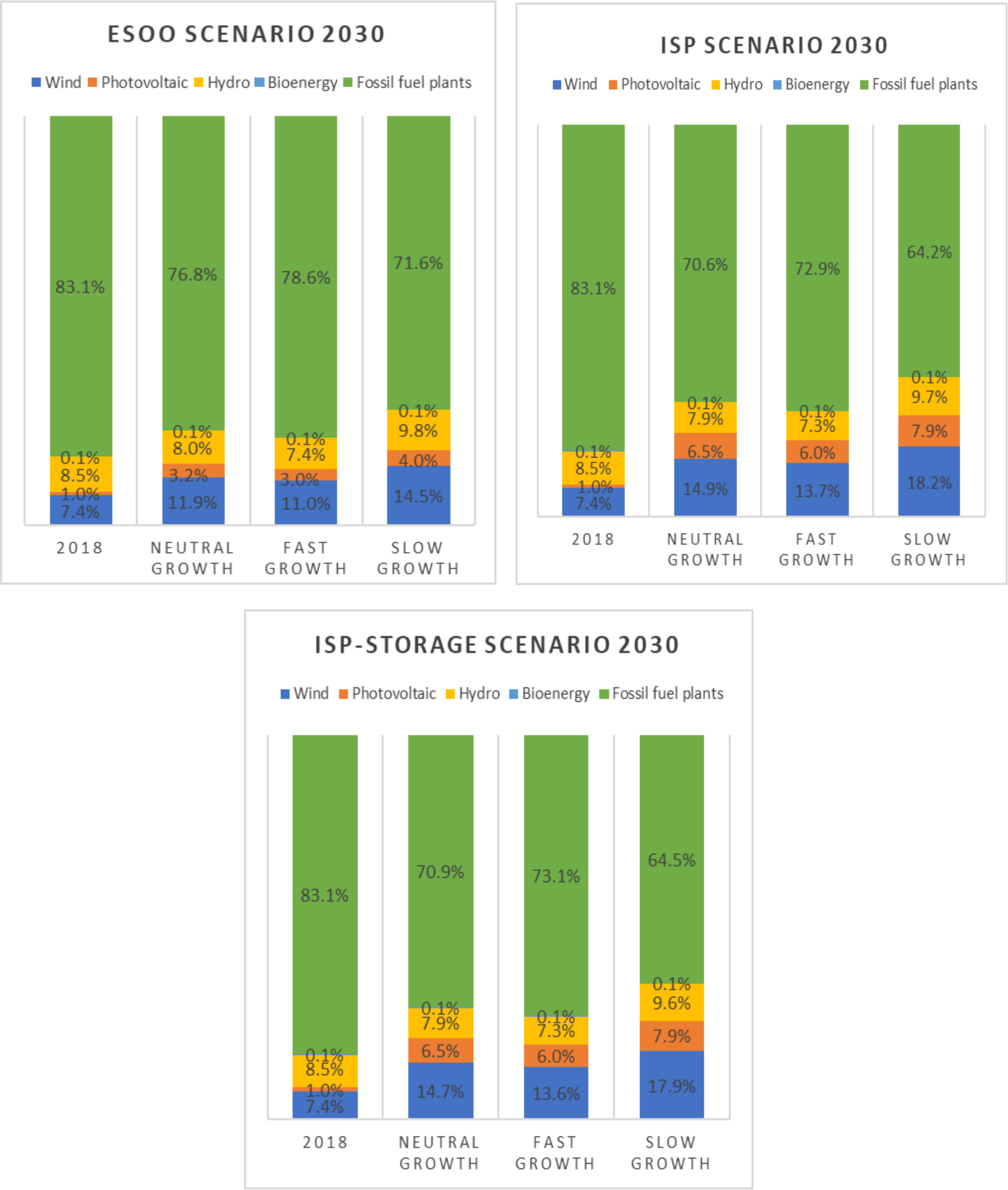


Figure 6.5: 2030 Electricity mix for the ESOO – low RES, ISP – high RES, ISP – high RES with Storage for different electricity demands, under the economic simulation.

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.

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

The storage of electricity during off-peak hours prevents the lack of electricity supply faced in the fast and neutral demands in the technical simulations of the ISP – high RES and ISP – high RES with Storage scenarios. This confirms the reliability of the economic simulation for the purpose of this work.
Table 6.7 presents the yearly storage consumption for each Scenario analysed in Figure 6.5, showing a net increase compared to the technical simulations.

Table 6.7: Pump/Battery storage consumptions with the economic simulation, under the three scenarios

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

The significant gap in terms of yearly total storage consumption between the ESOO – low RES, the ISP - high RES and the ISP – high RES with Storage is related to the different volume and capacity projected to be implemented by each scenario by 2030. A remarkably higher utilization of the storage systems in the ISP – high RES with Storage Scenario 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.

For instance, the ESOO – low RES scenario which has a low storage capacity, will rely more heavily on the use of other high flexible supply sources such as gas turbines, in order to meet the demand during peak periods.

The amount of electricity generated by renewable sources is the same as the values obtained in the technical simulations, accounting respectively for 47.32, 60.35 and 60.23 TWh for the ESOO - low RES, ISP – high RES and ISP – high RES with Storage scenarios.

The comparison regarding the electricity share from renewable sources between the technical and the economic simulation is shown in table 6.8 and 6.9, along with the carbon dioxide yearly emissions. The slightly lower renewable energy share and higher carbon dioxide emissions in the economic simulations reflect the considerations previously analysed regarding the greater electricity generation from coal power plants.

Table 6.8: Renewable energy share percentage comparison between technical and economic simulation

		Economic Simuation			*Technical Simulation*		
		Neutral	*Fast*	*Slow*	*Neutral*	*Fast*	*Slow*
% RES	*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%

Table 6.9: Carbon dioxide emission comparison between technical and economic simulation

		Economic Simulation			*Technical Simulation*		
		Neutral	*Fast*	*Slow*	*Neutral*	*Fast*	*Slow*
CO_2 *[Mt]*	*ESOO*	143.8	158.1	110.2	142.6	156.1	109.7
	ISP	130.8	142.3	99.4	128.2	139.7	97.4
	ISP-Storage	131.0	142.5	100.7	128.3	140.0	97.5

6.2.2 ISP – high RES & ISP – high RES with Storage including rooftop-PV systems

A last analysis concerning the economic simulation applied to the ISP – high RES and ISP – high RES with Storage scenario including the Solar-PV rooftop systems has been evaluated. Once again, the 2030 electricity mix obtained under these simulations are very similar to the results of the technical simulations, as displayed by figure 6.6, except for the yearly storage consumptions which sharply increase due to utilization during periods of low electricity price.

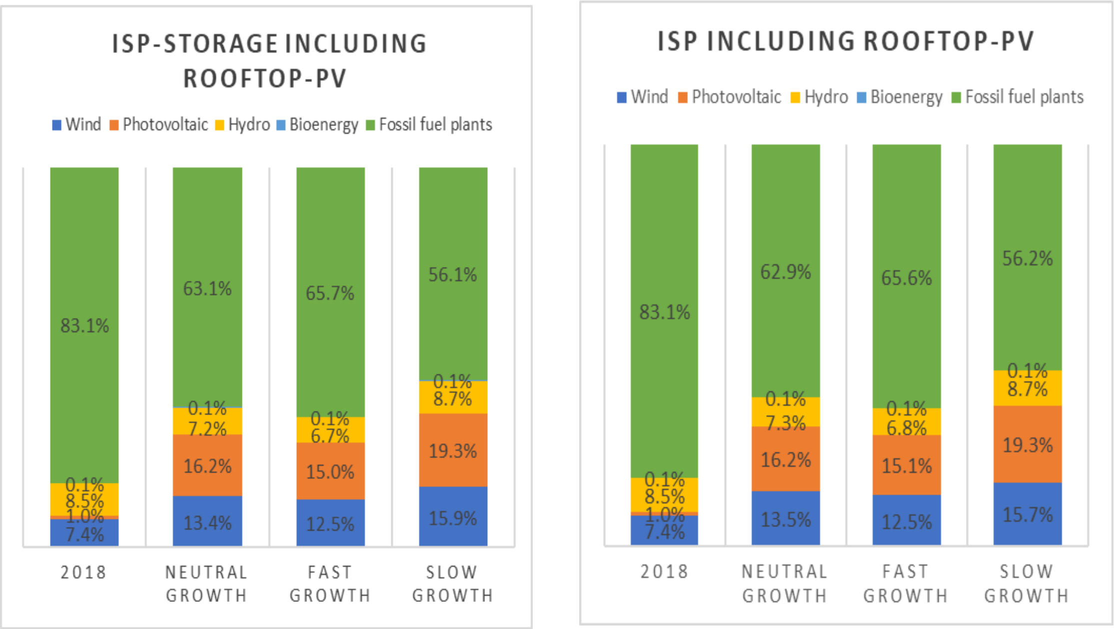


Figure 6.6: 2030 Electricity mix for the ISP – high RES and ISP – high RES with Storage including rooftop-PV systems under the economical simulation

With the introduction of rooftop-PV systems in this analysis, it is forecasted a significant decline in the price during the middle of the day, as a consequence of the substantial photovoltaic power production.

As a result, most of the energy storage consumption is concentrated during that time of the day, given the evident economic reasons.

A clarification of the above explanation is provided through figures 6.7 and 6.8. These describe an example of the balance of the electricity demand and supply in a summer day in January in Australia, where a high solar production during the day. These results have been obtained through the computation of the economic simulation for the ISP – high RES rooftop-PV model under the neutral electricity demand in 2030.

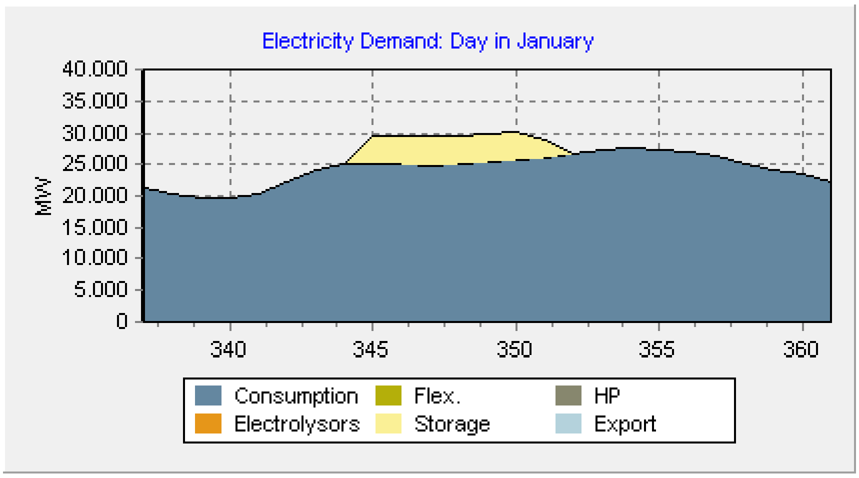


Figure 6.7: Electricity demand during a day in January 2030 under the ISP rooftop-PV scenario and neutral electricity demand

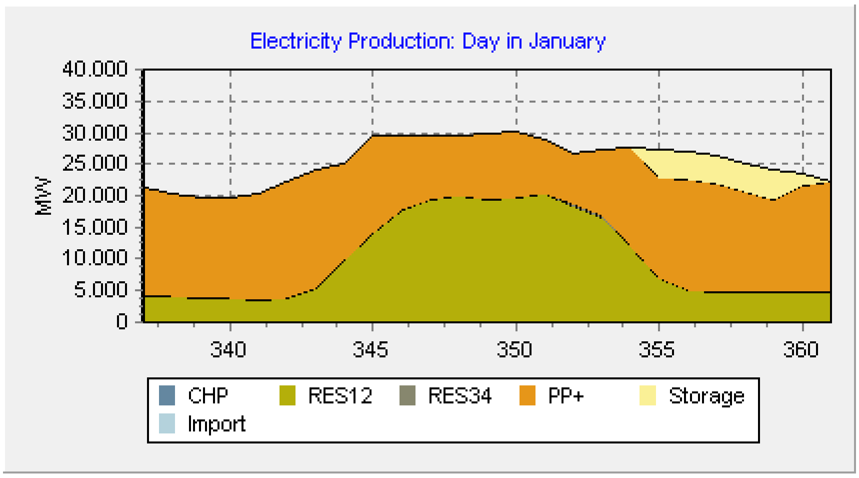


Figure 6.8: Electricity production during a day in January 2030 under the ISP – high RES rooftop-PV scenario and neutral demand (RES12: photovoltaic and wind energy, RES34: run-of-river and offshore wind energy, PP+: thermal and dam hydro power plants)

Figure 6.8 represents in orange the electricity supplied by dispatchable sources (fossil fuel power plants and dam hydro stations) and in green the electricity generation from photovoltaic and wind technologies.

During each moment of the day, the variable renewable power production can only provide a maximum of 70% of the demand. The rest of the power generation is provided by dispatchable sources, which need to contribute at least 30% of the electricity supply at any time for grid stabilization requirements [62]. During the middle of the day, the low fossil fuel consumption decreases the electricity price and makes it economically profitable to store the energy surplus, produced mostly by solar PV systems. This electricity is then discharged to meet the peak demand, which occurs around 6 pm.

As shown in table 6.10, the total yearly storage consumption increased with the inclusion of rooftop-PV systems in both the ISP – high RES and ISP – high RES with Storage scenarios. This results from the rise in renewable electricity production during mid-day and the subsequent drop in the hourly electricity prices.

Table 6.10: 2030 Storage consumption in the economic simulation under ISP – high RES & ISP – high RES with Storage including rooftop-PV

Pump/Battery- Yearly storage consumption		
	2030 ISP with rooftop PV	***2030 ISP-Storage with rooftop PV***
Fast Growth [TWh]	11.40	19.02
Neutral Growth [TWh]	11.54	19.27
Slow Growth [TWh]	11.73	19.86

These results underline that irrespective of the electricity demand growth which will happen in 2030, the investments for the implementation of new storage capacity (especially under the ISP – high RES with storage scenario) will play a crucial role in the Australian electricity distribution; ensuring dispatchability and flexibility to a large slice of the total power generated.

The economic simulations of the ISP – high RES and ISP – high RES with Storage scenarios including rooftop-PV are confirmed to be reliable due to their greater energy storage consumption, which is able to prevent any possibility of black-outs caused by shortages of power generation. This mitigates the issue faced in in the technical simulation.

6.2.3 Flexible demand sensitivity analysis

In the economic simulation, the ISP – high RES and ISP – high RES with Storage scenarios with the inclusion of the rooftop-PV capacity will need to curtail the extra power generated from renewables which will exceed both the demand and storage capacity. This occurs during certain peak generation moments along the year. 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. [62].

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 (as described in paragraph 2.3) which promotes methods of facilitating the integration of renewable energy, by matching the renewable energy output with the electricity demand. Currently, there are private energy retailer companies who have launched pilot projects financed by ARENA (Australian Renewable Energy Agency) in order to incentivize their customers to decrease their electricity use during peak demand hours. This is achieved through the exchange of "credits" which have a monetary value. [55]

Other 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. [109]

The model evaluated therefore shows that an hourly shift in the power consumption can reduce the curtailment of renewable energy by 2030.

Figures 6.9 and 6.10 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.

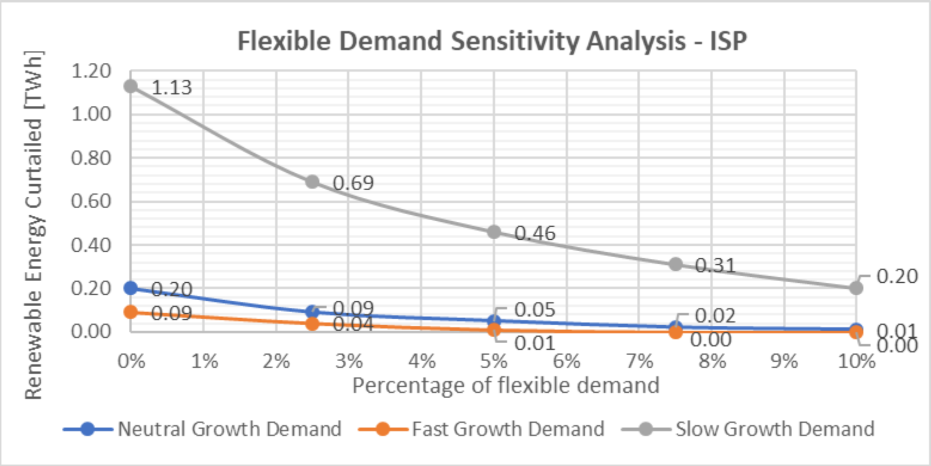


Figure 6.9: Flexible demand sensitivity analysis for the ISP – high RES scenario including rooftop-PV

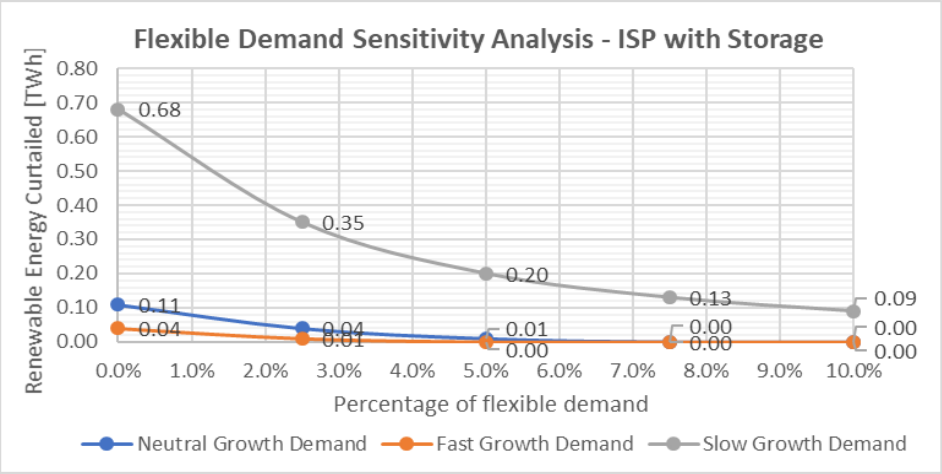


Figure 6.10: Flexible demand sensitivity analysis for the ISP – high RES with Storage scenario including rooftop-PV

Due to its greater storage capacity, the ISP – high RES with Storage scenario is able 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.

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 amount of renewable energy in excess is a small percentage compared to the total 2030 electricity generation, accounting for less than 1%, for each potential demand growth. In addition, when applying the flexible demand of 10%, the reduction of carbon dioxide emissions is considerably small compared to the total emissions, as showed in figure 6.11.

However, preventing the curtailments of “clean energy” by shifting the demand during the day could still provide electricity to a significant number of consumers. For instance, it has been estimated for the ISP Scenario, with a neutral electricity demand, in the case of 10% flexible demand, the amount of electricity saved from its curtailment corresponds to 190 GWh, which for is able to supply electricity to the appliances of over 160,000 households. The appliances considered in this example refer to dishwashers, washing machines, clothes driers, vacuums and irons, which consume a total of 3.19 KWh per day per household (from an Australian study [110] which has calculated the daily energy consumed by each household appliance). These appliances have been chosen as they are not necessarily utilised during one specific time of the day and could easily be used during the peak hours of renewable production.

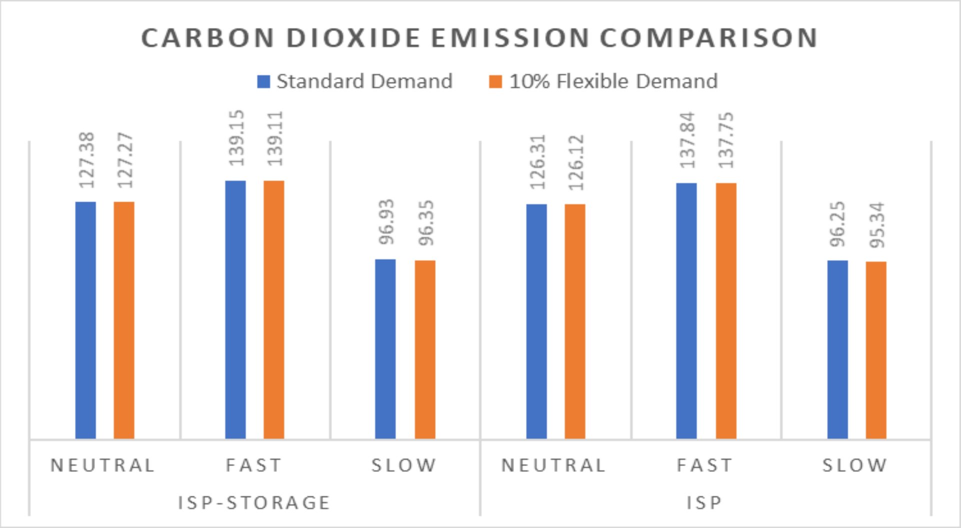


Figure 6.11: Carbon dioxide emissions comparing flexible demand and standard demand

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 study highlights the consumer's potential in taking an individual step towards shifting their energy consumption throughout the day. This has the collective impact of igniting change for a more sustainable future.

Chapter 7

Conclusion

This chapter provides a summary of the most relevant points elaborated during this work. Moreover, it suggests new improvements and areas of research that can be evaluated in greater depth in future studies concerning the modelling of the electricity system in the NEM.

This thesis 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.

Firstly, an overview on the NEM electricity system is provided, which details the changes and challenges, driven mostly by policies and economic factors, which are allowing a fast integration of renewable energy systems. Next, the methodology utilised for the modelling of the 2030 NEM electricity system was introduced. The modelling has been performed using the EnergyPlan software tool.
The reference model for the year 2018 and its calibration were implemented, comparing and validating the energy outputs of the model with 2018 historical energy data from the NEM. The reference model was vital as it served as the starting point for the 2030 electricity mix forecast.

The modelling of the 2030 Electricity mix in the NEM has been evaluated considering three different supply Scenarios: the ESOO – low RES, the ISP – high RES and the ISP – high RES with Storage.
The ESOO – low RES scenario evaluated a scenario which only considers the already committed or currently under-construction projects. The committed developments have a planning horizon which reach 2021.
The ISP – high RES scenario has been included in this work, as it forecasts the development of new energy projects with a horizon that reaches 2030. The ISP – high RES with Storage has a very similar installed power capacity for each energy source to the ISP – high RES scenario by 2030, but also includes the development of a significant pump-hydro storage project which will bring an additional capacity of 2,000 MW and a storage volume of 350 GWh.
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 technical simulation was relevant in this study in order to evaluate the amount of renewable energy generated along 2030 for the different supply scenarios considered. It highlighted that wind and solar energy, in the context of the supply from only large-scale generators, generated respectively 24.2 TWh and 6.6 TWh, compared to only 14.2 TWh generated from wind and the 1.9 TWh from photovoltaics in 2018. These results are due to the significant wind and solar developments considered under the ESOO scenario. This rise of wind and solar energy by 2030 was even higher under the ISP – high RES and ISP – high RES with Storage. Under both these scenarios there will be a yearly production of over 30 TWh for wind energy and over 14 TWh for photovoltaics by 2030.

However, 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.

These achievements translated in a net decrease of carbon emissions, from 148 Mt in 2018 to 127 Mt in 2030, which project Australia to make a further step towards a clean electricity system.

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. Firstly, EnergyPlan treats each energy supply source as an individual plant, aggregating all the national capacity, from several power plants belonging to the same technology, under the same supply source capacity. 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.

Given this context, future works related to the modelling of the electricity mix in Australia could undertake a deeper analysis on the electricity situation of each state in the NEM. This modelling could provide greater insight on which states will drive the shift towards a clean energy system in the future, as well as insights on the changes that will need to occur in specific states which remain highly dependent on fossil fuels.

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Annex A

2030 Cost Database

A.1 Investments costs, fixed O&M cost and technical lifetime for each technology

The table below shows the 2030 forecasted costs for each technology, provided by EnergyPlan.

Technology	**Investment Cost [M€/MW]**	**Fixed O&M [% of investment]**	**Lifetime [years]**
Large Power Plants	0.98	3.16	27
Pump Storage	7.5 [M€/GWh]	1.5	50
Pump	0.6	1.5	50
Turbine	0.6	1.5	50
Industrial CHP	68.3	7.3	25
Wind Onshore	1.3	2.59	25
Photovoltaic	1.1	1	30
River Hydro	3.3	2	50
Hydro Power	3.3	2	50
Hydro Storage	7.5 [M€/GWh]	1.5	50

A.2 Variable O&M costs for each technology

The table below shows the 2030 forecasted variable costs for each technology, provided by EnergyPlan.

Technology	**Variable O&M Cost [€/MWh]**
Thermal PP	2.65
Hydro Power	1.19
Pump	1.19
Turbine	1.19
Industrial CHP	2.7
Wind	0
PV	0
River Hydro	0