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Degree of Master of Science

Feasibility of the energy transition in Australia: A look into the 2022 Integrated System Plan's variable renewable energy trajectories through the lens of feasibility spaces

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Author’s declaration

No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

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ABSTRACT OF THESIS submitted by:

Jonathan ROQUE ALPAÑO for the degree of Master of Science and entitled: *Feasibility of the energy transition in Australia: A look into the 2022 Integrated System Plan's variable renewable energy trajectories through the lens of feasibility spaces*

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Fossil fuels have played an integral role in the development of modern societies, serving as a cornerstone for modern industrialization and energy generation. However, adopting a fossil-fuel dominated energy system has led to unprecedented rates of greenhouse gas emissions, contributing significantly to acute anthropogenic climate change. The energy transition away from fossil fuels has gained paramount importance as a way of addressing these challenges. Variable renewable energy (VRE) is central to Australia's decarbonisation agenda, prioritising scaling up solar and wind power to meet the increasing demand for energy currently satisfied by a market that leverages the country's abundant fossil fuel resources. This study aimed to examine Australia's trajectories for the development of utility-scale VRE capacity to 2050, as outlined in the Australian Energy Market Operator (AEMO)'s 2022 Integrated System Plan (ISP) for the National Electricity Market (NEM), and implement a feasibility space framework to comparatively assess and analyse these trends. The principle findings were that utility-scale wind power capacity in Australia will experience an almost threefold accelerated growth rate in capacity to 2050 relative to the rates during the period from 2013 to 2022. While this trajectory appears ambitious, the optimal wind resources in the country, partnered with the current established and planned political frameworks and incentive mechanisms for key energy players makes it feasible in all likelihood. Utility-scale solar trajectories are on track with historical trends in the country, which indicates feasibility, however, allows for the possibility of setting more ambitious solar targets. Compared with the reference case countries, India, Germany and Italy, the historic trends are relatively on track, however, the level of VRE capacity by 2050 fall substantially behind the targeted capacities for India and Germany already by 2030. Various aspects of the Australian energy transition are also outlined that need to be overcome by political will and skill in order to achieve the ISP trajectories easily, and be on par with the global energy landscape.

Keywords:
Australian Energy Market Operator, Integrated System Plan, National Electricity Market, Step Change scenario, feasibility, energy transition, variable renewable energy, trajectories, renewable energy targets

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I am sincerely grateful to my parents, whose unconditional support was felt every single day despite the thousands of kilometres in distance between us. This body of work is dedicated to you. You exemplify hard work and commitment in everything you do, and the fact that I strived to approach every step of this journey with similar values is a testament to the depth of your positive influence and upbringing. This achievement is yours as much as it is mine.

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List of Abbreviations

Australian Energy Market Operator (AEMO)

British Petroleum (BP)

Carbon Dioxide (CO_2)

Clean Development Mechanism (CDM)

Commonwealth Scientific and Industrial Research Organisation (CSIRO)

Community Energy Initiatives (CEI)

Concentrating solar power (CSP)

Department of Climate Change, Energy, the Environment and Water (DCCEEW)

Economy Incentive (EI)

Erneuerbare-Energien-Gesetzes (EEG)

Energy Information Administration (EIA)

European Commission (EC)

European Union (EU)

Exajoules (EJ)

Flue gas desulphurisation (FGD)

Geologic Resources Supply-Demand Model (GeRS-DeMo)

Gigaton (Gt)

Gigawatt (GW)

Gigawatt hour (GWh)

Global Energy Transformation (GET)

Internal Combustion Engine (ICE)

International Energy Agency (IEA)

International Institute for Applied Systems Analysis (IIASA)

Intergovernmental Panel on Climate Change (IPCC)

International Renewable Energy Agency (IRENA)

Integrated System Plan (ISP)

Joint Implementation (JI)

Kilometres (km)

Kilowatt (kW)

Large-scale Renewable Energy Target (LRET)

Leveraged Cost of Electricity (LCOE)

Mandatory Renewable Energy Target (MRET)

Megawatt (MW)

Megawatt-hour (MWh)

Micrometre (μm)

Million Barrels per day (mb/d)

Multi-level Perspective (MLP)

National Electricity Market (NEM)

National Renewable Energy Laboratory (NREL)

Nationally Determined Contribution (NDC)

Network Dynamics (ND)

Nitrous oxide (N_2O)

The Organization for Economic Cooperation and Development (OECD)

Paris Climate Conference (COP21)

Participation & Exchange (P&E)

Petajoules (PJ)

Photovoltaic (PV)

Planning and Process (P&P)

Renewable Energy (RE)

Renewable Energy Sources (RES)

Renewable Energy Target (RET)

Research Question (RQ)

Single Wire Earth Return (SWER)

Small-scale Renewable Energy Scheme (SRES)

Small-scale technology certificate (STC)

Special Report on Emission Scenarios (SRES)

Step Change Scenario (SCS)

Sustainable Development Goals (SDG)

Terawatt-hour (TWh)

Thermal Power Plants (TPPs)

Ton of oil equivalent (toe)

United Nations General Assembly (UNGA)

Variable Renewable Energy (VRE)

World Energy Council (WEC)

1 Introduction

1.1 Defining the problem

The demand for energy globally is increasing at an unprecedented rate. Given upward trajectories of population growth, accelerated rates of urbanization, and international economic development, the United States Energy Information Administration (EIA) forecast an estimated 50% increase in world energy use by 2050 (Sourmehi, 2021). Fossil fuels have stubbornly comprised 80% of the global energy mix for decades and is projected to maintain its position as the world's largest energy source in 2050 (IEA, 2022). This increasing trend in global energy consumption is appropriately manifested in the growth of energy-related CO2 emissions globally, which has increased by 7% in just the past 2 years, amounting to an alarming 36.8 billion tonnes, the highest in history (IEA, 2023a). Abundant global CO2 emissions is a primary contributor to climate change and needs to be regulated to collectively be on track to achieving the goal of limiting global warming to below 2 degrees Celsius, as outlined in the Paris Agreement adopted during the UN Climate Change Conference (COP21) (United Nations, n.d.). To expedite progress towards these targets, curtailing long-dominant global fossil fuel usage has been top-priority for multiple governments around the world in recent years to mitigate climate change. This urgent need for strategic action has provided impetus for a transition away from fossil fuel consumption towards renewable sources to generate majority of the world's energy needs, and to prevent the earth's biophysical thresholds and socio-economic tipping points from being surpassed (Adger et al., 2007; Moser et al., 2009; Werners et al., 2013). In Australia, the transition to renewable energy has been gaining momentum in recent years, with electricity generation more than doubling over the past decade (Department of Climate Change, Energy, the Environment and Water (DCCEEW), n.d.). This national action is facilitated by the government and private sector's initiative to reduce the country's long-standing strong dependence on fossil fuel and meet its international climate commitments. However, questions remain about the prospect of the different renewable energy technologies in Australia, and the feasibility of the forecasted targets in the context of the country's unique circumstances.

1.2 Research Objective & Methodology

This thesis aims to explore the prospect of variable renewable energy in Australia and examine the feasibility of the national energy transition targets. Particularly, the feasibility of the wind and solar trajectories to 2050 under the Step Change Scenario (SCS) as outlined by the Australian Energy Market Operator (AEMO)'s Integrated System Plan (ISP) for Australia's National Electricity Market (NEM). This is done by firstly examining the current state of the fossil fuel-dominated global energy system, how this came to be, and the effects of the prevalent adoption of such a system. Afterwards, the global energy transition is examined, along with the principal factors that are currently driving it, placing specific focus on the Australian electricity market transformation.

The specific research objectives of this thesis are the following:

1) To investigate Australia's and the global current energy landscape and net zero transition initiatives through a comprehensive literature review that will provide the foundation for the successive research
2) To thoroughly scrutinise the targets set out on Australia's ISP for the NEM given historical and contemporary trends towards achieving previous similar targets
3) To contextualise Australia's variable renewable energy trajectories through a comparative analysis alongside global targets
4) To explore Australia's electricity market transformation and to determine whether it is feasible and attainable given the established timeline

The thesis will utilize the feasibility space framework, defining Australia's SCS goals as outlined in the 2022 ISP as the target case. Various similar situations from different countries will be defined as reference cases to contextualize Australia's renewable energy trajectories, along with Australia's previous trends of utility-scale variable renewable energy capacity deployment. The feasibility space framework will be further discussed in-depth in Chapter 3 of this thesis.

Overall, the feasibility of these specific renewable energy targets in Australia has, for the most part, remained insufficiently examined. Even more, Australia's renewable energy targets and commitments have inadequately been comparatively assessed in the context of other countries' goals, which this thesis hopes to address.

1.3 Research questions

This thesis aims to assess the feasibility of two specific targets as outlined in the AEMO ISP's most likely Step Change Scenario for Australia's NEM:

i. The ninefold increase of utility-scale variable renewable energy (VRE) by 2030, further doubling by 2040 and again by 2050 (from 15GW to 140GW), and

ii. The substantial growth of distributed storage and fivefold increase of distributed photovoltaic (PV) capacity (from 15GW to 70GW), with majority coupled with an energy storage system

To achieve this aim, the thesis is structured around the following research questions:

1. **What factors drive the rate of variable renewable energy deployment in Australia and globally?**
2. **Is the Step Change Scenario (SCS) outlined in the AEMO's ISP feasible under realistic assumptions?**

3. **How do the trajectories of solar and wind energy capacity in Australia compare to trends and targets on a global scale?**
4. **How does policy and regulatory support influence the feasibility of renewable energy deployment in Australia moving forward?**

Research question (RQ) 1 focuses specifically on the technological, socio-technical, and political driving factors that are significantly influencing the global energy transition away from non-renewable sources. Addressing this RQ entails delving deep into existing energy transition literature to identify driving factors in the global energy transition initiative, then tailoring and uniquely identifying the application of these factors within the Australian context as a crucial step in implementing the feasibility space framework. Australia's history and long-standing dependence on fossil fuels for both domestic generation of energy needs, and as a primary constituent significantly contributing to the country's GDP and dominant position in the global energy market will be lightly covered. A connection will be established between the broader, global context and how Australia's energy landscape fits into this picture, and vice versa.

RQ2 and RQ3 will focus specifically on the conditions defined in the Step Change Scenario of the 2022 AEMO ISP. Specific targets from this strategic document will be closely scrutinised and defined as the target case in the implementation of a feasibility space framework. Feasibility of these conditions will be determined by their position on the feasibility space relative to the reference cases. As part of this, Australia's historical utility-scale VRE capacity deployment over the past decade will be examined, as facilitated by the Renewable Energy Target (RET) previously set to be achieved by 2020. Under RQ3, targets from specific target countries that have shown similar historical trends during a transition to renewable energy will be highlighted and defined as reference cases to contextualize and compare Australia's targets. All target and reference cases will be measured and normalised, then mapped on a feasibility space with the goal of constructing a feasibility space based on outcome distribution.

RQ4 will investigate the Australian policy frameworks currently in place on a local, federal, and national scale, to underpin the national energy transition initiative. Key legislations and policy will be highlighted, and connections will be established regarding these mandates and how they serve to facilitate or hinder the contemporary energy transition in the country.

1.4 Thesis structure

Chapter 1 establishes the fundamental research interests and provides a general introduction underlying the purpose for conducting such research. The principle problem and relevant research questions that the thesis aims to address are identified. The objectives of the research are then framed, which guide the direction of the study, followed by a general description on the specific methods that were employed to achieve these goals. Lastly, the structure of the thesis is outlined to assist and inform readers.

Chapter 2 presents the literature review section of the thesis, covering a range of subjects that underpin the research topic. Firstly, the fossil fuel complex is covered, which includes the historical development of the incumbent fossil-fuel dominated global energy system we are currently leveraging, its causal links with the unprecedented rates of anthropogenic climate change taking place, and the urgent global decarbonisation agenda primarily through transitioning away from the path of fossil fuel dependence into a more prevalent deployment of variable renewable energy. The concept of feasibility and its various domains and existing frameworks are introduced, along with its topicality in the context of the energy transition, which establishes the scene for the succeeding chapter.

Chapter 3 firstly identifies research gaps in the extensive review of existing literature on energy transition. This chapter then introduces specific targets from the Step Change Scenario as outlined in the AEMO's 2022 ISP for the NEM, which will be the focal point of the entire thesis. The feasibility space framework is then introduced and explained thoroughly, explaining how this framework will be implemented in the context of assessing the feasibility of the VRE trajectories outlined in the 2022 ISP.

Chapter 4 comprehensively explains the various stages to the implementation of the feasibility space framework, and outlines all the results that were gathered. The target and reference cases are clearly defined as part of the establishment of the framework's outside view. Afterwards, the inside view entails determining primary driving factors specific to the Australian energy transition, which political will and skill will need to overcome for a substantially greater rate of VRE deployment.

Chapter 5 discusses the preliminary findings and results of the overall study, interpreting the results, before extensively covering the different specific political factors that have influenced the energy transition and ultimately contributed to the results. Various essential political frameworks are outlined, which are instrumental in shaping the national energy transition moving forward.

Chapter 6 serves as the culmination by firstly identifying how this thesis contributes to the existing body of work on the intersection between energy transitions and feasibility assessments. This chapter outlines the challenges that were experienced in the creation of the thesis, defining its limitations, while providing means in which future research and studies can build upon it.

Overall, this thesis aims to provide a comprehensive assessment of the feasibility of renewable energy targets in Australia, contextualized by similar global targets. The findings of this thesis will be of interest to policymakers, industry stakeholders, and anyone concerned with the future of Australia's energy system and its impact on the environment.

2 Literature Review

This chapter will provide an extensive review of existing literature that covers a wide range of subjects underpinning the overarching topic of the thesis. It will first provide a historic background on the diffusion of fossil fuel consumption, before discussing the resulting contemporary fossil fuel complex and global heavy dependence on conventional fuel types. Afterwards, this chapter will discuss the causal link between the incumbent fossil fuel-dominated energy system and the emerging issue of anthropogenic climate change. Then, it will discuss in detail the current landscape of the low-carbon energy transition and its different governing factors, the current energy landscape in the Australian context, as well as the concept of feasibility and the various ways in which it has been defined, quantified, and evaluated. Lastly, current gaps in existing knowledge is outlined, along with the key challenges in the global energy transition.

2.1 Introduction

The urgency and feasibility of the global energy transition and different climate change mitigation measures have been covered from multiple perspectives across a wide range of academic literature. The diffusion of renewable energy has an extensive history, from early development with primitive and rudimental infrastructure, to the contemporary technological advancements responsible for facilitating increased rates of uptake. Renewable energy has emerged as a crucial topic of discussion globally, as governments and societies strive to mitigate and abate the adverse effects of climate change and transition away from traditional energy sources to renewable ones. This thesis is embedded within existing literature, aiming to draw and delve into previous studies assessing the feasibility of different energy transition pathways. This literature review section will be compartmentalised into multiple sub-sections, and will provide an extensive review of existing literature that covers a wide range of subjects underpinning the overarching topic of the thesis. It will first provide a historic background on the diffusion of fossil fuel consumption, before discussing the resulting contemporary fossil fuel complex and global heavy dependence on conventional fuel types. Afterwards, this chapter will discuss the causal link between the incumbent fossil fuel-dominated energy system and the emerging issue of anthropogenic climate change. Then, it will discuss in detail the current landscape of the low-carbon energy transition and its different governing factors, the current energy landscape in the Australian context, as well as the concept of feasibility and the various ways in which it has been defined, quantified, and evaluated. Lastly, current gaps in existing knowledge is outlined, along with the key challenges in the global energy transition. By examining the existing body of research and scholarly articles, this review seeks to shed light on the progress made, gaps in knowledge, and potential pathways for the successful integration and expansion of renewable energy in Australia's national energy mix.

2.2 Fossil Fuel Complex

The discovery and extraction of fossil fuels, including coal, oil, and natural gas, revolutionised energy production and significantly expedited industrialisation. As such, this subsection will cover the global diffusion and development of fossil fuel usage for energy production historically, its place and relevance within the Australian context, as well as its economic relevance, and the environmental implications of a prevalent uptake of fossil fuels that eventually heralded the contemporary global transition into renewable energy sources.

2.2.1 Historical Diffusion of Fossil Fuel Usage

Prior to the European Industrial Revolution, human history has shown that fossil fuels had no notable impacts on economic activity, with momentary and strictly local exceptions. Industrial revolutions have historically had profound impacts on global demand for energy, as this serves as an indispensable fundamental material that empowers the development of industrial economies. Fossil fuels have proven to be the primary energy source that facilitated the previous three industrial revolutions (Yang et al., 2021). The emergence of coal as a primary resource in the energy mix and economy can be attributed to the first Industrial Revolution, commencing in the 18th century in Britain, which subsequently spread to other parts of the world. The two main activities that increased demand for coal during this time were coke for the manufacture of iron, and to power steam engines. In the 1700s, prior to coal becoming the preferred energy source, it was competing with wood as the primary thermal energy source, underpinned by a multitude of reasons. First and foremost was the systematic transition from an 'organic economy' that was fuelled by wood, to a 'mineral-based energy economy' in Britain (Wrigley, 2013). Furthermore, the transition was facilitated by periods of wood shortages, given a finite area of land where it could grow, as well as a disparity in the ease of transport between the two. Where wood had to be acquired from different regions and posed logistical problems to transport due to size, coal did not pose the same challenges. From an economic standpoint, coal emerged as the primary energy source during this period, as it served to substitute rudimentary human and animal labour power, which was instrumental in significantly increasing industrial productivity (Pirani, 2018). Ultimately, this, partnered with the sheer abundance of coal, allowed it to become the dominant global energy source during this period. Coal did not make the industrial revolution, but rather enabled its significant rates of diffusion and development, exhibiting the economic and political value and power in energy. The scale of advantage brought about by extensive coal usage was evident in the unprecedented urban development experienced by Britain during this time. By the late 19th century, almost half of England and Wales was urbanised, as opposed to 18 per cent in France, and 25 per cent in the Netherlands, Italy, and Belgium (Xu et al., 2018). Furthermore, the fuel transition of Britain's municipal lighting from vegetable or whale oil to coal gas during this time essentially lengthened the working day significantly, significantly increasing economic productivity. This move from previous traditional and primitive energy sources to coal proved to be one of the first of many historical energy transitions. Moreover, this proved to be a crucial time that ultimately showed the transition from a global economy that was predominantly handicraft and agrarian, to one which was dominated by machine manufacturing and industry.

The second Industrial Revolution and the dawn of the 20th century gave rise to various innovations utilising technological systems that further underpinned fossil fuel dependence. Among these, the most significant would be the internal combustion engine (ICE), which was instrumental in ushering the significant production and use of oil (van der Kooij, 2017). The integration of ICEs into vehicles such as trucks, cars, ships, and the eventual invention of the plane, contributed greatly to global oil demand (Allen, 2011). Still, to this day, ICEs that operate on fossil fuel oil continue to prove nearly a quarter of the world's energy, exhibiting the significance of this particular technological innovation (Reitz et al., 2019). The substantial levels of oil production also brought about the induction and proliferation of the petrochemical industry, which ultimately further increased the scale of oil manufacture, and global fossil fuel dependency. The turn of the century also saw the emergence of modern mines in every continent, which resulted in a prominent sixfold increase in coal output globally, as measured in millions of tonnes of coal equivalent (see Figure 1). The significant majority of fossil fuel consumption and production, however, remained within Britain, Germany, France, and the USA (Pirani, 2018).

Another notable development that had significant implications for fossil fuel consumption during the second Industrial Revolution was the propagation of electricity and the subsequent establishment of extensive electrical distribution systems. These were instrumental in enabling electricity to be more accessible and practical, further increasing the rates of urbanization and supporting unprecedented rates of economic development (Haradhan, 2019).

The increased availability and accessibility of electricity gave rise to the electrification urban and industrial electrification. This coincided with the rapid emergence and growth of the textiles, iron, steel and manufacturing industries which required substantial amounts of energy to power its systems and machinery (Groumpos, 2021). In addition to this, a transportation revolution was taking place as railway systems were established, and the ICE became more widely adopted in automobiles, while the significant rates of urbanisation and growth of cities meant an increasing population, and ultimately greater demand for heating, transportation, and lighting. These systems and demands were predominantly met by fossil fuels.

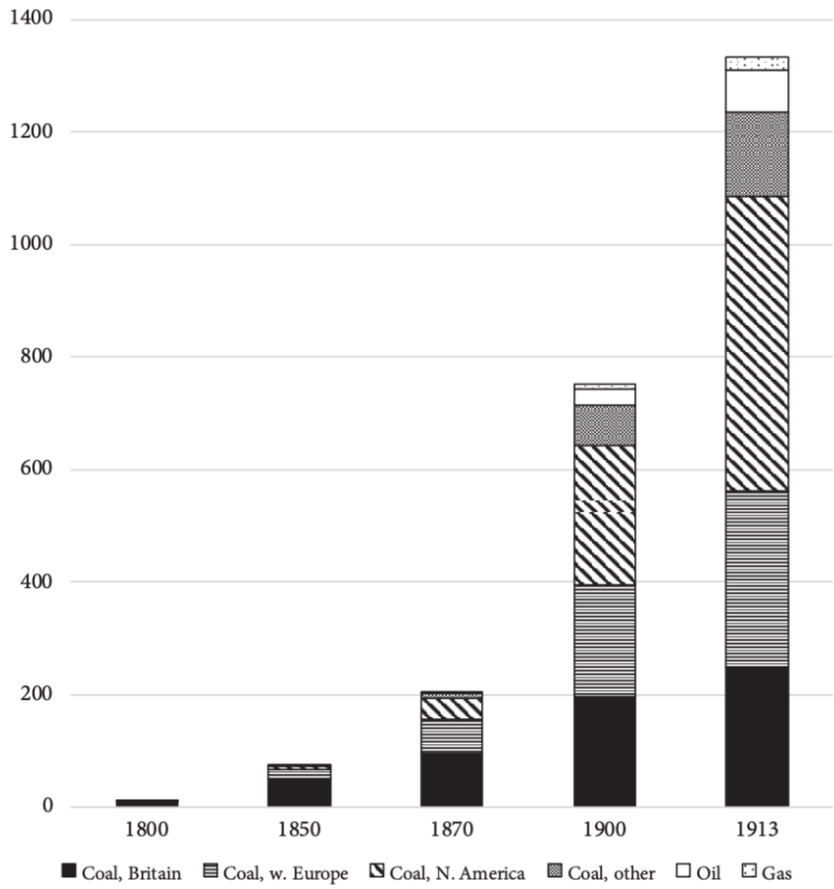
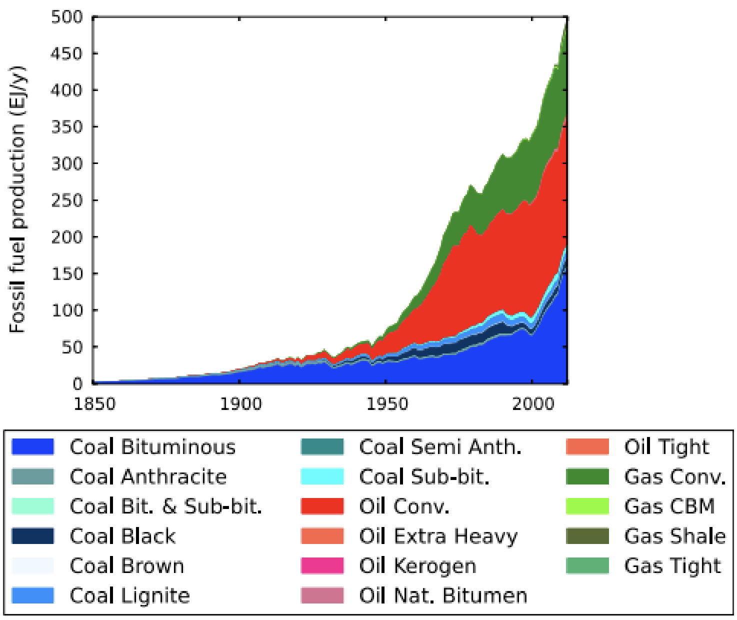


Figure 1: Production of fossil fuel in the first two Industrial Revolutions

(source: Pirani, 2018).

As a result, oil refining and coal mining processes developed rapidly, as did consumption of coal, oil, and natural gas. During this period, coal output experienced an average annual growth rate of 3%, while output of oil grew annually at an average of 7%. Towards the end of the second Industrial Revolution, coal consumption annually accounted for greater than 75% of the annual energy consumption, while oil consumption increased 94000% from 3 PJ to 2,823 PJ, ultimately accounting for 12.5% of total energy consumption (Yang et al., 2021).

These two periods in history paved the way for the technological innovations and systems that we experience in modern times, however, they were also instrumental in supporting the contemporary energy demand that continues to increase drastically, and the current levels of fossil fuel consumption. Modelling of Mohr et al., (2015), utilising the Geologic Resources Supply-Demand Model (GeRS-DeMo), provides a valuable visualisation, which outlines the steadily increasing trend of historic global gneral fossil fuel production for the period from 1850 to 2000 (see Figure 2). Appendix Figures 20, 21 and 22, also provide a model visualisations of the historic production rates of coal, oil, and gas across several regions that include Australia, China, the USA and Germany, among others. Though the three fuel types have developed at different rates temporally and geographically, the same increasing trend is evident throughout.



(d) Fossil Fuels

Figure 2: Global historic fossil fuel production

(source: Mohr et al., 2015).

2.2.2 Contemporary Fossil Fuel Landscape Models

While prevalent and extensive utilisation of fossil fuels commenced in the nineteenth century, greater than 50% of fossil fuels consumed historically were combusted in the period since 1950 (Pirani, 2018). Currently, fossil fuels remain crucial in supplying global energy needs, comprising greater than 80% of the world's primary energy consumption (Mohr et al., 2015). Scenarios modelled in British Petroleum (BP)'s Energy Outlook 35 have shown that primary energy demand is forecasted to increase by 41% in the period between 2012 and 2035, with an average annual growth of 1.5%. This increased demand will continue to be predominantly supplied by conventional energy sources such as fossil fuels, which include coal, gas, and oil (see Figure 2). In the fossil fuels sphere, gas will exhibit the highest rates of growth to 2035 at 1.9% per annum, with coal growth at 1.1% per annum, and oil with the slowest rate of growth at 0.8% (BP, 2014). During this period, fossil fuel shares gradually evolve. Gas shares show a steady gain rate, while the share of oil in the global energy mix proceeds at a declining rate. The position of oil as the predominant fuel is briefly challenged by coal, which gains shares steadily towards 2035. By 2035, coal, oil, and gas aggregate to around a 27% share in the global energy mix, and there will not be a single dominant fuel type – a first since the Industrial Revolution. Collectively, fossil fuels show a decreasing trend and lose share but will maintain their position as the dominant energy form in 2035, accounting for an 81% share of the global energy mix, compared to 86% in 2012 (BP, 2014). Global primary energy consumption is forecasted to continue to increase in the period between 2020 to 2100, with fossil fuels continuing to meet majority of the world's demand. To contextualise this trend, the author investigated various existing literature containing projections from key energy organisations and compiled findings into Table 1.

Table 1: Global Primary Energy Consumption Projections from 2020-2100, in exajoules (EJ)

Organisation & publication year	2020	2030	2050	2100
European Commission (EC) (2006)	570-610	650-705	820-935	N/A
International Institute for Applied Systems Analysis (IIASA) (2007) (adopted from Riahi et al., 2007).	555-630	N/A	800-1175	985-1740
Shell International (2008)	630-650	690-735	770-880	N/A
World Energy Council (WEC) (2007) (Caille et al., 2007).	615-675	700-845	845-1150	N/A
International Atomic Energy Agency (IAEA) (2009)	585-650	670-815	N/A	N/A
International Energy Agency (IEA) (2010)	N/A	605-705	N/A	N/A
Tellus Institute (2010) (adopted from Raskin et al., 2010)	504-644	489-793	425-1003	243-1200
Energy Information Administration (EIA) (2010)	600-645	675-780	N/A	N/A
British Petroleum (BP) (2011)	565-635	600-760	N/A	N/A

Figure 2 shows the evolution of the energy mix with the 20 countries used as reference cases. This underpins the assumption that though the production and demand for fossil fuels around the world will continue to increase now into the future in order to satisfy majority of the evolving global energy needs, its share in the energy mix will gradually decline in favour of other non-fossil fuel energy sources. This shows that the global fuel mix diversifies over time. Historically, as global economies and GDP grew, the fuel mix showed a proclivity to become more diversified, supported by technological innovations, endowment of resources, and the underlying economic structure. (Mahalingam et al., 2018). A premium is set on fuel types that are considered cleaner and more convenient, and the subsequent transition between preferred fuel types are guided by relative prices (Soytas et al., 2003).

Scenarios modelled in the IEA's World Energy Outlook have served to support the trends as shown in BP's report. According to the IEA, the demand for oil globally is forecasted to increase from 86.7 million barrels per day (mb/d) in 2011 to 101.4 mb/d in 2035 (IEA, 2013). While demand continues to show an increasing trend to 2035, the average rate of demand growth gradually decreases, from 1.1% annually towards 2020 to just 0.4% per annum thereafter, as a result of the emergence of alternative fuel types, and the demand decrease in majority of Organization for Economic Cooperation and Development (OECD) markets, despite increasing demand in most non-OECD markets.

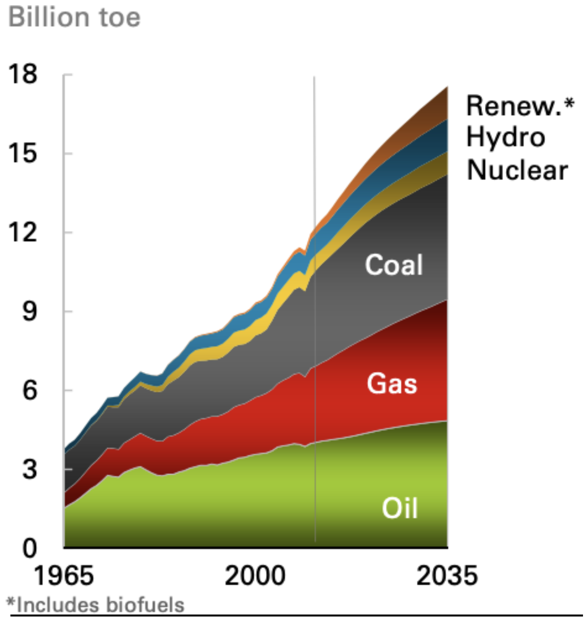


Figure 3: Global consumption by fuel type

(source: BP, 2014).

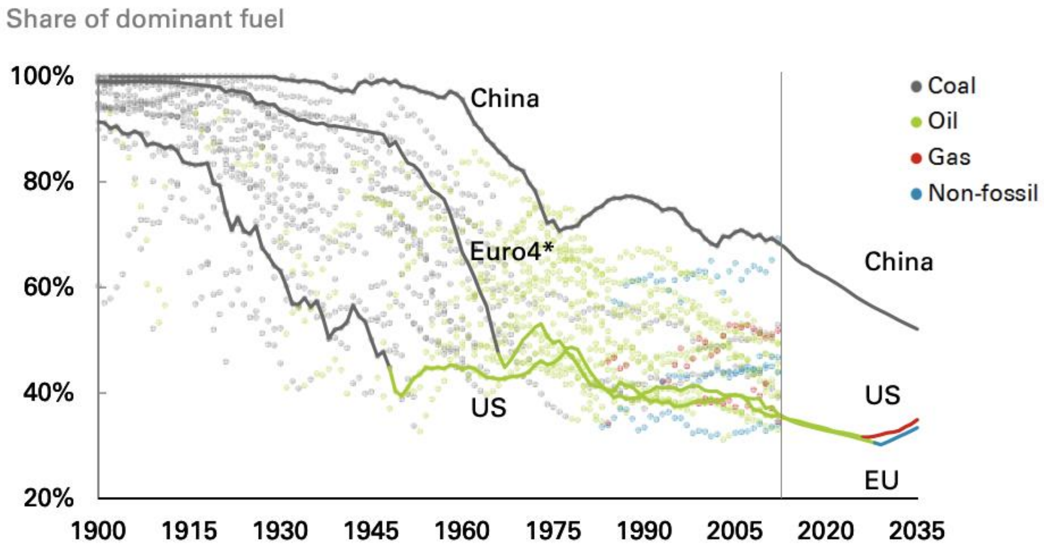


Figure 4: Fuel Mix evolution across 20 major countries

(source: BP, 2014).

Scenarios as modelled by the IEA and BP integrate and take into account a variety of factors which include technological development, demand, and a range of policy agreement assumptions which change regional production capacity. This literature makes it evident that while the rates of fossil fuel demand and production are projected to decline in the future, they remain predominant and will maintain its position as the dominant fuel type to meet global energy requirements.

2.2.3 Causal Links with Anthropogenic Climate Change

The unprecedented rates of fossil fuel consumption has proven to be inextricably linked to the expedition of climate change. Energy production and the combustion of fossil fuels have been the principal contributors to the release of greenhouse gases (GHG)s into the atmosphere, fundamentally establishing a causal link among future energy production with anthropogenic GHG emission and global warming induced by human activity (Höök & Tang, 2013). This is underpinned by the modelling done by Patzek & Croft (2010), which provided a quantitative link across major coal-producing countries, their ultimate coal production and peak rates, as well as ultimate carbon dioxide (CO_2) emissions and peak rates (see Table 1). Various studies have shown that there is a positive correlation between rates of fossil fuel combustion and GHG emissions, leading to question marks regarding sustainable fossil fuel mining and usage.

Table 2: Summary of major coal-producing countries' CO2 emissions and coal production

Country	EJ peak[a] (year)	Ultimate coal production (EJ)	Peak coal rate (EJ/y)	Ultimate CO_2 emissions (Gt)	Peak CO_2 rate (Gt/y)
China	2011	4015.6	75.8	365.0	6.9
USA[b]	2015	2756.7	26.8	250.5	2.4
Australia	2042	1714.5	23.5	155.8	2.1
Germany/Poland	1987	1104.4	14.9	100.4	1.4
FSU[c]	1990	1070.3	20.3	97.3	1.8
India	2011	862.6	13.6	78.4	1.2
UK	1912	753.0	7.7	68.4	0.7
S. Africa	2007	478.6	6.8	43.5	0.6
Mongolia	2105	279.2	3.2	25.4	0.3
Indonesia	2012	135.5	5.8	12.3	0.5
Global ultimate/peak	2011	13,170.5	160	1197.0	15.0

[a] Note that sometimes the peaks of produced coal tonnes and EJ do not coincide.
[b] Excluding Alaskan coal
[c] The Former Soviet Union, excluding the Russian Far East coal.

The extraction and subsequent use of fossil fuels have had and are continuing to have significant adverse effects on the Earth's planetary boundaries. At the forefront of the anthropogenic climate change debate is fossil fuels' GHG emissions, specifically in the form of CO_2, nitrous oxide (N_2O), and methane (CH_4). Relative to pre-industrial levels, these three greenhouse gases have shown an increase of 40%, 20%, and 150% respectively (Okafor et al., 2021). Furthermore, 65% of global anthropogenic CO_2 emissions result from fossil fuel combustion. Of these emissions, natural gas would account for 20 percent, while oil and coal account for 35 and 45 percent. Ultimately, approximately two-thirds of global GHG emissions are a by-product of energy production and consumption processes (Covert et al., 2016).

The 2000 Special Report on Emission Scenarios (SRES) further underpins and accentuates the causal link between CO_2 emissions as a result of energy production and anthropogenic global warming. This document, which outlines 40 scenarios for the future of fossil fuel production, is crucial in assisting the Intergovernmental Panel on Climate Change (IPCC) to assess and forecast future climate change (IPCC, 2000). Climate change and global warming as a result of GHG emissions have been proven to be inextricably linked to fossil-fuelled energy production. Figure 5 shows the mean, median, and percentile values of CO_2 emissions to 2100 from the 40 scenarios outlined in the SRES (Sivertsson, 2004). While these projections are noticeably smaller than the historical trends of CO_2 emissions presented by the IEA (2010) (Appendix; Figure 23), the conclusion is consistent across both studies that fossil fuel utilisation is singlehandedly the most dominant source of global GHG emissions (Höök, 2010). Van Vuuren & O'Neill (2006) account for this discrepancy by providing a mechanism showing that global CO_2 emission inventories have a variance of around 15% contingent on source and methodology. Ultimately, however, they support the IEA and the IPCC's SRES similar argument attributing emissions to fossil fuel use (Van Vuuren & O'Neill, 2006). As such, the global transition away from fossil-fuel dominated energy systems is a collective action that is of utmost urgency. Under the scenario that no dominant programs that sequester or reduce CO_2 emissions are activated, models have forecasted that the 26 gigatons (Gt) of CO_2 emissions measured in 2000 will drastically increase to 77 Gt by 2100, with levels of atmospheric CO_2 rising from 370 parts per million (ppm) to 750 ppm (Lincoln, 2005).

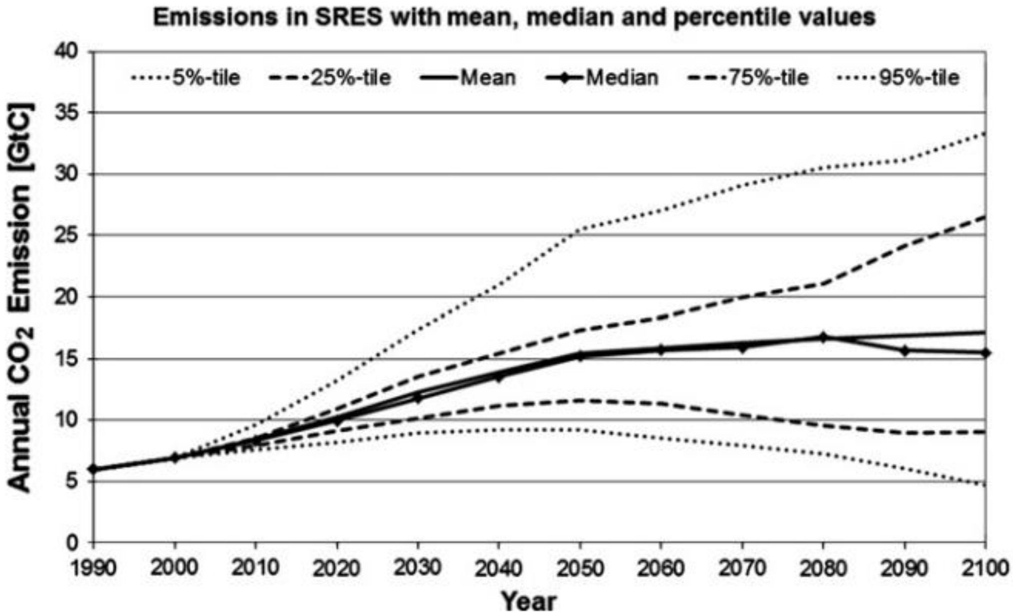


Figure 5: Mean, median and percentile values of CO2 emissions from the 40 IPCC SRES scenarios

(source: IPCC, 2000; adapted from Sivertsson, 2004).

Furthermore, the 2014 IPCC Working Group II Report expresses strong confidence in the high risks of global aggregate impacts linked to a global average temperature increase exceeding 2°C (IPCC, 2014; Scott et al., 2015). Between 1880 and 2012, the average temperature of the globe increased by 0.85 ℃. Presently, there are increased variation in temperatures and severe weather, resulting in increased degree and incidence of hot days across most regions of the globe. Relative to pre-industrial levels, a temperature increase of between 1.5 ℃–4.8 ℃ is estimated by the year 2100 (IPCC, 2013).

More than the causal link between gaseous emissions and fossil fuel use, the entire lifecycle of such non-renewable fuel types, from its extraction, transportation, storage, utilisation and postutilisation, pose additional adverse environmental issues (Vallero, 2020). In the case of coal combustion, a significant volume of particulate matter (PM) in the form of ash is released into the atmosphere, further contributing to anthropogenic climate change and global warming (Fuzzi et al., 2015; Jacobson, 2002; Rai, 2016). Furthermore, fine particulate matter (PM), such as PM_{10} and $PM_{2.5}$, possessing diameters below 10 micrometres (μm), have been shown to have significantly adverse effects to human health by damaging the pulmonary and cardiovascular systems (Alfaro-Moreno et al., 2007; D'Amato & Akdis, 2020). Compounding the inauspicious effects of fossil fuel usage to the environment are the risks posed to public health, further reinforcing the urgency of a collective global transition away from these systems.

Furthermore, the extraction of fossil fuels have largely been crucial in contributing to wastewater and solid waste pollution. A causal link has been established between pollutant concentration in bodies of water within the immediate vicinities of coal and oil extraction sites, with sulfur as the most abundant (Giri, 2014; Arkoç, 2016). The exploration and extraction of natural gas and oil has historically resulted in land degradation, soil compaction, and disturbances to vegetation, impacting local biodiversity and ecosystems. Significant amounts of gypsum from limestone-based flue gas desulphurisation (FGD), along with bottom and fly ash, are produced through the combustion of fossil fuels. These excess by-products that contain abundant volumes of toxic chemicals pose the possibility of pollutants leaching into waterbodies, which has been a major environmental concern (Pudasainee, 2020).

2.3 Transition from Path of Fossil Fuel Dependence

Energy transitions, though possessing a multitude of different definitions, is generally defined around the introduction of new sources of primary energy, and its emergence in claiming a significant share in the global energy mix (Sovacool, 2016a). While some studies have expressed the preference towards the term "low-carbon transition" as this is a definition that encompasses a wider categorisation and is reflective of the current observed reality (Johnston, 2020). Smil (2010a)'s definition presents a definitive threshold by defining an energy transition as the time that elapses between the emergence of a new prime mover or fuel to occupying 25% of the national or global market share. Grubler (2014) goes further by introducing the concept of a "grand transition," which takes place once a new fuel type comprises 50% of a market.

Zou et al., (2016) have outlined the following significant periods in the history of energy transitions in the primary energy mix:

i. Transition from biomass (wood) to coal

ii. Transition from coal to hydrocarbons (oil and gas), and

iii. Transition from conventional fossil fuel to renewable energy

Table 3: Five varying definitions of energy transitions

Five definitions of energy transitions.

Definition	Source
A change in fuels (e.g., from wood to coal or coal to oil) and their associated technologies (e.g., from steam engines to internal combustion engines)	Hirsh and Jones [22]
Shifts in the fuel source for energy production and the technologies used to exploit that fuel	Miller et al. [23]
A particularly significant set of changes to the patterns of energy use in a society, potentially affecting resources, carriers, converters, and services	O'Connor [24]
The switch from an economic system dependent on one or a series of energy sources and technologies to another	Fouquet and Pearson [25]
The time that elapses between the introduction of a new primary energy source, or prime mover, and its rise to claiming a substantial share of the overall market	Smil [26]

Table 3, adopted from Sovacool (2016), contains five definitions of energy transitions across existing literature. It is also important to consider that in scenarios wherein a single energy transition is described, as is the case from biomass to coal, a multitude of different transitions are taking place either at different times, or in parallel (Fouquet, 2008; Fouquet, 2010).

2.3.1 Defining Variable Renewable Energy

Though the definition for renewable or "low-carbon" energy varies across existing literature, Owusu (2016) defines an energy source as renewable contingent on their capacity to replenish naturally without risk of depletion in the earth. Key renewable energy technologies include photovoltaics (PV), modern biomass, wave and tidal, and wind energy (Gross et al., 2003). Unlike non-renewable energy sources such as fossil fuels (coal, oil, and natural gas), which have finite deposits and form over multiple millennia, renewable energy sources are considered sustainable and have a much smaller environmental impact.

This thesis focuses solely on two specific renewable energy sources – wind and solar. As the name suggests, wind energy utilises wind turbines to facilitate the conversion of wind's kinetic energy into mechanical power or electricity. The collected mechanical power can be subsequently utilised to carry out diverse tasks or converted into usable electricity through the use of a generator (Eriksson et al., 2008; Kalmikov, 2017). Solar technologies, on the other hand, are concerned with converting electromagnetic radiation emitted by the sun into electrical energy, which can then be leveraged to generate electricity or stored in the form of batteries or thermal storage. The generation of electricity could be directly through PVs, which absorbs sunlight through the cells in the panel, in turn producing electrical charges that move accordingly with internal electrical fields within that cell. This ultimately facilitates the flow of energy (Jungbluth, 2009). indirectly through concentrating solar power (CSP) technologies that use different mirror configurations to concentrate sunlight into a receiver, which then heats a high temperature fluid (Sharma, 2011).

Wind and solar have variable supply and are considered variable renewable energy (VRE) sources (Sinsel et al., 2020). VRE differs from conventional renewable energy technologies across a multitude of aspects, and categorisation of technologies as VRE is contingent on the following parameters. VRE generators are (1) site-constrained, (2) have relatively low shortrun costs, (3) are modular in its design with a compact size and, (4) are largely non-synchronous, relative to conventional renewable energy generators. As such, output of VRE technologies are volatile and vary significantly depending on the availability and variability of its primary resource (IEA, 2014).

2.3.2 Historic Perspective of Energy Transitions

Anthropogenic climate change is a complex challenge that emerges as a result of the intricate interactions between three particular parameters – environment, economics, and energy. While energy remains crucial in the quest for economic growth and the development of society and technology, it is also singlehandedly contributing substantially to a myriad of environmental issues. While these three realms have historically been viewed and documented by previous studies as separate and independent from one another, supporting a smooth energy transition can only be achieved by viewing them as a single issue with which a holistic issue must be implemented (Höök & Tang, 2013). To effectively facilitate the current ongoing global transformation in energy systems, it is important to view energy transitions from a historical perspective, drawing upon previous transitional periods to gather knowledge and observe trends that could potentially apply in the contemporary situation. The historical perspective will be pivotal in strategizing key energy transition challenges moving forward.

For majority of history, such widescale structural energy transition would not have been familiar as decisions were previously decided on an individual, local, or regional scale with either limited coordination or none whatsoever (Smil, 2010). Historical periods of transition between energy sources were also facilitated by a variety of reason such as convenience, technical innovation, energy quality, resource scarcity of scales, cost, pollution, and energy quality, with specific forms of energy emerging as most dominant due to the abundance of resource supply and the ease of use (Solomon, 2011). Society is not required to or expected to continue the usage of a specific energy source in the event that a better option becomes available.

Factors that have previously stimulated energy transitions are inextricably interrelated. Firstly, the historical preference shift away from forests and diverse sources of biomass were brought about by the depletion of local and regional supply, with shortage following shortly after (Melosi, 2017). This similar trend is currently observable and applies to the contemporary transitionary situation (Capellán-Pérez et al., 2014). Minerals and fossil fuels are considered finite resources and non-renewable on a human scale. In light of constantly increasing demand and rates of extraction and consumption, a significant number of studies have shown concern regarding fossil fuel reserves and its implications on energy production given the current level of dependency (Bebbington et al., 2020; Shafiee & Topal, 2008; Singh & Singh, 2012). Shafiee & Topal (2009)'s work presents a new formula establishing a correlation between fossil fuel reserves and a number of main variables, and calculates the timeline in which fossil fuel reserves are most likely to be depleted. This formula, modified from the Klass (1998) model and so similarly operates under a continuous compound rate, computes that fossil fuel reserves for oil, gas, and coal will be depleted within 35, 37, and 107 years respectively (Shafiee & Topal, 2009). As such, coal will be the sole usable fossil fuel after 2042, remaining available until 2112, with reserves depleting shortly thereafter.

Prior to the effects of depletion becoming apparent, the changes and disparity in energy source costs play a significant role in facilitating an energy transition (Solomon, 2011). Such was the case in the Industrial Revolution wherein deforestation and wood scarcity became significant issues, making it impractical and expensive to rely on wood as the primary energy source. Correspondingly, wood prices increased significantly while the abundance and strategic location of coal reserves meant prices remained low, making it the predominant and preferred energy source. The same is taking place currently, with the price of renewable energy sources steadily decreasing, making them increasingly competitive with fossil fuels. Technological advancements, government incentives, and economies of scale have played pivotal roles in driving down the costs of renewable energy technologies.

Historical timing and temporal dynamics of energy transitions are of considerable importance when strategizing the current transitional period. Since the period during the industrial revolution, the average time that elapses from the introduction of new core energy technology, to its widescale diffusion, to occupying 80% of the global energy share is around 95 years (Sovacool, 2016b; Fouquet, 2016a). Transitions among energy sources have historically shown to be long-drawn out, lasting a period that spans decade or even centuries, which will contemporarily be unlikely to assist in addressing the urgency of climate change mitigation targets. Grubler (2014) and Smil (2010b) have suggested that energy transitions have been historically slow as a result of techno-economic rationales, which include the required time to construct massive energy infrastructure, for new core technologies to experience the benefits of learning and economies of scale, as well as the general hesitance and unwillingness to forego sunken investments at the outset (Pearson, 2018). Giddens (2009) describes this as the "climate paradox" – once humanity comes to the realisation that a shift is needed towards low-carbon energy forms, the point of return would already have been surpassed. As such, given the challenges of anthropogenic climate change, the 21st century energy transition will need to be substantially more rapid.

Presenting another perspective, Sovacool & Geels (2016) argue that rapid transitions have taken place in the past, and thus provides the foundation for a similar outcome in future transition scenarios. Supporting this sentiment, Kern & Rogge (2016) present the idea that historic energy transitions were not consciously governed, but rather were initiatives that emerged resulting from the discovery of new energy sources, the emerging availability of new services, or technological innovation significantly reducing their relative cost. The current energy transition, on the other hand, involves an abundance of diverse actors engaged and committed to governing the global low-carbon transition. As such, the transformation of the current energy system is expected to occur at a more rapid rate relative to past transitions.

Furthermore, historical analysis is particularly valuable when determining the lock-in strategies, path dependence, destabilisation and responses of incumbent actors in the low-carbon energy transition. The evolution of energy systems can be path dependent, which entails that the present and future trajectories of a particular system are highly influenced by and are reflective of the actions and events leading to the present state (Foxon, 2007; Fouquet, 2016b). A historical sequence of events could result in the lock-in of an energy system despite conditions, which were previously conducive to this lock-in period, no longer being presently relevant. A number of lock-in mechanisms are covered within the literature of Arthur (1994) and Klitkou et al., (2015), encompassing network externalities, economies of scope and scale, collective action, differentiation of power, effects of institutional learning, and the interrelatedness of technology. Increasing returns, specifically, contribute significantly to technological lock-in, enabling incumbent systems to accumulate various socio-technical advantages, such as steadily decreasing costs, which impedes the rate in which a potentially superior alternative is adopted and deployed (Arthur, 1994; Klitkou et al., 2015). Existing systems have proven to be difficult to dislodged as a result of a combination of lock-in processes, which facilitate developments in path dependency.

The comprehensive analysis of historical energy transitions are a central aspect of various studies drawing upon a multi-level perspective (MLP), an approach developed through the work of Kemp et al., (2001). The MLP utilises evolutionary economics, in conjunction with neo-institutional and structuration theory, as well as study of science and technology. MLP studies have proposed that transitions are introduced and emerge as a product of the dynamic interactions between three key aspects. Socio-technical regimes, which are parameters and practices that were developed historically and assist in stabilising incumbent systems, interact with an exogenous socio-technical landscape and niches, which are loci for significant technological innovation (Geels, 2002). As such, transitions have historically shown to shift across regimes.

2.3.3 Contemporary Decarbonisation

Under the scenario of increasing demand, a global energy system that is predominantly fossil-fuel based will present a multitude of fundamental problems due to increasing dependency on a robust import market, as well as extensive trade imbalances across various regions (Saygin et al., 2015). Faced with the prospect of global climate change and dwindling petroleum and fossil fuel supplies, urgent action is needed to transition away from a path of fossil fuel dependence to sustainable energy systems. Various studies have strongly asserted that a shift towards a low-carbon economy is a crucial step in achieving the demand and outcry for climate stability (Foxon et al., 2008; Grubb et al., 2008). Given the gravity of the threat presented by fossil fuel-driven anthropogenic climate change, the shift away from the production and consumption of fossil fuels to renewable energy (RE) has been touted as a core strategy in the establishment of sustainable energy systems. As such, decarbonisation initiatives and an overall global energy transition is currently taking place supported primarily by increasing concern for environmental safety, along with energy security and volatile economics (Okafor et al., 2021). Echoing the common sentiments among key energy analysts, Grayson (2017) expressed that the process of transitioning away from fossil fuels is underway, supported by empirical and quantitative proof in the form of annually increasing electricity capacity generated from renewable sources (Grayson, 2017).

At the forefront of a low-carbon transition is the reduction of GHG emissions from the energy sector, regardless of technology or fuel. This collective shift encompasses both profound economic and technical innovations in the field of energy production, as well as supply and consumption, with the specific objective of curtailing the energy industry's adverse effects on the environment (Gitelman, 2023). Furthermore, the challenge of an energy transition incorporates several factors for consideration.

Firstly, an increased share of nuclear energy and renewable energy sources (RES) in the global mix and within the framework of the energy sector's generating capacities, as these sources are considered zero-emission (Sofuoğlu & Kirikkaleli, 2023). This transformation involves promoting the use of renewable energy sources such as solar, wind, hydro, geothermal, and biomass. Secondly, determining the optimal balance between energy efficiency and eco-friendliness of thermal power plants (TPPs) (Gielen, 2017). While renewable and nuclear energy are crucial for reducing emissions, thermal power plants that utilise fossil fuels remain necessary in achieving energy needs under specific assumptions and applications. Thirdly, the improvement and augmentation of energy efficiency by means of demand-side management programs, which entails implementing measures and technologies to control and optimize energy consumption patterns on the consumer side (Dzyuba & Solovyeva, 2020). This can include promoting energy-efficient appliances, incentivizing off-peak electricity usage, and encouraging conservation practices to reduce overall energy demand. Lastly, encouraging the widespread adoption of electricity over fossil fuels for various energy-intensive processes (Henderson & Sen, 2021). This transformation aims to shift energy consumption away from fossil fuels and towards electricity for various applications, such as transportation, heating, and industrial processes. By electrifying these sectors, they can be powered by cleaner energy sources, leading to reduced emissions and environmental impact. The implementation of these measures would ensure that the energy sector makes significant strides towards emission reduction and supporting the global transition initiative.

2.3.4 Driving Factors in the Low-Carbon Transition

There are various elements in play that are currently driving the low-carbon energy transition. At the forefront of the transition and covering international boundaries are various historic climate action commitments. Under the United National Framework Convention on Climate Change (UNFCCC), global agreements have been reached given the need for urgent climate action. The Paris Agreement establishes a collective goal of keeping global warming below 2°C, while limiting it to 1.5°C above pre-industrial levels, with the transition towards renewable playing a critical role in meeting these goals (United Nations, 2015). Through singing the climate pledge, 190 signatory nations committed to curtailing CO_2 and other GHGs, and by prioritising scaling up the deployment of renewable energies within their borders, energy-related CO_2 is expected to be significantly reduced. The Nationally Determined Contributors (NDC) analysis conducted by the International Renewable Energy Agency (IRENA) five years after the establishment of the pledge determined that out of the 188 ratifying parties that submitted NDCs to the UNFCCC, 170 NDCs or 90% had renewables energy central to their agenda, with 134 or 71% outlining concretely quantified renewable energy targets (IRENA, 2019).

In a similar vein, the UNFCCC's Kyoto Protocol of 1997 supported the low-carbon energy transition through its Clean Development Mechanism (CDM), enabling Annex I countries to invest substantially into emission reduction projects in developing countries, with a significant majority being renewable energy technology and infrastructure (UNFCCC, 1997). The Joint Implementation (JI) mechanism, on the other hand, developed collaboration on renewable energy technologies between Annex I countries, facilitating knowledge sharing and contributing significantly to global emission reduction initiatives and renewable energy deployment rates.

Another climate action commitment that is currently facilitating the low-carbon energy transition is the United Nations General Assembly (UNGA)'s Sustainable Development Goals (SDGs), which outlines "Agenda 2030" as a pathway to address environmental issues, along with inequality and injustice and extreme poverty (Lu et al., 2015). Central to Agenda 2030 is the focus towards renewable energy. SDG 7, specifically, provides a global goal on renewable energy by outlining three key collective targets – to secure universal, reliable and affordable access to energy services, to significantly increase renewable energy share in the global energy mix, and the twofold increase in the rate of energy efficiency improvement globally. (McCollum et al., 2017). The SDG 7's contributions to achieving the goals of other SDGs and its facilitation of the low-carbon energy transition are well-documented and has been covered by multiple studies (Allen et al., 2016; McCollum et al., 2018; Nerini et al., 2018; Nilsson et al., 2016; von Stetchow et al., 2016; Bowen et al., 2016).

Renewable energy has been increasingly competitive as costs for low-carbon technologies have shown a drastically decreasing trend over time. In many regions, renewable energy has already reached price parity or become cheaper than fossil fuels, particularly when considering the overall lifecycle costs, including maintenance and environmental impacts. The period from 2010 to 2021 experienced a major development in the competitiveness of renewable energy, with the global weighted average levelized cost of electricity (LCOE) of VRE projects decreasing significantly. During this time, global weighted average LCOEs for onshore wind, offshore wind, utility-scale solar PV and CSP projects decreasing by 68%, 60%, 88% and 68%, respectively (see Table 4, adopted from IRENA, 2022).

Table 4: Global weighted average LCOE, total installed costs, and capacity factor of RE technologies for the period from 2010 to 2021

	2010	2021	Percent change	2010	2021	Percent change	2010	2021	Percent change
Bioenergy	2 714	2 353	-13%	72	68	-6%	0.078	0.067	-14%
Geothermal	2 714	3 991	47%	87	77	-11%	0.050	0.068	34%
Hydropower	1 315	2 135	62%	44	45	2%	0.039	0.048	24%
Solar PV	4 808	857	-82%	14	17	25%	0.417	0.048	-88%
CSP	9 422	9 091	-4%	30	80	167%	0.358	0.114	-68%
Onshore wind	2 042	1 325	-35%	27	39	44%	0.102	0.033	-68%
Offshore wind	4 876	2 858	-41%	38	39	3%	0.188	0.075	-60%

The global weighted average cost of newly-commissioned PV, and onshore and offshore wind power projects decreased significantly in 2021 despite increasing equipment and material costs. A 13% decrease in the global weighted average LCOE of new offshore wind projects and new utility-scale solar PV projects was observed in 2021, with the LCOE of new onshore wind projects falling by 15% (IRENA, 2022). The new capacity generated by newly commissioned VRE projects in 2021 is forecasted to reduce the costs of electricity generation in 2022 by more than 55 billion USD (IRENA, 2022). Furthermore, 163 GW, or two-thirds of the newly installed renewable power in 2021 proved to be lower in cost relative to the cheapest coal-powered option in the world.

Conversely, fossil fuel prices have been subject to volatility due to various geopolitical events, fluctuations in global markets, as well as constraints in supply and reserves. While some fossil fuel technologies would still experience lower upfront costs, the long-term trend indicates that renewable energy will continue to become more economically advantageous and sustainable in the pursuit of a cleaner low-carbon energy system (Ari et al., 2022).

To gain a better understanding of the other further driving factors in the low-carbon energy transition, these are best compartmentalised into specific clusters – planning and process (P&P), participation and exchange (P&E), network dynamics (ND), and economic incentive

(EI). Upon the extensive review of existing literature, the author has collated the various identified driving factors facilitating the contemporary energy transition (see Table 5).

Table 5: Driving factors of energy transition identified within existing literature

Category	**Driving factors identified**	**Literature**
P&P	Longevity and temporal aspect of transitional process	Geels (2005)
	Energy-specific planning	Musall & Kuik (2011)
	Goal and target monitoring	Lipp (2007); Späth (2012)
	Support by policymakers	Schreuer et al., (2010); Bulkeley & Kern (2006); Boon & Dieperink (2014)
	Consistency in policy and legal conditions	Negro et al., (2012); Hekkert et al., (2007); Walker (2008)
P&E	Public involvement and local participation	Walker & Cass (2007); Devine-Wright (2005); Walker (2011); Rydin et al., (2013);
	Knowledge-sharing with experts in the field	Bos & Brown (2012); McCormick & Kåberger (2007)
ND	Involvement and commitment of key actors	Walker (2008); Späth & Rohracher (2010)
	Presence and extent of actor networks	Smith (2012); Späth & Rohracher (2010)
	Heterogeneity of actors and diversity of their specialties	Fischer & Newig (2016); Farla et al., (2012); Rydin et al., (2013); Geels (2012)
	Strength and number of opposing actors	Lipp (2007); Negro et al., (2012); Boon & Dieperink (2014)

EI	Source of funding	Bulkeley & Kern (2006); Walker (2011); Hecher et al., (2016); Musall & Kuik (2011)
	Community Energy Initiatives (CEI)	Seyfang & Smith (2007)
	Implications on regional economy	Blumer et al., (2013); Karpenstein-Machan & Schmuck (2007)

The way in which temporal longevity affects the low-carbon transition has been discussed previously in this sub-section.

Establishing targets and goals is instrumental in the transformation of energy systems as they provide orientation and direction to assist in the coordination of the different actors involved in the transition. Furthermore, these targets are quantifiable, thereby allowing them to be assessed and evaluated to inform policy.

Under "support by policymakers," various existing literature have stated the importance of a clearly stated and effectively-relayed government commitment in the transformation of the RE market, in conjunction with a sense of urgency regarding the process from government sector. Inconsistency in legal and political conditions present challenges that hinder the development of RE. Stable legal conditions and policy continuity collectively provide assurance, greatly influencing the participation and willingness of various actors.

Participation from the local communities positively influence public perception of renewable energy, which has beneficial spill over effects in terms of political and financial involvement.

Sharing and exchange of knowledge with experts is important for communities due to the significant complexity of RE development, both with regards to new and emerging technologies but also the legal aspect. The socio-technical regime can be altered through the development of mutually beneficial and quality relationship between various involved actors.

The presence of key actors in the form of individuals and institutions substantially increases the likelihood of a successful outcome, while an extensive network for actors provides a platform to define new fields of action and to determine issues of concern, while contributing to confidence building. The heterogeneity of involved actors and diversity in the skills and specialties they bring decrease uncertainty across a range of disciplines, and ensures that the interests of a larger number of sectors are voiced. On the other hands, the strength and number of opposing actors have proven to be systemic problems in the diffusion of new RE technologies.

RE development and the construction of relevant infrastructure requires financing, and a higher heterogenieity in funding structures eliminates the possibility of sole dependency or entrapment.

CEI utilises contextualised knowledge on a local scale which positively influences RE development. Additionally, CEI's generate benefits in the form of financial return and a sense of satisfaction, as perceived by the public.

Lastly, positive economic implications is crucial in driving the implementation of RE development, and has previously shown to be a key factor that determines the success of RE projects. Relaying the benefits of upscaling RE development to the economy supports and legitimises decision makers.

2.3.5 Current Trends for RE deployment

Through the expansion of policy support, increasing concerns for energy security, and the constantly improving competitiveness against conventional fuel alternatives, renewable energy is currently showing signs of positive development. In 2022 alone, there was an 8% increase in RE supply from solar, wind, geothermal, ocean, and hydro energy sources. As a result, the share of these RE sources in the global energy supply collectively increased by 0.4%, now occupying a total of 5.5% (IEA, 2023a). Furthermore, additions in the global RE capacity is forecasted to increase by a further 107 GW, which is the largest increase historically, to amass a total of 440 GW of capacity in 2023. This addition alone accounts for greater than the entire installed power capacity of Spain and Germany combined (IEA, 2023a). Two-thirds of this year's projected increase in global RE capacity will come from solar PV through both small-scale distributive systems and large utility-scale.

Lastly, onshore wind capacity additions are set to increase by 70% in 2023 to 107 GW, the highest it has ever been historically. This comes after two consecutive years of decline due primarily to COVID-19 restrictions, among others, which hindered the commissioning of new RE projects across different regions.

2.4 Australian Energy Crossroads

Australia, considered a developed country, is ranked ninth globally in terms of primary energy usage per capita, despite having a relatively small population (Falk & Settle, 2011). As a high per-capita-energy user, Australia currently still utilises a predominantly fossil fuel-powered energy system, with a heavy reliance particularly on coal. Since 1986, the country has remained the single largest global exporter of coal (Australian Bureau of Agricultural and Resource Economics (ABARE), 2008). According to the DCCEEW (2022), fossil fuels continue to account for a significant 92% in Australia's primary energy mix for the period from 2020 to 2021. Oil occupies the largest portion of the national primary energy mix at 36%, while coal and gas account for 29% and 27%, respectively (DCCEEW, 2022). The remaining 8% of the energy mix is accounted for by RE sources (see Figure 6). Abundant reserves and subsequent low costs for non-renewable energy sources have resulted in an embedded preference towards fossil fuels, making this the single largest source of carbon pollution (Bahadori et al., 2013).

The production and combustion of fossil fuels produce a significant 78% of Australia's total GHG emissions (Hua et al., 2016). On a global scale, 1.5% of GHG emissions is generated from Australia, placing Australia within the 20 highest-emitting nations in the world (Curran, 2012). Australia produces a higher level of carbon pollution per head of population than all other developed countries in the world, including United States, which has the world's biggest economy (Effendi & Coursivanos, 2012).

Australia's strong dependence upon fossil fuels is increasingly threatened by the challenges in climate change, energy security and supply security (Bahadori et al., 2013). In a bid to meet climate targets and to address the aforementioned challenges, Australia has shown recent development in curtailing production and consumption of non-renewable energy sources, and leveraging favourable conditions to effectively scale up renewable energy technologies to diversify its national energy mix. Results from stimulation analyses have further reinforced the prospect of RE in Australia, showing the country's enormous potentialities for increasing the rate of RE deployment nationally (Shafiullah et al., 2012).

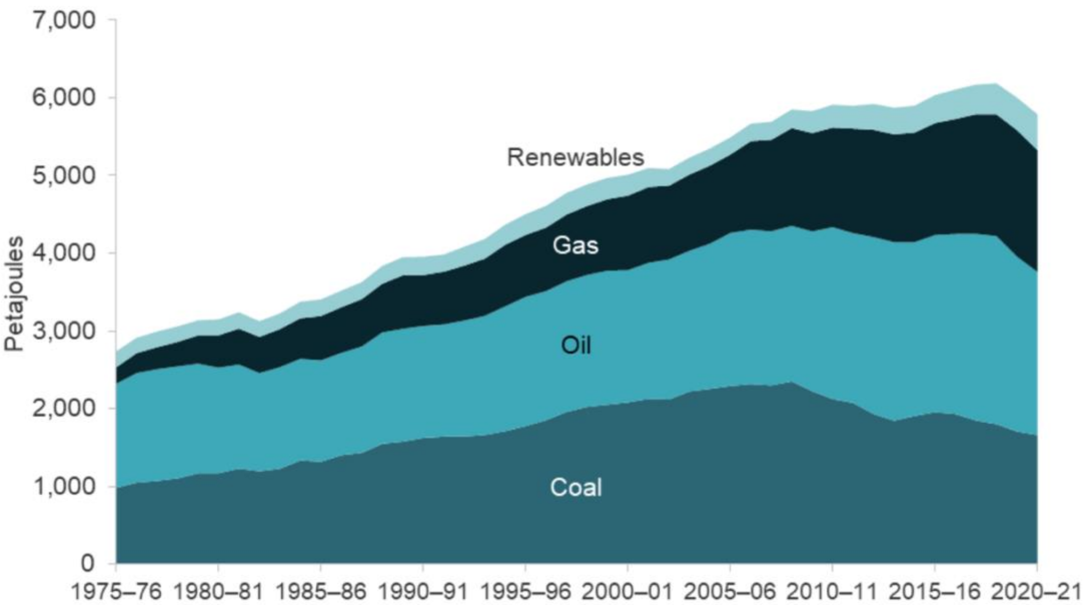


Figure 6: Energy consumption in Australia by fuel type, from 1975 – 2021

(source: DCCEEW, 2022).

Currently, the increased urgency for climate action and facilitation of a national energy transition has seen the production of energy from renewable sources experience a 10% increase in 2021 alone, spearheaded by the expansion of VRE technology such as solar and wind (DCCEEW, 2022a). This, along with other substantial developments have resulted in RE accounting for 29% of Australia's total national electricity generation, with solar, wind, and hydro comprising 12%, 10%, and 6%, respectively. (DCCEEW, n.d.). This transition in sourcing for energy production has manifested in Australia's GHG emission over the period from June 2021 to June 2022 being 21.6% below 2005 levels, which is the determined baseline year for the country's 2030 goal to be achieved as signatory of the Paris Agreement (DCCEEW, 2022b).

2.5 Feasibility

2.5.1 Domains of Feasibility in an Energy Transition

The feasibility of energy transitions have been largely examined through a multitude of scopes and implementing various frameworks, contingent on the primary variable being assessed. Existing literature has covered various domains with regards to the feasibility of the modern energy transition.

Technical or technological feasibility evaluates the availability, maturity, and scalability of renewable energy technologies. Assessments examine whether these technologies can meet the energy demand, their cost-effectiveness, and the ease of their integration into incumbent energy systems. The technical feasibility of renewable energy systems across different regions have been covered extensively by the works of Bouhal et al., (2018); Brown (2018); Cao & Alanne (2015); Jacob & Liyanapathirana (2018); Itiki et al., (2020); Ma et al., (2014) and many others. The energy transition must prove to be economically viable and sustainable in the long run. Studies in this domain by the likes of Chauhan & Saini (2016); Park (2017); Rinaldi et al., (2021); Meesenburg et al., (2020); Eze et al., (2022); He et al., (2022); Fthenakis (2009); Singh et al., (2017), and Schetinger et al., (2020) typically utilise mechanisms such as comprehensive financial modelling, cost-benefit analyses, and investment requirement assessments to determine that an energy transition is financially achievable without significantly compromising the equally important global goal of economic growth and development. Assessment of economic feasibility is often conducted in conjunction with the technical domain of feasibility to produce a techno-economic assessment.

The success of an energy transition is contingent on social acceptance and support from both the general public and political networks. Socio-political analyses are especially concerned with factors including regulatory frameworks, stakeholder engagement, public perception and attitude, as well as the highly crucial political will to implement relevant policies and measures to facilitate the low-carbon transition. The socio-political feasibility of the energy transition and other climate mitigation pathways are covered extensively through the works of Sheikh (2016); Moula et al., (2013); Freeman (2021); Paravantis & Kontoulis (2020), and Lucas et al., (2021).

The low-carbon transition is driven primarily by the urgent need to curtail GHG emissions and mitigate negative environmental impacts. Through the implementation of an environmental feasibility study, the potential environmental benefits of the energy transition are studied closely, taking into consideration overall impact on natural resources and ecosystems. Various studies aim to empirically explore comparative impacts between RE systems and non-renewable energy systems. Studies that implement this methodology include Thompson & Duggirala (2009); Shafiullah et al., (2012); Dar & Asif (2023); Nassar & Alsadi (2016); Rafique & Bahaidarah (2019); Cosmi et al., (2003), and Adefarati & Bansal (2019).

2.5.2 Existing Feasibility Assessment Frameworks

In the review of existing literature, several frameworks and methodologies were identified and implemented across disciplines to assess the different aspects of feasibility of renewable energy target.

IRENA's REmap presents the REmap analysis framework, which provides a comprehensive systematic approach for countries to evaluate their respective renewable energy potentials, and to determine the most suitable pathways and RE technologies to leverage according to their needs and resources in order to achieve specific RE targets. The REmap framework utilises a bottom-up approach, primarily conducting analyses on a national scale, in collaboration with local experts in respective regions, with collected national data and results aggregated and fed into an analysis on the global scale. The resulting collated roadmap encompasses RE power technologies, as well as technological options in the transport, heating, and cooling sectors (IRENA, 2014). In conjunction, IRENA also utilises the Global Energy Transformation (GET) model, which evaluates the global low-carbon transition and its feasibility to achieve specific RE targets on a global scale. The comprehensive roadmap to 2050 expands IRENA's REmap, further covering various technological pathways and policy frameworks to ensure a future with sustainable energy (IRENA, 2019).

The work of Budak et al., (2019) presents a systematic approach in the assessment of renewable energy by leveraging an analytic hierarchy framework to determine and develop energy alternatives. The framework is embedded in a number of multi-criteria decision-making approaches including the analytic network process (ANP), and the technique for order preference by similarity to ideal solution (TOPSIS), and extensively integrates data analytics with expert input to assist policymakers to develop long-term strategies in the development of RE.

2.6 Knowledge Gaps and Challenges

During past energy transitions, clear private benefits were explicit and observable for both producers and consumers in opting to shift to new energy technologies and sources, whereas the same benefits are not as obvious for current low-carbon technologies (Fouquet, 2012a). As the contemporary energy transition will be in the best interest of the public good of mitigating climate damage, and given its perceived urgency, further extensive qualitative research must be conducted into purposive transitions that have taken place in the past, similar to the work of Fouquet (2012b).

Furthermore, York (2012) and York & Bell (2019) present an alternative perspective that challenges the prospect of an energy transition, and asserts that we are currently in a phase of addition, as opposed to transition. Various energy analysts, including the IPCC, have implicitly assumed that each unit in the global energy mix provided by a non-fossil fuel source displaces a proportional single unit provided by fossil fuel sources (Hoag, 2011; IPCC, 2011; IPCC, 2007). This fundamental assumption, however, fails to reflexively account for actor agency, neglecting the volatility of economic systems and unpredictability of human behaviour. The examination of net effects shows that curtailing the consumption of a single resource type, either through improving efficiency or the development of alternatives, does not produce the intended outcome. Calculations done by York (2012) have shown that over the previous 50 years and across a majority of countries, the average pattern exhibits that a single unit of total national energy generated from non-fossil fuel sources substitutes less than a quarter of a unit of energy generated from fossil fuel sources. Furthermore, literature from York & Bell (2019) have proven that the use of conventional fossil fuel sources continues to show an increasing trend, despite rapid growth in newer renewable sources. Contemporary energy production trends similarly present evidence that despite RE sources comprising an increasingly significant share in overall global energy production, they fail to displace fossil fuels but rather continue to expand the overall global energy production (York & Bell, 2019). As such, these studies have challenged the conventional notion indicating that curtailing fossil fuel consumption is sufficient in various climate change mitigation pathways. The author's review of existing literature on energy have yielded a multitude of studies framed by the assumption of a contemporary period of energy transition. Further examination and study must delve deep into this topic as the characterisation of RE development as a transition has the potential to impede on the implementation of valuable policies aimed at reducing the consumption of fossil fuels, and further structural changes are required in conjunction with the expansion of RE energy production.

Lastly, the comprehensive discussion and study in the field of renewable energy is predominantly and centrally focused on the electricity sector, given the significant growth in wind energy and solar PV. However, electricity accounts for only a fifth of energy consumption globally, and there is a noticeable gap in knowledge and existing literature for RE sources within other sectors, such as heating and transportation (IEA, 2023b).

3 Theoretical Framework

3.1 Research Gap and Motivation

Upon extensive review of existing literature on the energy transition and various previous work on feasibility assessments, there has been a noticeable gap in the studies of scale, as well as a majority of energy transition literature being more descriptive and based on interpretation, as opposed to quantitative with measurable and number-based data. While both are inextricably connected and are equally crucial in the examination of the energy transition and different climate change mitigation pathways, there is a discernible discrepancy in the volume and depth between qualitative and quantitative studies on the topic. Moreover, the qualitative and quantitative aspects of the energy transition have largely been considered as separate entities, and have mostly been examined as such. However, there is value in studying the energy transition and its feasibility taking into consideration the complex interplay between descriptive and quantifiable data. Furthermore, the historical aspect of the energy transition has also largely been studied independent from the contemporary landscape, despite the fact that previous energy lock-in mechanisms, frameworks, and initiatives have heavily influenced incumbent systems. Various questions regarding the contemporary energy transition can be addressed or at least better understood through historical analysis and observing previous trends, as influenced by actor agency.

Majority of available literature is also limited in their scope, often focused solely on a single specific economy or energy technology. Existing literature on the energy transition is vastly available on a local or regional scale, but generalisable conclusions on the global scale cannot be drawn with a lack of perspective for similar observable trends and dynamics in other countries. As such, various aspects of the energy transition are viewed through a restricted scope, and are generally not comparatively assessed through a global perspective, which is essential when strategizing. A number of these studies have also been critiqued heavily for their predominantly theoretical nature, failing to take into account agency of actors included in the studies, proving to be non-operational or applicable in actuality.

There is also only a small amount of available literature that proactively delve deep into targets and milestones set by different nations. While most countries have expressed specific climate or energy commitments and objectives to reach within a defined timeframe, more examination needs to be conducted into the mechanisms that are implemented to achieve these goals. Beyond this, national climate targets need to be contextualised and standardised alongside the targets of other countries or overarching international institutions, especially given the contemporary universal trend of transitioning to adopting a low-carbon dominated energy system.

This thesis aims to study and reconcile the qualitative and quantitative aspects of the energy transition, and appropriately uses the feasibility space framework, designed for this very purpose, as well as placing the different RE targets across different countries within a comparative framework.

3.2 The Step Change Scenario in the Australian Energy Market Operator's 2022 Integrated System Plan

This thesis is primarily concerned with the targets outlined in the Australian Energy Market Operator (AEMO)'s 2022 Integrated System Plan (ISP) for the National Electricity Market (NEM). The creation of the ISP in 2018 and its succeeding biennial reiterations present the most robust 'whole of system plan' in order to facilitate Australia's current energy transformation, by prioritising a twofold agenda: to provide support for Australia's ambitions and commitment towards net zero, as well as displacing legacy energy fuel types with low-cost RE sources (AEMO, 2022). The optimal development plan outlined in the 2022 ISP strives to achieve these aims through enabling various mechanisms:

(i) holistic electrification of the different sectors of society through the transition towards firmed renewable energy sources, carried out through:
   a. doubling electricity generation;
   b. prioritising withdrawal of coal-fired generation;
   c. enabling a ninefold increase in utility-scale capacity of VRE sources, and
   d. enabling a fivefold increase in distributed PV capacity, while significantly growing distributed storage

(ii) trebling the firming capacity generated by new RE technology alternatives;

(iii) implementing significant technical and market reforms to enable bi-directional power flow and,

(iv) identifying and delivering current and future actionable projects aimed at establishing 10,000 kilometres (km) of new transmission that connect geographically and technologically diverse, low-cost generation (AEMO, 2022).

The creation of the 2022 ISP builds upon the opportunities identified in the 2020 ISP, and comes as a result of two years of exhaustive and rigorous engagement with more than 1,500 NEM stakeholders, from law and policy makers to energy consumers and sector representatives.

To this end, extensive consultation with industry has produced five scenarios that encompass multiple plausible futures for Australia's NEM, each with variable emission reduction rates, level of energy decentralisation, and electricity demand. The following scenarios are listed below:

(i) Slow Change

(ii) Progressive Change

(iii) Step Change

(iv) Hydrogen Superpower

The Slow Change scenario operates within a challenging and volatile economic environment in the aftermath of the COVID-19 pandemic, resulting in significantly slower developments in net zero emissions action.

The Progressive Change scenario presents a progressive economy-wide achievement of the net zero emissions target, compartmentalising development by decades. The 2020s will see the continuation of existing trends in NEM emission reduction, while the 2030s is forecasted to give rise to commercially viable alternatives to the current high-emitting heavy industry.

Ultimately, the 2040s will generate almost double the total NEM capacity, alongside a robust economy-wide decarbonisation initiative and rapid rates of industrial electrification.

The Hydrogen Superpower scenario is characterised by significant innovation and breakthroughs within the technology sector, with an almost fourfold increase in energy consumption in the NEM, underpinning a hydrogen export industry (AEMO, 2022) (see Table 6; adopted from 2022 AEMO ISP).

Step Change has been determined by a vast number of stakeholders and energy industry experts to be the scenario that will prevail in all likelihood, and is the central focus of this thesis. Under the Step Change scenario, the high rate of the energy sector transformation will be predominantly consumer-led. As opposed to the accumulative action as presented by the Progressive Change Scenario, which gains momentum gradually, Step Change entails a fast rate of initial action towards the net zero policy commitments, with a consistent fast-paced transformation of the energy system from being fossil-fuel dominated to being predominantly RE-powered.

Table 6: 2022 ISP Scenarios and Input Assumptions

DEMAND	Slow Change		Progressive Change		Step Change		Hydrogen Superpower	
Electrification	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**
- Road transport that is EV (%)	2	36	5	84	12	99	18	94
- Residential EVs still relying on convenience charging (%)	82	58	75	44	70	31	66	22
- Industrial Electrification (TWh)	-24	-21	4	92	27	54	37	64
- Residential Electrification (TWh)	0	0	0.2	15	4	13	2	4
- Energy efficiency savings (TWh)	8	19	14	40	22	55	22	56
Underlying Consumption								
- NEM Underlying Consumption (TWh)	163	213	201	394	222	336	243	330
- Hydrogen consumption - domestic (TWh)	0	0	0	32	0.1	58	2	132
- Hydrogen consumption - export, incl. green steel (TWh)	0	0	0	0	0	0	49	816
- Total underlying consumption (TWh)	**163**	**213**	**201**	**425**	**223**	**394**	**294**	**1,278**
SUPPLY								
Distributed PV Generation (TWh)	39	58	39	80	45	93	51	112
Household daily consumption potential stored in batteries (%)	3	5	5	22	12	38	13	39
Underlying consumption met by DER (%)	24	27	20	19	20	24	17	9
Coal generation (% of total electricity production)	32	5	38	2	21	0	6	0
NEM emissions (MT CO_2-e)	53.3	13.0	77.2	22.4	48.1	6.8	20.6	6.6
2020 NEM emissions (% of)	38	9	54	16	34	5	15	5

3.3 Feasibility Space Framework

This thesis is embedded in the body of work by Jewell & Cherp (2023), and will utilise the feasibility space framework as presented within the literature. Despite the varying definitions of feasibility across a multitude of existing literature, this thesis is primarily concerned with two: The IPCC (2022)'s definition of feasible as "the potential for a mitigation or adaption option to be implemented," and Jewell & Cherp (2023)'s more succinct and panoptic definition of "do-able under realistic assumptions."

The feasibility space provides a framework for the assessment of the feasibility of a climate mitigation pathway through either implementation level, context or characteristic, by providing a virtual multidimensional space wherein the position of the primary option dictates its feasibility (Jewell & Cherp, 2023). Central to the implementation of this feasibility is the reconciliation of the "inside view" and "outside view" of a climate option, as introduced by Kahneman & Lovallo (1993). As presented by these authors, the "inside view" can be best described as placing high focus on a particular case, taking into consideration the entire plan and identifiable barriers that potentially impede its completion, and constructing scenarios of future progress. On the other hand, the "outside view" is less concerned with the intricate details of the particular case, but rather involves focusing on the data and statistics of various previous cases presenting a similarity across different relevant aspects as the case in hand (Kahneman & Lovallo, 1993).

In the context of assessing the feasibility of different climate mitigation pathways, the "inside view" entails viewing a climate mitigation pathway as a unique challenge, and understanding the detailed barriers across multiple aspects that could determine the success of its adoption. The "outside view" entails considering historical analogies of the same climate mitigation pathway, either through examining the historical implementation of the same climate option in that country, or studying the implementation across different regions. In reconciling these two broad and narrow perspectives, decision-making and forecasting can be significantly refined. This framework will be implemented in the examination of the 2022 ISP's outlined targets. Jewell & Cherp (2023), and the means to which the aforementioned aims will be achieved is stated in Chapter 4.

4 Methods and Results

4.1 Establishing the Target Case (Outside view)

To implement the feasibility space, the target case must first be clearly defined and stated, addressing the following crucial elements of a feasibility assessment: feasibility of what, and feasibility when and where? (Jewell & Cherp, 2020). In this case, that would be the targeted growth for VRE sources in Australia, particularly utility-scale solar and wind capacity, for the period from 2023 to 2050, as outlined in the AEMO's 2022 ISP. To this end, the content of the 2022 ISP was extensively reviewed, with focus towards the four scenarios of plausible futures presented. The SCS was picked out, as it has been determined to be the most realistic and likely scenario to play out over this timeframe, and is the primary focus of this thesis. Data from the forecast graphs in the 2022 ISP for utility-scale solar and wind capacity development was extracted, specifically isolating the SCS data. The extracted and collected data for solar and wind was then input into a table to effectively quantify Australia's VRE capacity development over the specified timeframe (see Table 7 & 8).

Table 7: Growth of utility-scale wind capacity under the Step Change Scenario

Wind Capacity (GW)	2023-2026	2026-2029	2029-2032	2032-2035	2035-2038	2038-2041	2041-2044	2044-2047	2047-2050
0 (baseline value)	8	18	26	33	38	42	54	60	68

Table 8: Growth of utility-scale solar capacity under the Step Change Scenario

Solar Capacity (GW)	2023-2026	2026-2029	2029-2032	2032-2035	2035-2038	2038-2041	2041-2044	2044-2047	2047-2050
0 (baseline value)	1	4	7	11	17	28	42	48	68

The 2022 ISP only outlines the development of VRE capacity from 2023 onwards, considering the baseline value for 2023 as 0 MW. As such, it was crucial to establish a baseline value that reflected Australia's current VRE capacity. As a starting point, IRENA's Renewable Capacity Statistics 2022 has determined that Australia currently has around 10,134 MW of total installed wind power capacity as of 2022, while 7,716 MW of new solar PV capacity was installed in 2022 alone, contributing to a net total of 26,792 MW of solar PV capacity currently (IRENA, 2022). As majority of literature utilises gigawatts (GW) as a standard of measurement for capacity, these values for current capacity of wind and solar power will be standardised to 10.134 GW and 26.792 GW, respectively. This serves as the starting plot point for the succeeding graphs, and is important for the subsequent steps in the methodology.

To further establish the target case, the collected datasets will then be plotted into a graph to provide a visualisation, and facilitate a better understanding of noticeable trends in VRE capacity development (see Figures 7, 8 & 9).

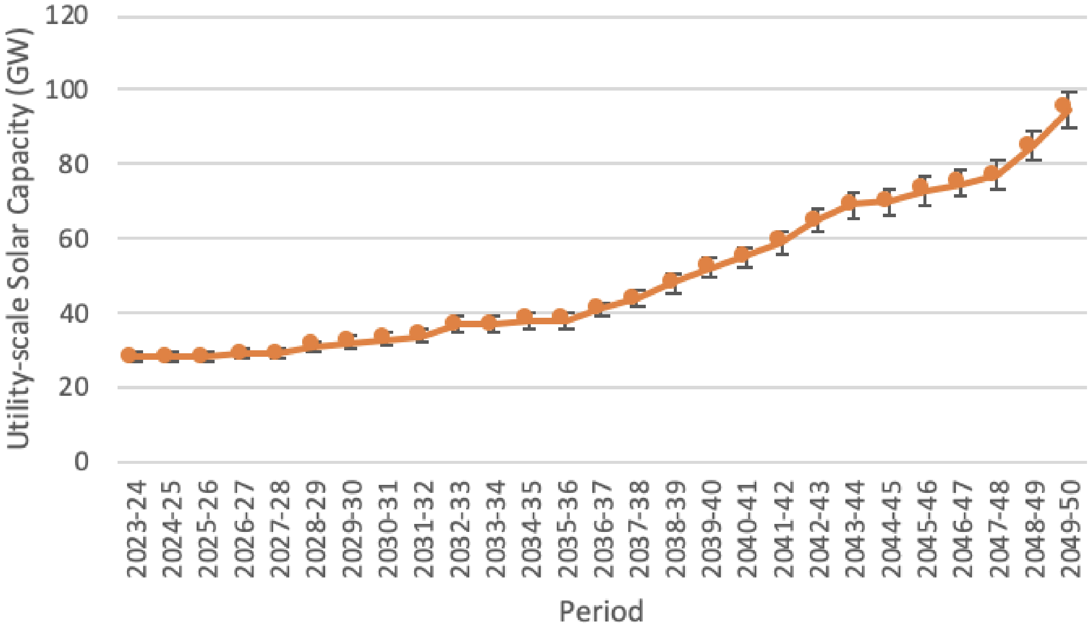


Figure 7: Future trajectory of utility-scale solar capacity development in Australia under the SCS

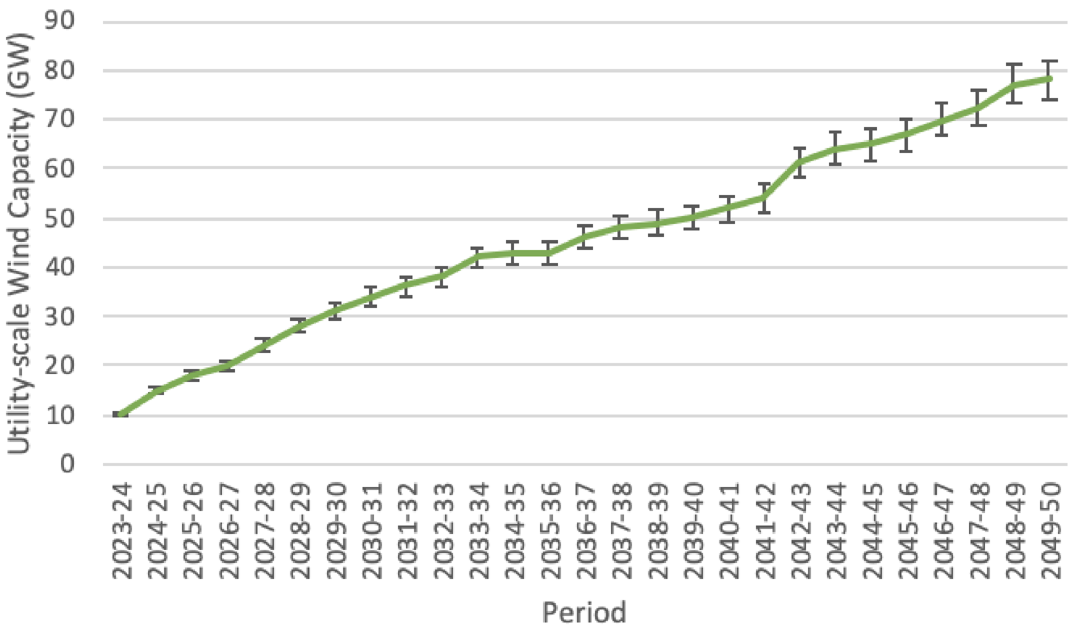


Figure 8: Future trajectory of utility-scale wind capacity development in Australia under the SCS

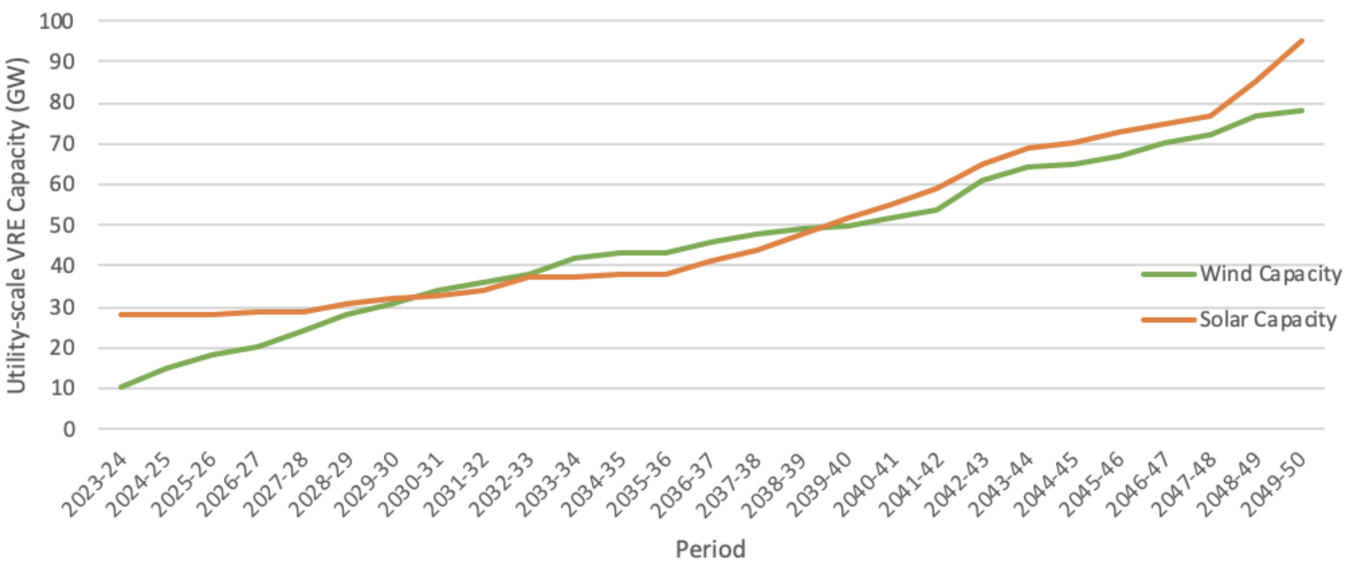


Figure 9: Future trajectory of VRE capacity development in Australia under the SCS

4.2 Establishing the Reference Cases (Outside view)

Once the target case has been clearly defined, the reference cases must then be determined and stated. Guided by the definition provided by Kahneman & Lovall (1993), the reference cases will be compartmentalised into two primary components – the historical trends of VRE capacity development within Australia, as governed by the MRET, and the targets and trends of VRE capacity development on a global scale.

Firstly, the development of Australia’s wind and solar capacity from 2013 to 2022 was isolated and extracted by examining IRENA’s Renewable Capacity Statistics 2023, which outlines comprehensive statistics on renewable power generation capacity globally over the past decade (IRENA, 2023). The same process is carried out, firstly by tabulating the isolated data, graphing the historical trends, then integrating this data with the graph presented on Figure 9 (see Table 9; Figure 10; Figure 11; Figure 12; Figure 13). It is worth noting that the future VRE capacity trajectory data provided in the 2022 ISP is integral and measured in GW, while the data in IRENA’s Renewable Capacity Statistics are measured in MW. To account for this, the unit of measurement for IRENA’s statistics were standardised to GW, and rounded up or down accordingly in order to arrive at integral values measured in GW. This allows for the applicability of the collected data within the same graph, in order to effectively compare similar or contrasting trends. This would establish the reference case, as previous trends of VRE capacity development will provide a historical analogy to underpin the target case.

Table 9: Historical growth of utility-scale VRE capacity in Australia over the last decade

	2013-2014	2014-2015	2015-2016	2016-2017	2017-2018	2018-2019	2019-2020	2020-2021	2021-2022
Wind Capacity (GW)	3.797	4.181	4.324	4.812	5.442	6.279	8.603	8.951	10.134
Solar Capacity (GW)	5.287	5.946	6.689	7.354	8.626	12.970	17.986	22.870	26.792

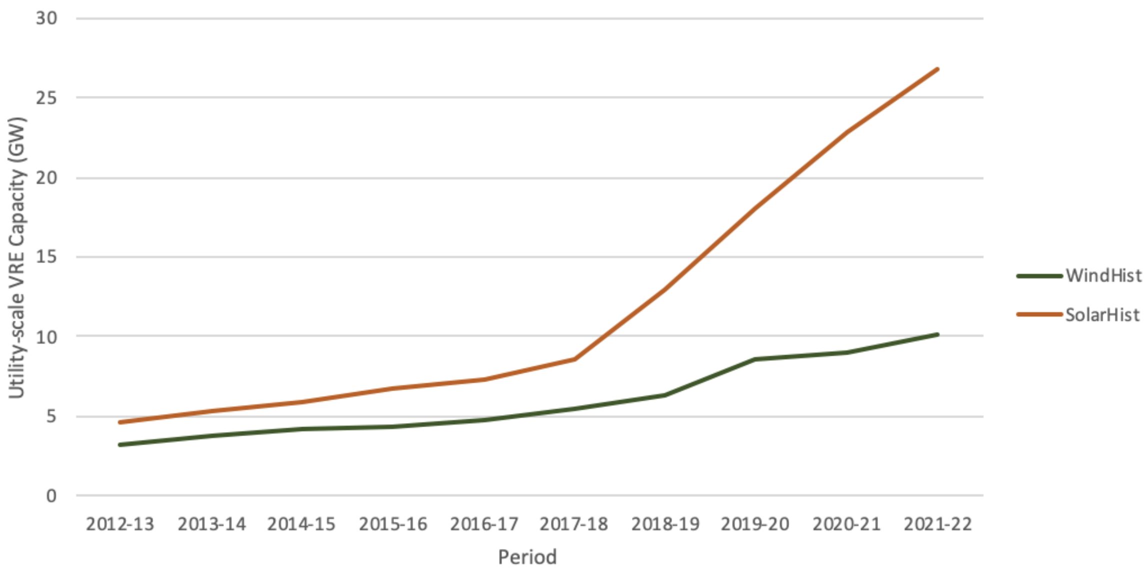


Figure 10: Historical trends of VRE capacity development in Australia

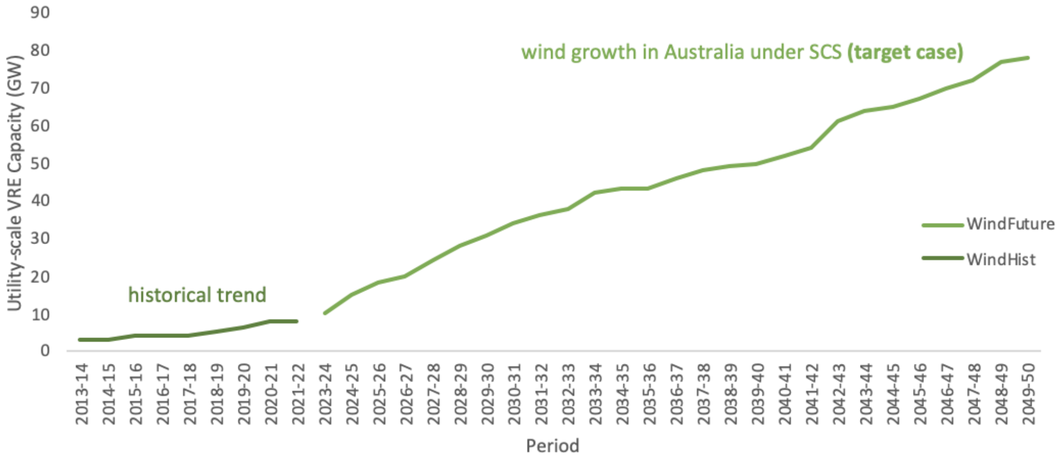


Figure 11: Wind growth in Australia under SCS against historical trend

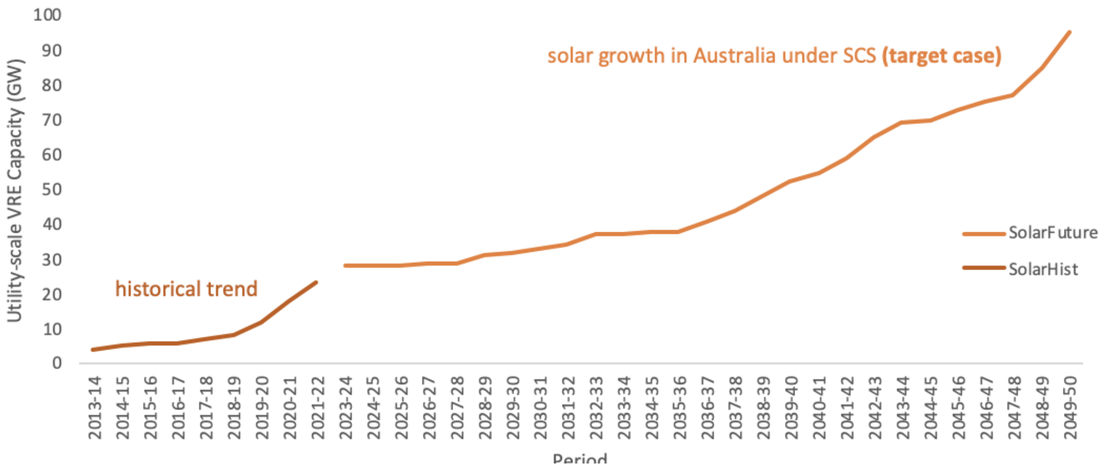


Figure 12: Solar growth in Australia under SCS against historical trend

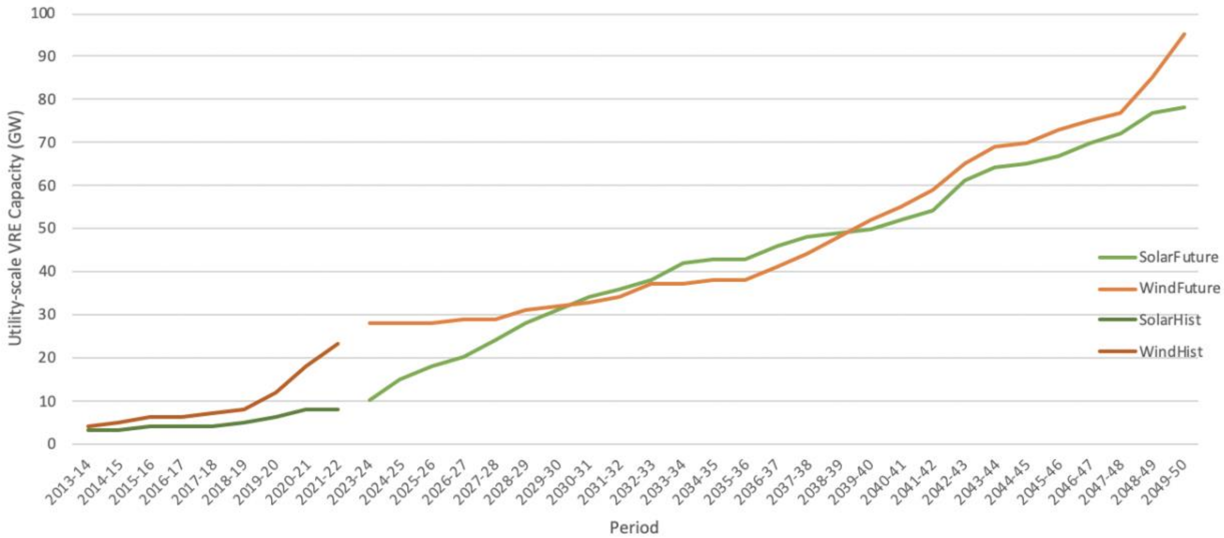


Figure 13: Historical trend and future trajectory of VRE capacity in Australia

Figure 10 shows that while the capacity of solar and wind power showed similar trends of development from 2012 to 2017, wind stayed on the same trajectory whereas solar experienced an evident accelerated growth in capacity from the period between 2017 and 2022. The boom during this period can be attributed to a number of factors, as outlined in the Climate Council's State of Solar 2016. In the five years prior to 2016, there was a 58% drop in the price for solar power in Australia, with industrial-scale solar plants providing significantly cheaper power relative to nuclear and fossil plants (Climate Council, 2017). During this period, electricity sourced from solar parks averaged at A$110 per megawatt hour (MWh), forecasted to further decrease over time, while electricity sourced from new coal power stations were averaging around A$160. 2016 also saw a significant number of large-scale solar PV installations across Australia, with 20 new projects coming online in 2017, and 70 GW of solar PV installed in 2016 alone. In conjunction with this, a further 3,700 MW of large-scale solar was in the Australian government's pipeline (Climate Council, 2017). Facilitating the accelerated rate of solar deployment in Australia, more than 6,500 households adopted solar and battery storage, with uptake forecasted to triple in 2017. This specifically exemplifies the untapped potential to integrate energy storage technology with large-scale solar.

The second phase in establishing the reference cases in the feasibility space is considering the global perspective, and embedding Australia's SCS ambitions within the targets set by different countries. To achieve this aim, extensive review was conducted around climate commitment statements and national energy policies globally. Specific focus was set on countries who have definitively outlined specific targets for wind and solar capacity. These include the following:

(i) **Germany:** 100 GW of solar PV, and 115 GW of onshore wind capacity by 2030, as outlined in their 2021 Erneuerbare-Energien-Gesetzes (Renewable Energy Sources Act);

(ii) **India:** 280 GW of solar power, and 140 GW of wind power by 2030, as stated by the Indian government, and outlined in the Global Wind Energy Council India's "Accelerating Onshore Wind Capacity Addition in India to Achieve the 2030 Target" document;

(iii) **Italy:** 50 GW of installed solar power capacity, and 18 GW of installed wind power capacity by 2030, as outlined in the Italy Ministry of Economic Development (MISE)'s Strategia Energetica Nazionale (National Energy Strategy).

Table 10 provides an overview of each reference case country's VRE capacity targets by 2030. IRENA's Renewable Capacity Statistics 2023 was once again used to extract historical data for each reference country from 2013 to 2022. These datasets feed into Figures 14 and 15, in order to individually embed them within a global perspective, and to effectively compare and contextualise each reference country's ambitions with one another.

Table 10: Reference case countries' VRE capacity targets by 2030

Country	Solar Capacity (GW)	Wind Capacity (GW)
Germany	100	115
India	280	140
Italy	50	18

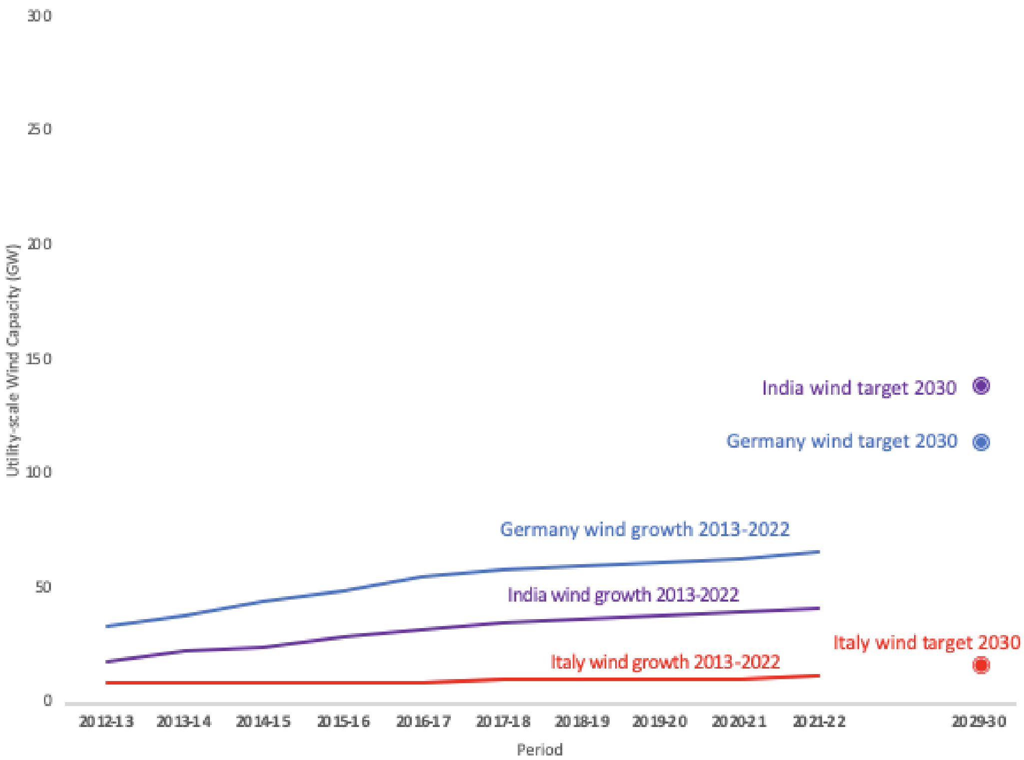


Figure 14: Wind capacity growth and 2030 targets for reference case countries

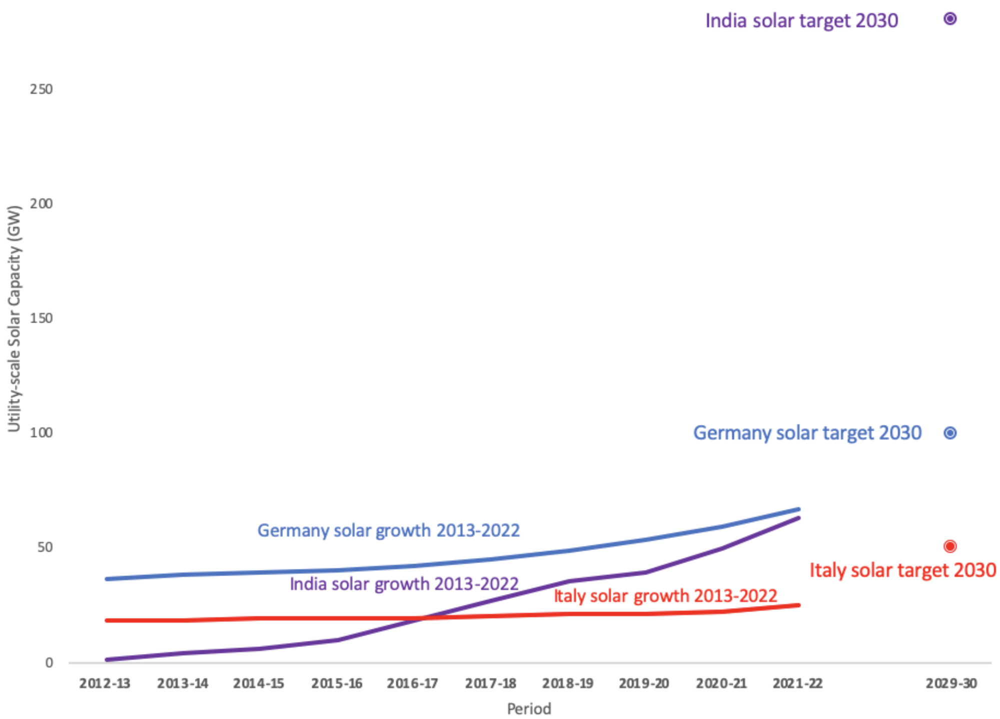


Figure 15: Solar capacity growth and 2030 targets for reference case countries

For Figure 14, the trajectories of Germany, India and Italy are all evenly spaced, and all exhibit similar wind capacity development trends over the past decade. While Italy's set wind target by 2030 appears completely feasible relative to their historic trajectory, India and Germany both set highly ambitious targets at 140 and 115 GW of capacity, respectively. Despite India starting at a lower amount of utility-scale VRE capacity, their 2030 targets are substantially higher than Germany's. Whether or not this target will be achieved remains to be seen, however, given their historic trajectory, a significant step up in political will and support to facilitate a greater rate of VRE deployment will be required.

For Figure 15, Italy shows a fairly linear growth rate with relatively minimal growth in solar capacity for the period between 2013 and 2022. A similar development trend can be observed with Germany's solar growth, which shows a low growth rate at the graph's starting point, which gradually accelerates towards present day. India's growth rate in solar capacity is the highest out of the three reference countries, almost coinciding with Germany in solar capacity by 2022. The most discernible feature of Figure 15 is India's set solar capacity target of 280 GW by 2030. Although highly ambitious, the historical trend of solar capacity growth in the country is a promising sign with regards to achieving this target. Italy and Germany's set solar target by 2030 appear to be highly likely to be achieved given the trajectory of their capacity development over the past decade.

4.3 Constructing the Feasibility Space

The target case has been clearly established and stated as the future trajectory of utility-scale solar and wind capacity in Australia, as outlined in the AEMO's 2022 ISP for the NEM. Figures 8 and 9 visualise the forecasted development in VRE capacity. The reference cases have also been established. This was done firstly by extracting the installed wind and solar capacity in Australia from 2013 to 2022, and graphing against the target case, which is the future trajectory of VRE capacity. Construction of the feasibility space will allow the forecasted trajectory of a specific VRE type to be compared and contrasted to historical trends within the same region, as well as development trends and targets set by the reference case countries. The feasibility spaces for solar and wind capacity development in Australia has been created in Figures 16 and 17, which take into account these factors. Included in the graph are the forecasted 2050 VRE capacities under the Slow Change, Progressive Change, and Hydrogen Superpower scenarios outlined in the 2022 ISP. For Figure 16, the Hydrogen Superpower scenario has been omitted as this outlier value will significantly increase the range and skew the data, and these different ISP scenarios were only included in the graph for reference, and to put the SCS trajectory into perspective.

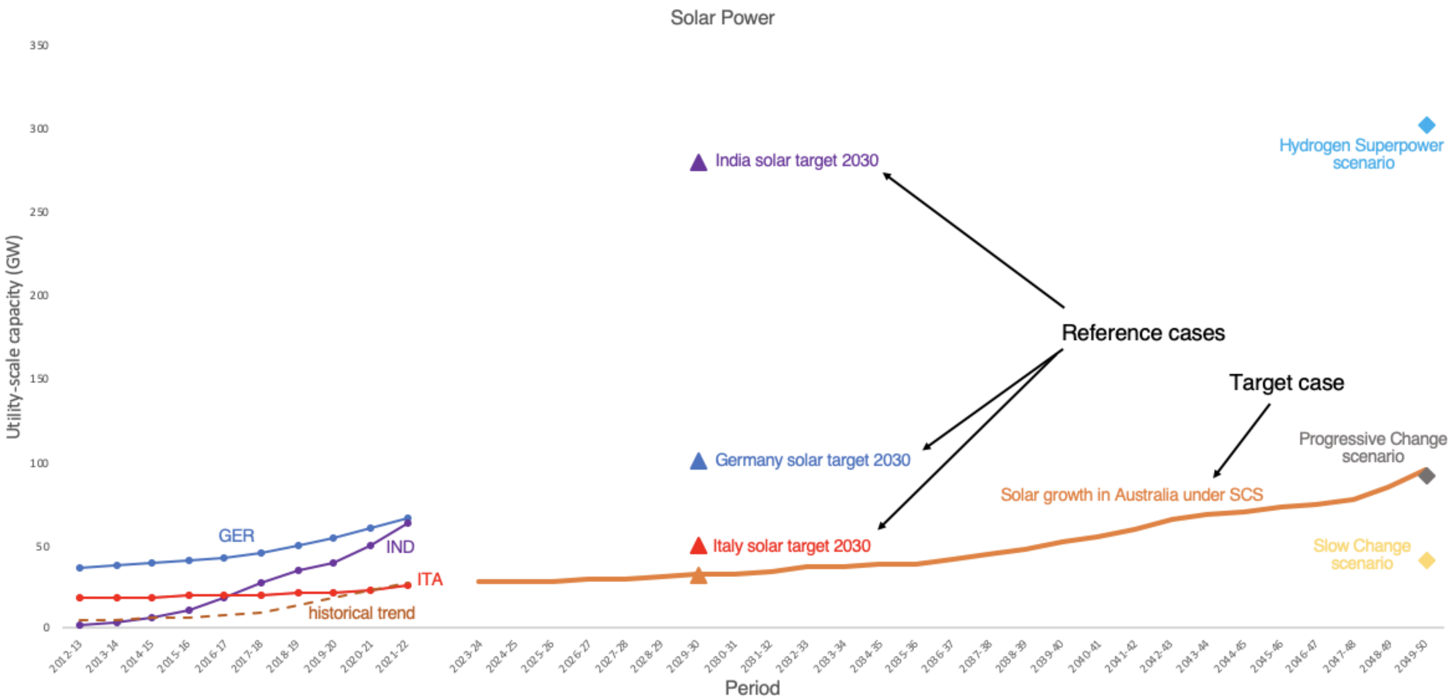


Figure 16: Feasibility space for wind power in Australia assuming the SCS

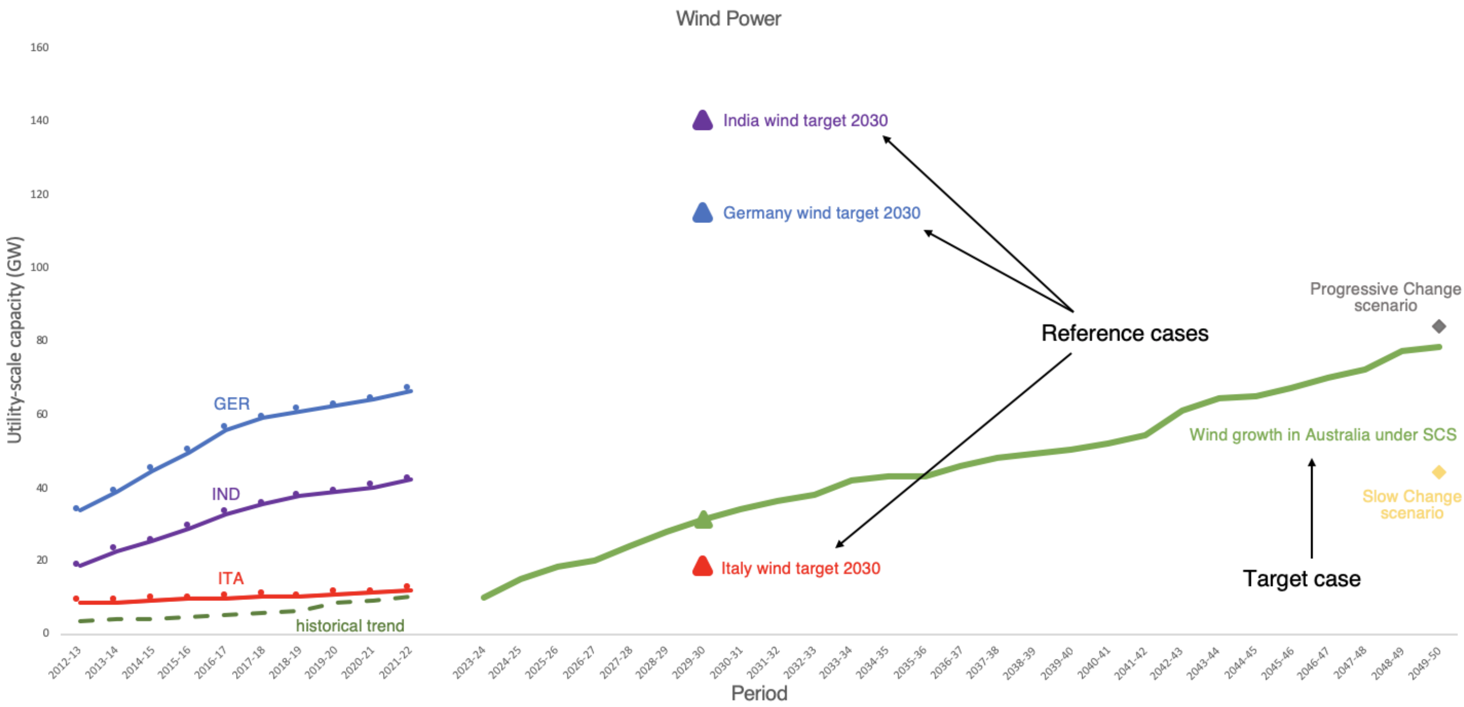


Figure 17: Feasibility space for solar power in Australia assuming the SCS

4.4 Establishing the Inside View

Establishing the inside view entails identifying detailed barriers that impede or hinder the achievement of energy transition targets and future trajectories of VRE deployment. Some detailed barriers to global energy transitions have already been determined and outlined by the author in Table 5 under section 2.3.4. Majority of these outlined barriers also largely apply to the Australian context, however, there are also various exclusive barriers underpinned by existing literature. Firstly, with greater than 7.6 million km² in land area and a relatively small population of 26 million people, Australia has one of the lowest population densities in the world. While this provides benefits in other aspects, this also presents unique barriers and challenges to a greater rate of renewable energy deployment. Australia has a significant number of small community-scale or regional projects, as conditions in these areas are typically ideal for leveraging for renewable energy. However, the low population density and vast distances mean that these projects are far removed from major centres of supply and demand. In

Australia, renewable energy products are usually located further away from the grid as opposed to conventional coal-fired generators. This adversely affects the associated electrical system's Marginal Loss Factor (MLF), which increases proportional to the distance between the point of generation to demand. With rural networks typically utilising cost effective conductors like galvanised steel, and structured with overhead power lines, the AEMO estimates that around 10% of total electricity transported is incurred as losses (AEMO, n.d.). As such, the high MLF disincentives stakeholders to build and invest new renewable projects in regions that potentially hold optimal resources, such as consistently strong wind speeds and high solar irradiance.

Furthermore, there are specific phenomena that adversely affects the greater uptake of renewable energy in the country. Firstly, with regards to the costs of grid connection, the 'first mover' concept presents a unique challenge to new generators attempting to enter the market. Distribution within Australia is, for the most part, a unidirectional network, leveraging Single Wire Earth Return (SWER) lines in order to compensate for the great distances to provide service to sparse populations located further from capital cities. Current policies across most federal jurisdictions in Australia entail that generators newly entering the market are required to pay associated costs when connecting their generator to the grid (Byrnes et al., 2013). In turn, this significantly increases the capital expenditure required for most renewable energy projects in the country. Meanwhile, subsequent generators are able to leverage the reinforced network without incurring the same upfront costs, creating a 'first mover' disadvantage and greatly disincentivising the commissioning of renewable energy projects. This presents a unique challenge in finding the balance between establishing renewable energy projects in regions with optimal resources, and maintaining the proximity, quality, and integrity of the grid.

A well-documented and substantially echoed sentiment within Australia is the "not in my backyard" phenomena. This has been a recurring theme historically in Australia, especially with regards to the vehement opposition to the construction of wind farms. While the public have largely expressed favour towards a greater share of renewables in the national energy mix, this usually comes with a caveat that infrastructure and its effects should not impede on their current lifestyles in even the slightest way. The public want to experience the benefits of a greater renewable share but want to be positioned as far away as possible to the associated infrastructure and its effects, which are largely minimal and negligible. In conjunction with this, renewables present a unique challenge in the form of a 'network effect'. Larger-scale renewable technologies are relatively in the inception phase, and as such, can somewhat behave unpredictably and possess potential uncertainties. As a result, institutions and consumers are faced with a relatively simple choice between competing networks wherein one has legacy inputs that are largely predictable and stable, and the other remains volatile and immature. Businesses and individuals using conventional energy sources have shown an inclination to remain favourable to technologies they are familiar with. Only when markets and governments provide the right incentives for consumers to favour one network over another can rate of renewable uptake truly be accelerated. Once renewable energy constitute a larger share of the national energy mix, consumers will be more supportive and willing to be involved with these technologies. Ultimately, this increased involvement and willingness from consumer individuals and institutions will present various solutions to unique renewable technology challenges such as supply intermittency and variation in voltage.

Lastly, unique challenges are presented with regards to the structure of the Australian government and the resulting uncertainty in policy and regulation. The Commonwealth of Australia is considered a federal parliamentary democracy, comprised by federal, state and local governments with respective but sometimes overlapping jurisdictions. While this is effective in ensuring the accountability and progress of each local sector, competing priorities between governments present the challenge of establishing a united policy structure across jurisdictions and ultimately, a concerted national effort for a greater uptake of renewable energy technologies. Quiggins (2001) covers how these competing priorities and overlapping jurisdictions present unique challenges in the context of the Australian Murray Darling basin's management. Implementation of effective energy policy requires constitutional liabilities, agreement in markets, and intergovernmental collaboration. As such, the discord between governments present complex policy frameworks that provide existing energy stakeholders with unnecessarily onerous and conflicting requirements for compliance, while creating a barrier for new generators. This results in a significantly inhibited integration of new renewable technologies, and a smaller share of renewables within the national energy mix.

5 Discussion

5.1 Interpretation of results

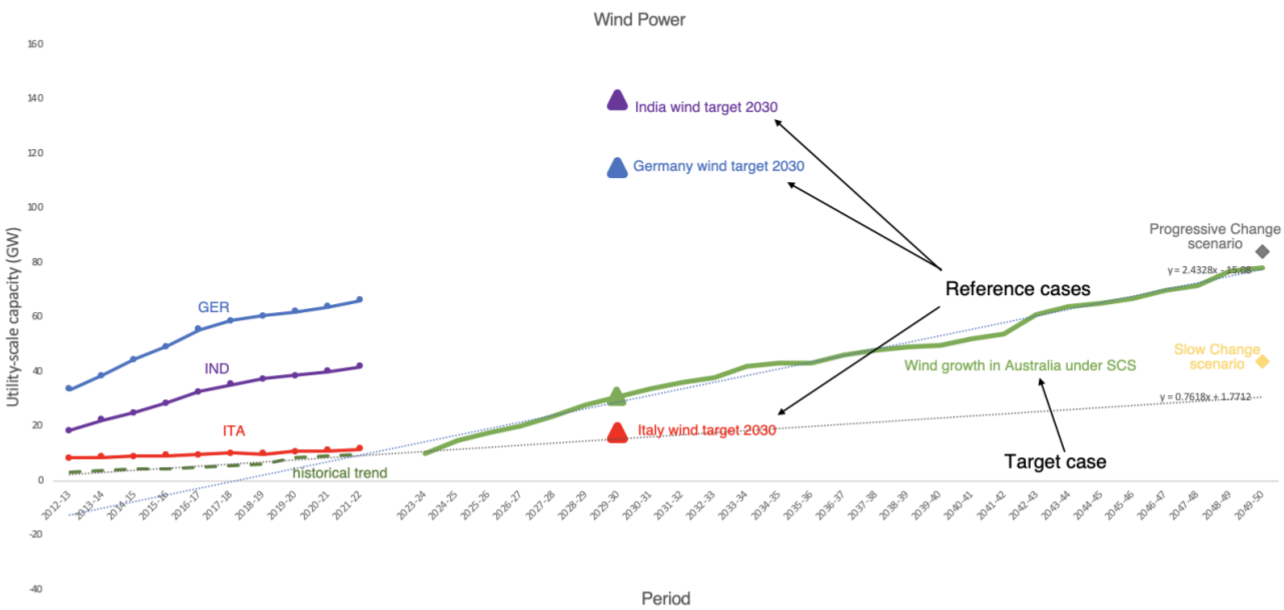


Figure 18: Trendlines for feasibility space of wind power in Australia under SCS

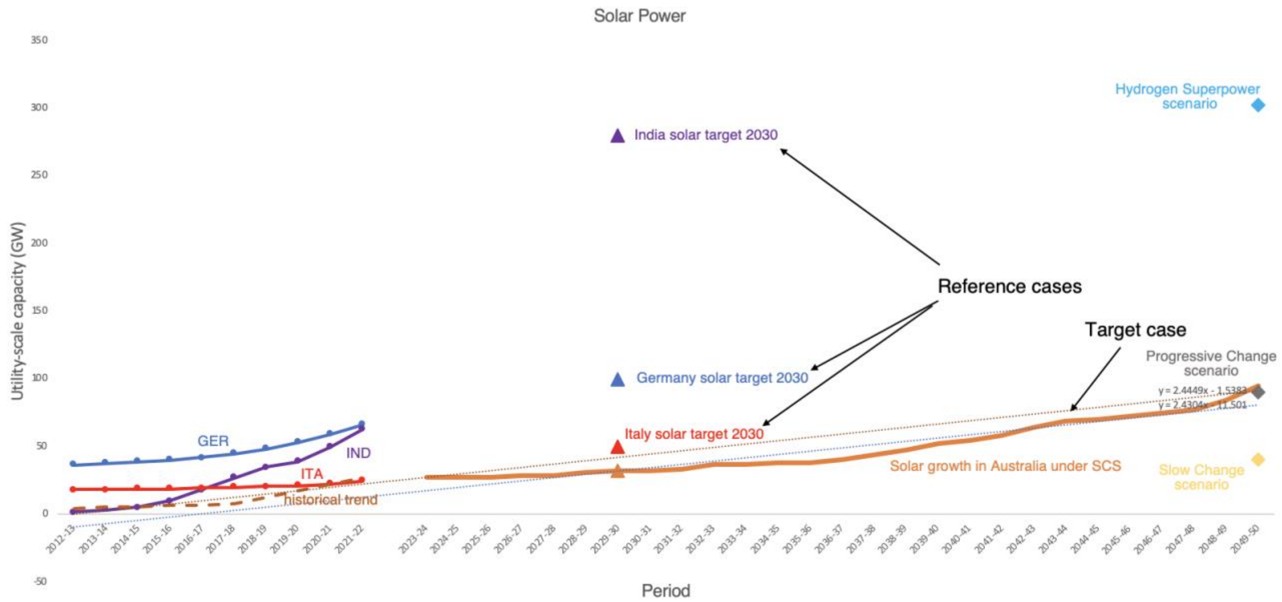


Figure 19: Trendlines for feasibility space of solar power in Australia under SCS

Analysis of the created feasibility spaces included implementing trendlines, inspecting the slopes, and interpreting the deviance in slopes between the trend and trajectory. The trendline slopes would signify the growth rate of VRE capacity, and the deviance between the historical trend and trajectory would suggest the extent of action and initiative that is required to reach the established targets. The plotting of the reference countries' historical trends and set 2030 targets is crucial in putting Australia's VRE landscape into perspective.

The historical trend of wind power in Australia from 2013 to 2020 show similarities to that of Italy, in terms of capacity volume and growth rate during this period. However, by 2030, the forecasted trajectory of wind power in Australia has surpassed, and is greater than the targets set in Italy's National Energy Strategy. India and Germany exhibit similar development growths in wind capacity from 2013 to 2022, and both countries have set concrete targets for 2030. Germany's set targets entail an almost double increase in wind capacity from current levels, while India's sets an even more ambitious target of tripling their current utility-scale wind power capacity. To more effectively compare the historical trend of wind power capacity development in Australia with the forecasted trajectory of development to 2050, trendlines were implemented for Figure 16, with specific focus on the deviation in slope (see Figure 18). The historical trend produced a slope of 0.76, while the forecasted trajectory showed a more than threefold greater slope of 2.43. As such, the achievement of the forecasted SCS trajectory is feasible under the condition that conditions are established to significantly accelerate the rate of utility-scale wind capacity development than that from the period of 2013 to 2022. Furthermore, the forecasted utility-scale wind capacity by 2030 in Australia is significantly lower than the wind targets set by Germany and Italy for that same timeframe. Whether the trajectory of utility-scale wind growth for Australia under the SCS is feasible remains to be seen, however achievement of this feat would require addressing the issues outlined in the inside view, greater social acceptance and involvement, as well as policy and regulatory support to provide the appropriate incentive frameworks for key stakeholders in the energy sector.

As for Figure 19, the solar growth in Australia under the SCS appears completely on track with the historical trend of development from 2013 to 2022. Examining the trendlines of the two, the historical trend yields a slope of 2.44 while the SCS trajectory produces a slightly lower slope of 2.43. This entails that the trajectory of solar capacity growth to 2050 under the SCS is on track with the historical trend, and no notable acceleration in growth rate is observed. While this indicates feasibility, this is also indicative of a possible lack of ambition and willingness from the government and key stakeholders to further scale up deployment of solar technologies nationally to increase its share in the national energy mix. This is especially true given that historical trends of utility-scale solar capacity development appears on par with the reference case countries, bar India, it would appear feasible and highly beneficial to establish more ambitious solar targets.

Achieving and surpassing the trajectories for VRE in Australia is heavily contingent on addressing the issues outlined within the inside view. Firstly, the disadvantage for first movers can be significantly mitigated by mandating succeeding generators, who are looking to leverage the reinforced network, to pay a percentage of the upgrade costs already paid, allowing first movers to recover a proportion of the capital costs they initially shouldered. With regards to the "not in my backyard" phenomena in the context of the energy transition, various renewable energy projects globally and nationally have shown that social support and acceptance proportionally increases with local participation during deployment. The government's priority of increasing transparency with and involvement of local communities in the deployment of renewable energy technologies will significantly contribute to social acceptance, ultimately assisting in increasing the rate of RE deployment nationally.

Historical political discourse regarding the energy sector has specifically highlighted the dysfunctional relationship between the state and federal level. The feasibility of the contemporary national energy transition relies on solutions underpinned by cooperative federalism. The Australian government has attempted to address the discord across the levels of government several times, primarily through establishing policies aimed at providing direction for collective national action to deploy renewables.

5.2 Policy support underpinning rates of VRE deployment

Primarily, the inception of policy support for RE deployment in Australia can be attributed to the federal government's introduction of its flagship climate change strategy: Safeguarding the Future: Australia's Response to Climate Change in 2000. Under this scheme, the Australian Government presented the Mandatory Renewable Energy Target (MRET), marking the first mandatory renewable energy target regime. Prior to its mandate, renewable energy targets globally were largely aspirational (Kent & Mercer, 2006). The MRET was the keystone under the Renewable Energy (Electricity) Act of 2001, which outlined the following objectives:

(i) To stimulate additional electricity generation from renewable sources;

(ii) To reduce and curtail the levels of national GHG emissions; and

(iii) To ensure the ecological sustainability of renewable energy sources

To this end, the key measure of implementation for the aforementioned objectives was the keystone MRET, which aimed to build upon the existing 16,000 gigawatt hour (GWh) by generating an additional new 9,500GWh by 2010. This would result in a 4% increase in new renewable electricity generation in Australia, and a doubling of renewable generation relative to 1997 levels (Kent & Mercer, 2006).

The MRET scheme was revisited in 2009, with an expanded Renewable Energy Target (RET) being passed, ensuring that RE occupies 20% of the national electricity supply by 2020. The revision in the MRET entailed an increase in the target, from the previous 9.,500 GWh by 2010 to 45,000 GWh by 2020. As part of the amended mandate, the Australian government also introduced the concept of 'solar credits' multiplier, which aimed to further stimulate the installation of solar PV systems (St John, 2014). By 2011, the expanded RET was split into two major constituent schemes – the Large-scale RET (LRET) and the Small-scale Renewable Energy Scheme (SRES). The LRET financially incentivised the expansion and construction of renewable power stations like wind and solar farms in order to expedite progress towards the established 2020 target. Under this scheme, high-energy users are mandated to source a set proportion of their electricity from renewable sources in the form of large-scale generation certificates (LGCs), produced by major RE power stations, which are then sold to other high-energy users who are ultimately required to turn them over in order to meet their obligations under the LRET. On the other hand, the SRES establishes a financial incentive framework for individuals and institutions to install hydro and wind systems, air source heat pumps, as well as rooftop solar panels and solar water heaters. Small-scale technology certificates (STCs) are issued contingent on a particular system's anticipated power output, which is partially determined on its geographical position and date of installation. As with the LRET, major energy users are mandated to purchase a set number of STCs, which they are required to surrender as part of their obligations under the RET scheme. (Clean Energy Regulator, 2022). In 2015, the Australian Parliament further amended the RET, reducing the 41,000 GWh target to 33,000 GWh by 2020, with adjustments made around the interim and post-2020 targets.

The implementation of the RET is considered partly successful with the Australian Government announcing in 2019 that the LRET was achieved more than one year ahead of time (Clean Energy Regulator, 2022). This came after the Clean Energy Regulator's approval of the capacity generated from the 148.5 megawatt (MW) Cattle Hill wind farm project in Tasmania.

Furthermore, the Australian Government is currently implementing the following frameworks to accelerate the deployment of RE in the country: Powering Australia, Rewiring the Nation Plan, National Energy Performance Strategy, and the National Energy Transformation Partnership. The Powering Australia strategy sees the government committing A$20 billion to facilitate the urgent upgrade of the national electricity grid to accommodate for a greater share of renewable energy, and ultimately deliver cheaper and more reliable electricity to consumers. Additionally, A$100 million is allocated for investing in solar banks nationwide, which will provide cheaper electricity for renters and low-income households that are typically locked out of rooftop solar. Lastly, a significant number of community batteries will be installed across the country to facilitate and maximise the benefits experienced through Australia's transformation of solar (DCCEEW, n.d.).

The Rewiring the Nation Plan serves to complement this through the federal government's allocation of a A$20 billion budget towards the expansion and upgrade of the national to further drive down power prices and unlock the potential for new RE sources (IEA, 2023). The National Energy Performance Strategy also strives to address this discord through providing a national plan to accelerate the action on the demand side of the energy sector, with particular focus on improving energy efficiency and electrification of sectors (DCCEEW, n.d.). Lastly, the National Energy Transformation Partnership establishes a framework for national alignment and cooperative action across governments to implement the appropriate reforms to facilitate Australia's energy sector transformation (DCCEEW, 2022). While the indicators of success for these policies remain to be seen, the act of creating these alignment plans and implementing them on a national scale signals a promising step in underpinning the energy transition in Australia.

5.3 Further Considerations

The feasibility of the trajectories for the development of utility-scale VRE capacity in Australia, and the national energy transition as a whole, is further bolstered by the country's unique topography resulting in abundant VRE resources. The southern regions of the continent are situated directly in the trajectory of the westerly wind flows commonly referred to as the 'roaring 40s'. Wind speeds in these regions are extremely high, reaching speeds of 12 metres per second in the areas near the Bass Strait. These extremely viable wind resources extend hundreds and hundreds of kilometres further inland. Furthermore, more than 60,000 km of coastline provides an abundance of land surface to install offshore wind facilities (Yusaf et al., 2011). However, a variety of parameters are assessed to determine a capacity factor, which indicates viability of a site's conditions for renewable energy. These include local topography in the form of local terrain variability, and thermal effects. The high capacity factor possessed by Australia is indicative of the enormous potential for RE development (Coppin et al., 2003). Australia also receives around 58 million PJ of annual solar radiation, aggregating to more than 10,000 times the country's total energy consumption, and experiencing the highest solar radiation per square metre in the world, providing the most viable conditions for leveraging solar energy (Geoscience Australia, 2023) (Appendix; Figure 24).

Underpinning the sentiment regarding the question of feasibility in renewable energy trajectories and targets within Australia, modelling conducted by Wang & Dargaville (2009) have determined that 100% renewable electricity by 2050 in Australia appears to be feasible both economically and technically. Using a capacity expansion model that takes into account inertia constraints, detailed transmission, ramp rate, and the hourly variability of input from wind and solar sources, Wang & Dargaville concurred that a system with a 100% renewable share proves to be extremely reliable and secure, as well as cost-competitive relative to a predominantly fossil fuel-powered energy system. In the event that the proper incentives are in place, and government support is high, a carbon-neutral NEM will be able to provide secure and reliable energy for all consumers, and is proven to be economically achievable by 2050. The abundant VRE resources discussed above can be integrated into the national network easily, and without requiring substantial transmission extension. (Wang & Dargaville, 2009).

6 Conclusions

6.1 Contribution to literature

While various bodies of work have introduced and implemented different frameworks for assessing the feasibility of climate mitigation pathway, Jewell & Cherp (2023)'s feasibility space framework is relatively new, and its implementation especially in the field of the energy transition remains limited. It proves to be a valuable mechanism not only in contextualising a specific case, but also bridging the different aspects of the contemporary energy transition with historical trends. This thesis implements this framework, and hopes to contribute to its further development and succeeding adoption.

Furthermore, to the best of the author's knowledge, little to no literature currently exists that delves into the AEMO's 2022 ISP in depth, and especially examining the trajectory for VRE as outlined in the document. While different Australian national or federal energy and emissions targets have been examined in various previous bodies of literature, the ones specifically outlined in the ISP remain undissected. Where Australian energy targets and trajectories have been studied closely, they have not usually been compared and contrasted on a temporal and spatial scale by embedding them in the context of targets and trajectories set over a different timeframe, or by different countries around the world.

6.2 Limitations of the Study and Further Research

A more accurate implementation of the feasibility space framework can always be achieved contingent to the volume of reference cases used in the study. For this body of work, the pool of choices for reference case countries was highly limited as the set parameter were countries that have explicitly set specific targets for both solar and wind power by a specific timeframe, ideally 2050 to coincide with Australia. While selecting reference case countries, a recurring theme was clear in that almost all national targets set by 2050 involved the overarching mission of emissions reduction, as opposed to specific utility-scale VRE capacity. Furthermore, where specific national targets or trajectories were available for utility-scale VRE capacity, the timeframe set was for 2030, and this was manifested in the construction of the feasibility spaces. While it is unfortunate that little to no data was available to better compare and contrast Australia's trajectory to 2050, the reference case countries' 2030 were still valuable in putting the trajectories into perspective. As such, this body of work can be further improved or built upon by selecting a greater amount of reference case countries to compare with.

Next, the accuracy of this body of work can be further improved by isolating the types of VRE technologies. For this study, there was no distinction between onshore and offshore wind power, and solar CSP and PV. These technologies were all aggregated into binary categories of solar and wind. Isolating the data of these technologies could be valuable as the trajectories and targets of different countries could be constituted differently. Where one reference country possesses optimal resources and allocates specific focus on offshore wind power, others may have no offshore resources whatsoever and thus only set targets for onshore wind power. This study does not reflect the types of VRE technologies, but rather only serves to observe and compare trends in trajectories on a general scale.

In constructing the historical trends as a reference case, data was extracted from IRENA's Renewable Energy Statistics documents. However, both the 2022 and 2023 reiterations of these publications only cover the preceding decade. As such, the historical reference case in the feasibility spaces only covered the period from 2013 to 2022. Historical data specific to the development of utility-scale VRE capacity appeared limited, and this study could be improved further by utilising a more extensive range of historical data which will ultimately feed into a more accurate historical trend reference case.

Lastly, the means used to construct and analyse the feasibility spaces are admittedly rudimentary. This body of work can be built upon by using more advanced software to carry out these tasks.

6.3 Synthesis of Findings

This thesis fulfilled its objectives and aims set out in the introduction. The comprehensive literature review highlighted the fossil-fuel dominated current energy landscape both globally and within Australia, and provided a substantial foundation and background for the study of the contemporary energy transition. The trajectories and targets set out in the AEMO's 2022 ISP were sufficiently examined and contextualised through the use of a feasibility space framework. This allowed the trajectories in the ISP to be analysed through both highlighting the trends of utility-scale VRE capacity development in Australia over the past decade, as well as embedding the trajectories into the global context by comparatively analysing it relative the historic trends of other countries and their established 2030 targets for solar and wind. Through this process, it has been determined that the future trajectory of utility-scale solar energy capacity development in Australia is on track with the historic trend, which indicates feasibility, yet interestingly does not reflect accelerated action to scale up solar energy technology. The trend for wind growth in Australia under the SCS shows a threefold increase in rate of utility-scale capacity development by 2050 from the 2013 to 2022 rates. Greater examination needs to be done to determine its feasibility, however, achievement of this trajectory by 2050 is contingent on focusing on and addressing the issues outlined in the inside view. Currently, the Australian government has been implementing appropriate incentive mechanisms and policy support for greater rates of RE deployment within the country, thus increasing the likelihood of the ISP trajectories' feasibility. When compared with the historic trajectories and 2030 targets of the reference case countries, Germany, Italy and India, Australia's historic trend shows a much slower development rate for VRE deployment. By 2030, Australia's VRE capacity by 2030 is significantly less than the reference case countries' established targets, especially for Germany and India. This remains true for 2050, wherein the utility-scale VRE capacity in Australia is still markedly lower than the target already aimed to be achieved by Germany and India by 2030. While this builds a strong case for the feasibility of Australia's trajectories, this also leaves room for establishing more ambitious targets. In conjunction with this, multiple previous studies have shown that Australia has the most ideal wind and solar resources to leverage in their initiative to scale up VRE technologies, which further reinforces the potential feasibility of these VRE trajectories. With current strong political will from national, federal, and local governments, and the abundant natural resources available to leverage, Australia is well-positioned to facilitate the transformation of their energy market from fossil-fuels to low-carbon sources.

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8 Appendix

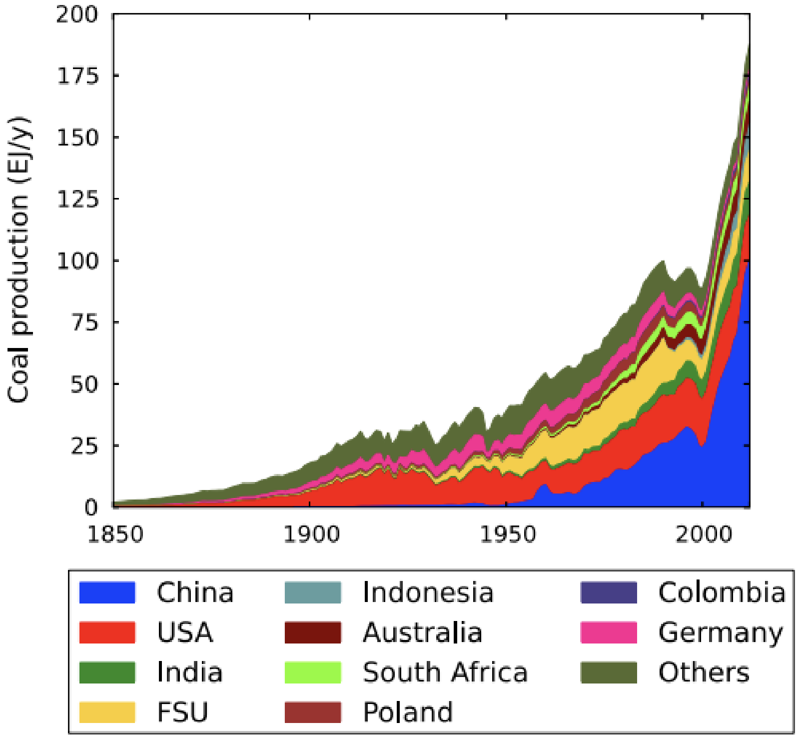

Figure 20: Global historic coal production

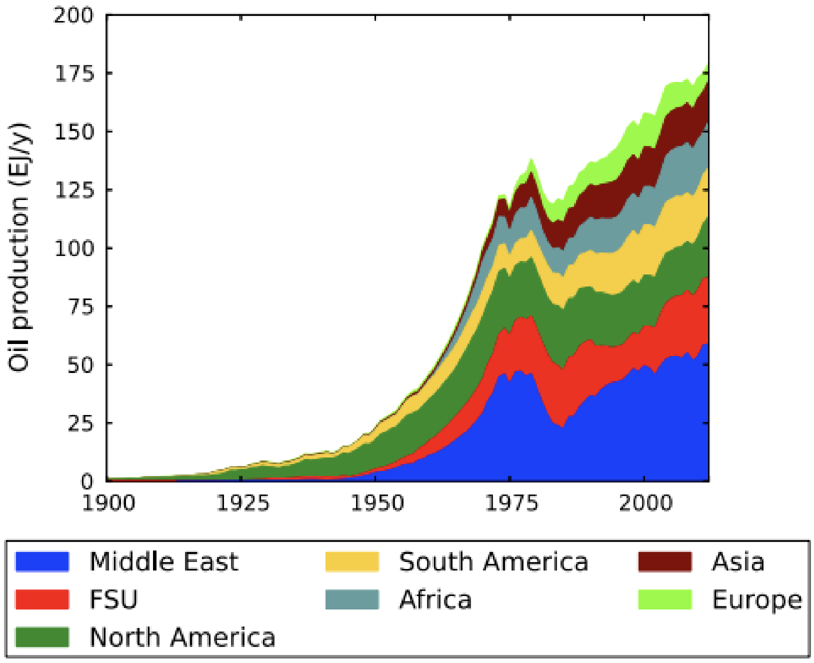

Figure 21: Global historic oil production

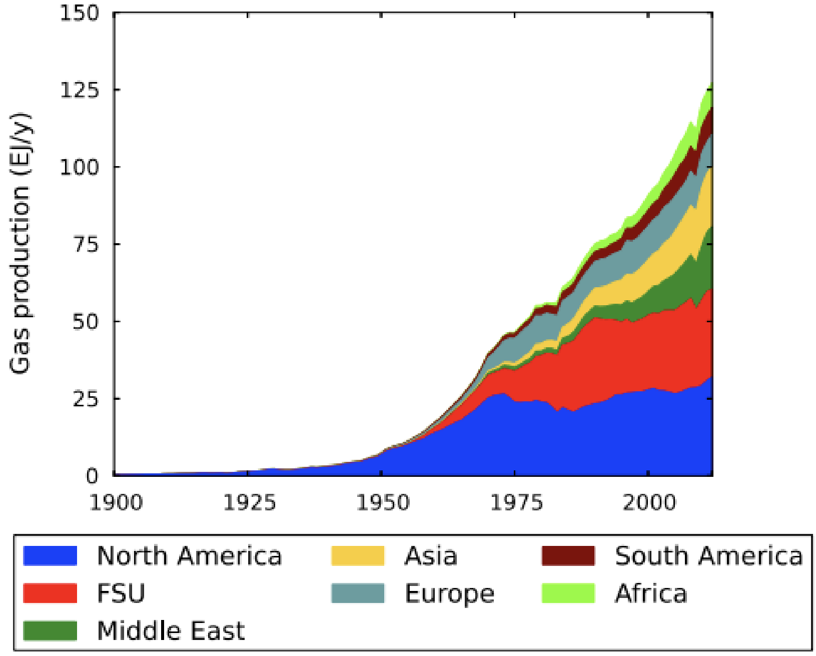

Figure 22: Global historic natural gas production

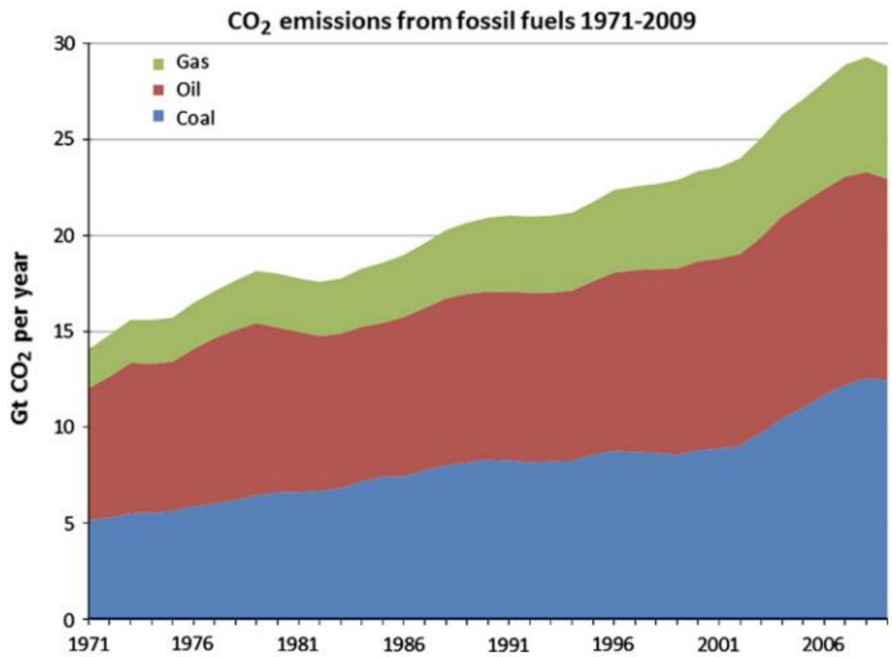

Figure 23: CO2 emission trends between 1971 and 2009 by fuel types

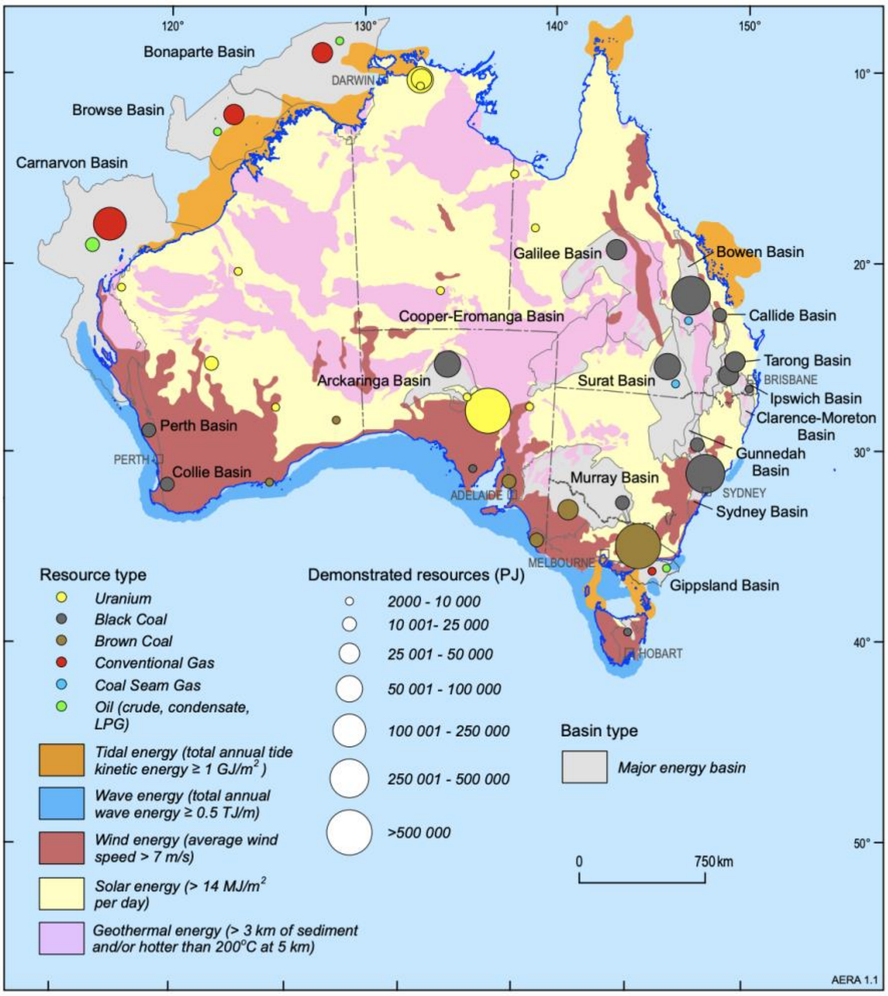

Figure 24: Map of Australia's major energy resources, hydro and bioenergy excluded