15 (2022) 100161

Contents lists available at ScienceDirect

International Journal of Thermofluids

journal homepage: www.sciencedirect.com/journal/international-journal-of-thermofluids

A systems thinking approach to address sustainability challenges to the energy sector

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ARTICLE INFO

Keywords:
Dynamic complexity
Feedback loop
GHG emissions
Energy security
Energy policy
Sustainable development

ABSTRACT

The energy sector is an intrinsically dynamic and complex system, and therefore its behaviour is not solely controlled by constituent components. Rather, it is a consequence of dynamic interactions among them. To properly manage such a system in a sustainable manner, it is necessary to understand the underlying dynamics of component interactions. Despite this, the interconnections between components of the energy sector in research and policy have received little attention. Here, we outline crucial limitations of previous efforts and emphasize the importance of using systems thinking in addressing the energy sector's sustainability challenges. We demonstrate this by a case study of the Australian energy sector, which has experienced emerging sustainability issues. Research findings show that current policies promoting energy development in the country are likely to be 'fixes that fail' that ultimately undermine sustainability. To achieve in building a sustainable energy sector, the policy must focus on implementing long-term solutions and avoid short-term quick fixes.

1. Introduction

Economic development and prosperity across the globe are directly linked to energy [1]. Therefore, sustainable energy development has now become a globally endorsed principle. The Agenda for Sustainable Development set 17 fundamental targets, of which the seventh SDG is fully devoted to sustainable energy development [2]. Many countries have placed this long-term commitment as a top government priority through implementing stringent policies and measures to promote sustainable energy development [3–7]. Nevertheless, despite these efforts, threats to energy sustainability are still in existence in many countries throughout the world. There are continuing negative impacts of the energy sector on the environment (CO_2 emissions) [8–11]; and persistent issues of energy security [12–14], as well concerns relating to social equity [15, 16].

Studies have highlighted the fact that the energy sector is a large and multifaceted industry that contains many interacting components. These may be in the form of manufacturing, refining, fuel extraction, and distribution [17]. The components are connected in a complex manner through a variety of causes and effects generated through multiple dimensions of economic, social, and environmental aspects [18]. The system is also influenced by various external factors, such as demand fluctuations [19] and diverse supply sources and complex utilisation [20]. The outbreak of epidemics is another factor that significantly affects energy systems. Specifically, over the past few months, the Covid-19 pandemic has changed energy demand patterns in a way that has pushed many industries in Australia such as oil, gas, and coal into a vulnerable position. In addition, the energy sector involves a diverse array of stakeholders (e.g. suppliers, intermediaries, and customers) [21], each of whom has different management objectives that make convergence criteria for sustainable outcomes a complex task [22]. All these factors together lead to the conclusion that the energy sector is a dynamically complex system.

In spite of an increasing awareness of energy systems' dynamics and complexity, previous efforts to understand its performance, and governmental policy and measures aimed at improving it are usually focused on isolated parts, and the interrelated and interdependent nature of the sector has received little attention. For example, Narayan and Smyth [23], and Finkel and Moses [24] focus mainly on electricity, while Blakers, Lu [25], and Elliston et al. [26] emphasise the importance

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https://doi.org/10.1016/j.ijft.2022.100161
Received 17 April 2022; Received in revised form 9 May 2022; Accepted 13 May 2022
Available online 16 May 2022

of renewable electricity technologies. In many cases, energy management, planning, and forecasting are largely based on techniques that depend on historical data such as time series [27–30]; or on subsystems energy models such as top-down models (e.g. GEM-E3) [31]; bottom-up models (e.g. E4cast model) [32]; hybrid models (e.g. GCM model) [33]; and an integration of top-down and bottom-up models [34]. These conventional approaches assume that the future will be similar to the past. However, energy systems are dynamically complex, so conditions often change rapidly, making these techniques unreliable. Therefore, silo approaches may fail to comprehend the complexity and underlying rationale of energy systems.

It is acknowledged that sustainability-related issues and challenges of energy systems are manifold and complex involving competing stakeholder expectations. It is not possible to address these issues and/or challenges separately. To address this shortcoming, the study of sustainable energy would benefit from the applications of systems thinking, incorporating insights from a variety of disciplines. This holistic approach, complemented by a new method of thinking and leadership, is based on the primacy of the whole system and interrelationships among its constituent components [35]. It provides synergistic analytic skills to tackle a complex problem [36]; to facilitate greater understanding of the leverage points and where are they located in the system—points where small changes are able to make large changes resulting in lasting improvements in the entire system [37]; and to formulate interventions to achieve desired results while avoiding unintended ones [38]. Importantly, it enables the prediction of both the outcomes and the unintended consequences of policy decisions, particularly intervention programs and strategies [39–41]. A very few studies, such as Zhao et al. [18] and Zuo et al. [42] used systems thinking approach to establish models of sustainable development of a 3E system (Economic-Energy-Environment), but none showed energy sources extraction pipeline and energy policy role as in the current study.

Applications of this fresh approach in the energy sector were largely absent in determining the relationship between energy structure, economics, environment, and energy policy, as a way to inform planning and decision-making to avoid unwanted implications. The aims of this study are: (i) to design a conceptual model of the energy sector; (ii) to analyze the potential consequences of current energy development policies using this model; and (iii) to provide suggestions for improvement of the policy towards sustainable energy development. A case study approach has been used, focusing on the Australian energy sector, which has faced emerging sustainability issues and is in critical need of reform [43, 44], and where there is a great deal of political debate on Renewable Energy (RE) and climate change, which signifies the need to take action to mitigate emissions [45]. The systems approach and recommendations presented in this study are likely to be applicable for other countries facing similar issues.

2. Methods

2.1. Case study: the Australian energy sector

In 2020-2021, the Australian economy and population grew by 1.5% and 0.1% respectively to reach around $2 trillion and 25.7 million. With this growth, energy consumption rose by 1.1% and production rose by 4%; energy exports grew by 4% and imports increased by 2% [46]. Australia has substantial conventional energy sources including coal and natural gas, and is ranked in the world's top 10 for coal, gas, and uranium production. The country is also endowed with abundant RE sources (e.g. solar, wind, and marine) [47].

There are three crucial challenges related to energy supply and use in Australia to: (i) ensure that there are enough accessible energy sources; (ii) assess the impact of future energy dependency and high oil prices; and (3) reduce greenhouse gas emissions [48]. In response, Australian sources of oil are finite; the transport fuel demand in the country is increasing, leading to an increased reliance on imports; and the other major fossil fuel source (gas) is expected to last for only a number of decades [49]. Furthermore, the Climate Change Performance Index (CCPI) rates Australia poorly in three categories: greenhouse gas emissions, energy use, and climate policy, where it is one of the biggest per-capita emissions countries globally [50]. These issues are interconnected with the continuing growth of economy and population, and they add to other challenges facing the Australian energy sector, such as the uncertainty in energy policy. The ambiguity in setting energy policies will effect Australia's future energy options and increase uncertainty; as a result, these uncertainties may be likely to discourage investment [51].

With growing energy demand over the last 40 years (1977-2017), as shown in Fig. 1, due to growth in both population and economy, the Australian energy sector is facing many challenges: (i) growing dependency on other countries to meet its energy needs (Fig. 2). In particular, Australia's energy mix has been dominated by oil (38%) [46], and oil price shocks have caused crises in Australia like those that occurred in 1973 and 1979, driven by a curtailment of supply, and that in 2008 caused by soaring demand, which resulted in a sharp rise in oil prices [52]; (ii) energy source depletion, and domestic accessibility such as oil and gas in the foreseeable future; and (iii) high Greenhouse Gas (GHG) emissions (e.g. CO_2) which cause deterioration of the environment (e.g. climate change). Fig. 1 shows the CO_2 equivalent from 1990-2017 which puts Australia among the countries with the biggest per capita emissions; and an incoherent energy policy which creates uncertainty, thus impeding investments in the energy sector (RE and non-RE), and affecting job creation as a vital part of the economy. Investment in the energy sector seriously impacts economic growth and job creation. High energy prices affect the manufacturing industry and the workforce. The closure of Australia's largest aluminum manufacturing company and subsequent laying off of workers is a good example [53]. In addition, three-quarters of Australia's power stations will be closing or will be replaced in the near future with a considerable impact on the economy, environment, workforce, and electricity prices. Based on the above, the Australian energy sector is regarded as unstable and is still far from being sustainable.

2.2. Developing a conceptual model for the Australian energy sector

The application of systems thinking and system dynamics approaches is an iterative process involving five main complementary steps: (1) problem clarification, (2) dynamic hypotheses formulation, (3) development of a simulation model, (4) model validation, and (5) policy design and evaluation [55], as shown in Fig. 3. The first two steps focus on qualitative modelling, that used for developing a conceptual model to present the dynamics underlying interactions among system components, which is the domain of systems thinking. The remaining three steps emphasise quantitative modelling, that used for developing a computer model to imitate the dynamic relations among the components which is the domain of system dynamics. In this study, the first two steps were employed to design a conceptual model of the Australian energy sector by using Causal Loop Diagrams (CLD).

A CLD is a visual diagram that maps the system. Basically, it contains three key components: variables, arrows that depict the causal relations among variables, and time delay or time lag between them. The causal relationships between variables shape Reinforcing (R) or Balancing (B) feedback loops. R loops are positive feedbacks that magnify changes (exponential growth or decline), while B loops are negative feedbacks which act to stabilise system behaviour over time.

In this study, the CLD has been developed using four main related stages. In the first stage, we highlighted key issues of the Australian energy sector, so-called variables, through reviewing the literature, media reports and policy documents. In the second stage, these variables have been used to develop an initial CLD by generating connections, polarities and a time delay between the variables. In the third stage, the initial CLD was amended and validated through consulting with

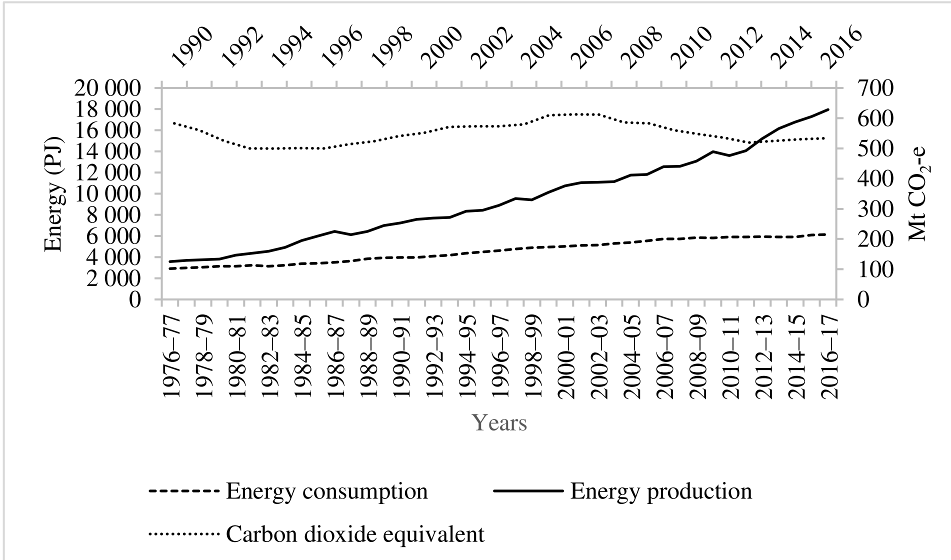

Fig. 1. Australian energy consumption, production, and carbon dioxide equivalent [46, 54].Australia's energy consumption rose by 0.6 % in 2018/19 to reach 6,196 PJ, compared with average growth of 0.7 % a year over the past ten years. Energy production rose by 6 % in 2018/19 to reach 19,711 PJ, compared with average growth of 3.9 % a year over the past ten years. Emissions at the end of 2019 are estimated to be 532.5 Mt CO2-e, down 0.9 % compared with the previous year.

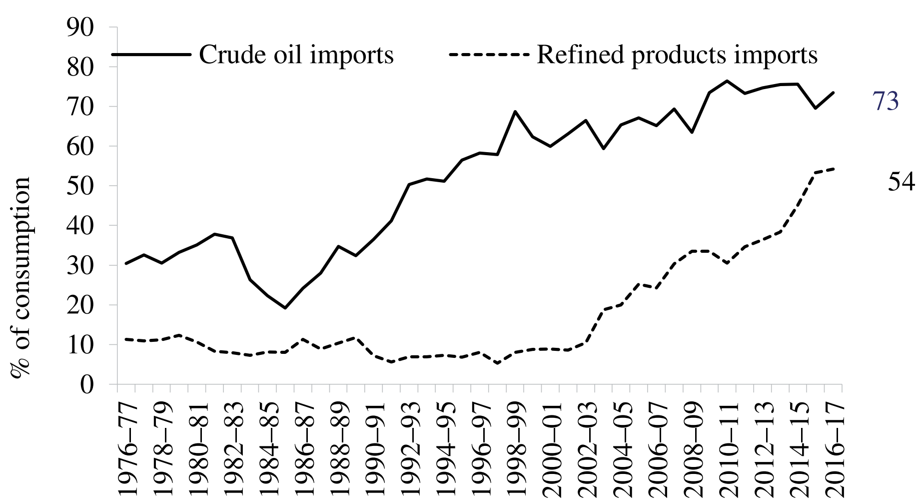

Fig. 2. Share of imports of crude and refined products in total consumption [46].

multiple experts in the Australian energy sector to create a working CLD. During expert consultation, the preliminary CLD was split into feedback loops and the experts were asked to suggest modifications to variables and their associated links. The working CLD was again reviewed to produce the final CLD for the Australian energy sector.

2.3. Leverage points and intervention strategies

As previously mentioned, CLDs enable an understanding of the dynamics, interconnection and relations of dynamically complex systems. Furthermore, it can also be utilized for identifying leverage points and interventions that may lead to lasting improvements in the entire system, although these points of power are non-intuitive and thus are difficult to identify [37]. However, system archetypes (SAs) once identified can reveal leverage points [38]. SAs are patterns that can be used to explain common behaviour of a wide range of systems [36]. For instance, Limits to Growth Archetype (LGA) illustrates circumstances where improvement in performance or growth (driven by R loops) is limited and cannot go on forever or may even decline (controlled by B loops). In this case, leverage is in the B loops; Therefore, to change the system's behaviour, the limiting factors has to be specified and amended [57]. The Fixes that Fail Archetype (FFA) presents situations where unexpected consequences result from well-planned actions [36]. With this archetype, the goal is to keep a long-term focus and avoid short-term quick fixes. Quick fixes would only be used to gain the time needed to implement long-term solutions [35].

3. Results

3.1. The conceptual model of the Australian energy sector

The final CLD of the Australian energy sector is shown in Fig. 4, which includes nine R (R1 to R9) and twelve B loops (B1 to B12). The CLD shows the interrelations between the major components of the energy sector which includes energy sources, energy production, supply and demand, energy economics, emissions and emissions policies, and energy policy developments. These loops are described in the next sections.

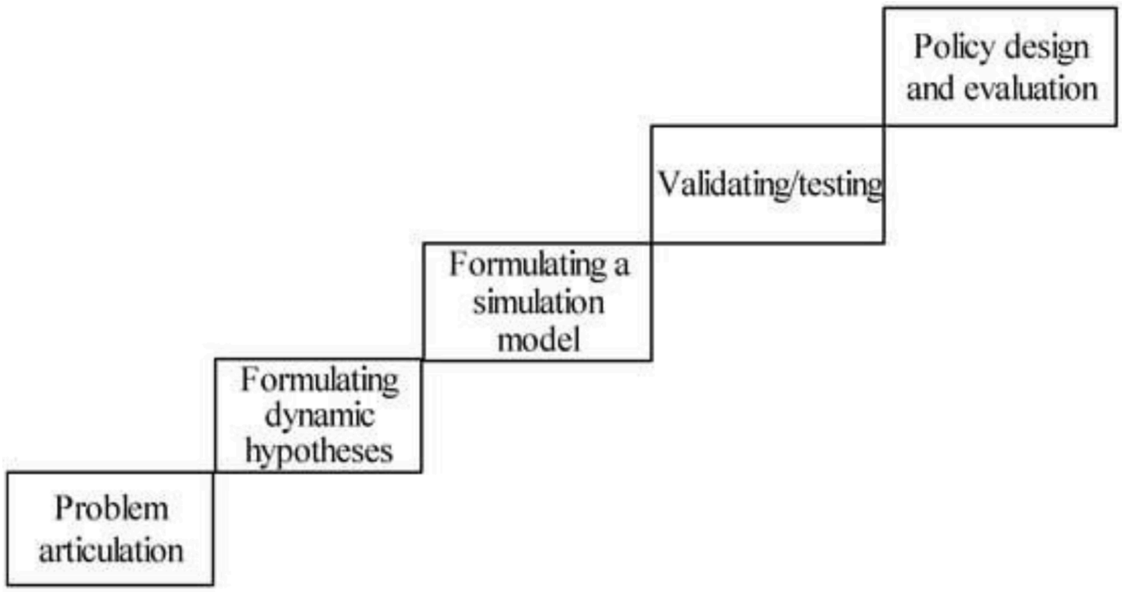

Fig. 3. The steps for systems thinking and systems dynamics approaches [56].

3.2. Description of the conceptual model of the Australian energy sector

3.2.1. Energy production capacity-economic loops

The interactions between energy production capacity and investments in new capacities, and Gross Domestic Product (GDP) are shown in Fig. 5. They include energy sources construction pipeline loops (R1, R2, B1, B2 and B5); supply-demand balance loops (R3, B3 and B4); and GDP loops (R4).

Energy sources construction pipeline loops contain two R (R1 and R2), and three B loops (B1, B2 and B5). These loops represent the construction and developmental pipelines of two major energy sources in Australia, namely RE and non-RE. Loops R1 and R2 reflect the total growth of RE and non-RE energy sources, considering that both capacities require an infrastructure construction delay. Loops B1 and B2 Reflect the total decrease in both capacities as a result of capacity bankruptcy and retirement. A limiting factor that causes bankruptcy is unprofitable capacity, while a limiting factor that causes capacity retirement is capacity lifespan. Balancing loop B5 reflects the desire to invest in additional capacities. New investment is a risk with a long-term pay-back. Therefore, it is motivated by strong energy revenues, or in other words, a strong expected return on investment (ROI). Although strong energy revenues can motivate many investors to invest and increase energy investment orders, this may lead to overcapacity which, in turn, could lead to price collapse, and then reduced energy revenues or negative ROI. So, to balance the system, demand growth or closures should bring demand up to supply. Disinvestment or closure is not resorted to until reduced negative energy revenue or profitability is sustained for a period of time. The capacity operating during this time continues to depress prices and profitability and to impede investment.

Supply-demand balance loops (R3, B3 and B4) show the link between energy price, energy supply, energy demand, and energy production capacity. The demand side includes transportation and non-transportation sectors (e.g., industry, household), while the supply side includes RE (e.g., biomass, solar, wind) and non-RE (coal, oil, and gas) sources. In 2018/2019, non-RE (coal, oil and gas) accounted for 94% and RE for only around 6% of Australia's energy mix [46]. These loops represent essential-core balancing loops (B3 and B4) that balance growth in capacity with growing energy demand. Energy price is the pivot point in this diagram, as it links energy supply, energy demand and energy production capacity and keeps supply-demand in balance (self-correction feedback balance). This is called the law of supply and demand [58]. Energy price provides an incentive to supply more capacity, however this may lead to overcapacity which in turn leads to a decrease in prices (loop B3). Loop B4 reflects the demand side; high energy demand would lead to higher energy prices, while low demand leads to lower energy prices [19, 59-61]. This supply-demand balance drives the energy production capacity as shown in Loop R3. The GDP loop (R4) shows the role of energy revenues in increasing GDP. GDP positively affects energy demand [30]. Energy demand increases the energy market price which, as a result, increases energy revenue and GDP.

3.2.2. Energy production capacity-social loop

Loop R5 shows the interactions between energy production capacity and social factors including employment opportunities, immigration and population (Fig. 6). The increasing need for energy production capacity will subsequently create employment opportunities and may attract a large number of immigrants seeking a better livelihood. As a result, this need increases population, which positively affects energy demand leading to increased energy production capacity [62–64].

3.2.3. Energy production capacity-emissions loops

The loops contained in Fig. 7 highlight the contribution of energy production to emissions. Climate change and problems associated with CO_2 emissions are principally an energy problem, as energy-use contributes 75% of greenhouse gas emissions [20]. Following Intended Nationally Determined Contributions (INDCs), Australia has sought to reduce emissions 5% below 2000 levels by 2020 and 26-28% below 2005 levels by 2030 [33]. Loops R6, B6, and B7 show the interaction between environmental issues (CO_2 emissions), energy production capacity, and energy policy. There are five options for the Australian energy policy to mitigate CO_2 emissions. These are nuclear power, Carbon Capture and Storage (CCS), investments in RE, energy conservation and investments in energy efficiency, and setting new norms for the supply and demand sides (loop B7).

Currently, Australia focuses on the third option, but mainly on the electricity sector, as it has a Renewable Energy Target (RET) that provides an incentive for investment in new renewable energy supply. Australia's RET is a government policy that aims to generate at least 33,000 GWh of electricity from RE sources by 2020, and to remain at that level until 2030. That represents more than 23.5% of Australia's electricity [65]. This target has already been achieved in 2020 and was

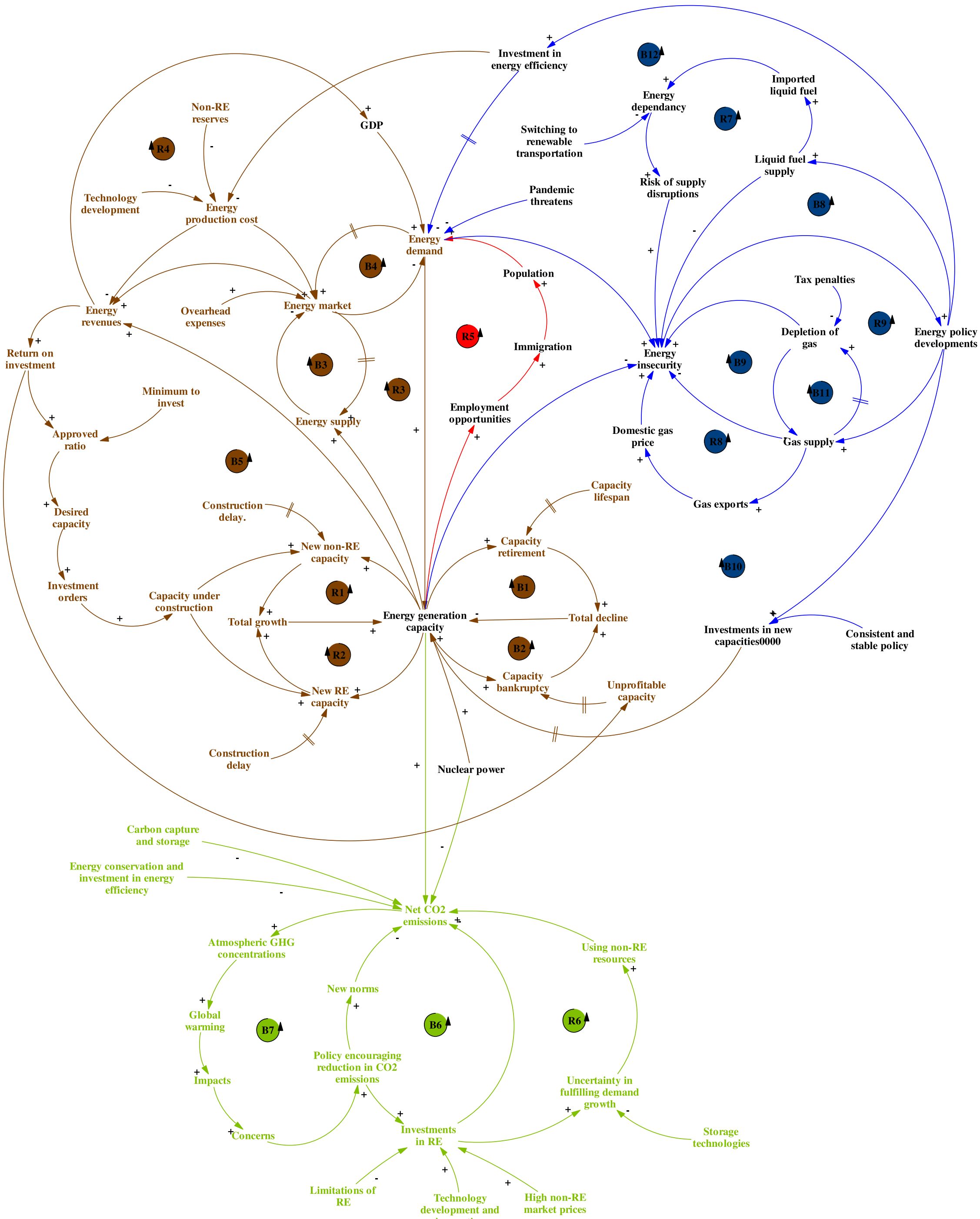

Fig. 4. The CLD of the Australian energy sector. (+) shows that variables move in the same direction, whilst (-) describes variables move in the opposite direction. (||) demonstrates a time delay between variables. R and B symbolize Reinforcing and Balancing loops respectively.

the highest level since 1960s [66].

There are several factors that may increase investments in RE, such as non-RE market prices, technology development, and consistent and stable RE policy. Technology development will increase the efficiency of power production and decrease costs, as well as improving scale and storage capacity. On the other hand, the limitations of RE supply capabilities reduce investments in new RE capacities and create uncertainty in future energy supplies, which in turn leads to the use of non-RE sources and thus increases CO_2 emissions. Some of these limitations are cost, small capacities, location, and reliability of supply.

Cost and scale can be overcome by technology development as mentioned before; the location issue can be solved by many developments such as extension to the grids connected to a number of RE feed-in points (e.g., wind farms, ocean power systems, solar plants, biomass plants) which can all feed into the common grid, and conversion of thermal energy into transportable energy (e.g., hydrogen); and reliability of supply is about delivering continuous power on demand. Continuous sources of RE (e.g. biomass and geothermal energy) have the capability to provide reliable and continuous power; discontinuous sources of RE (e.g. solar, wind) with storage technologies have the capability to enhance the flexibility of supply [67].

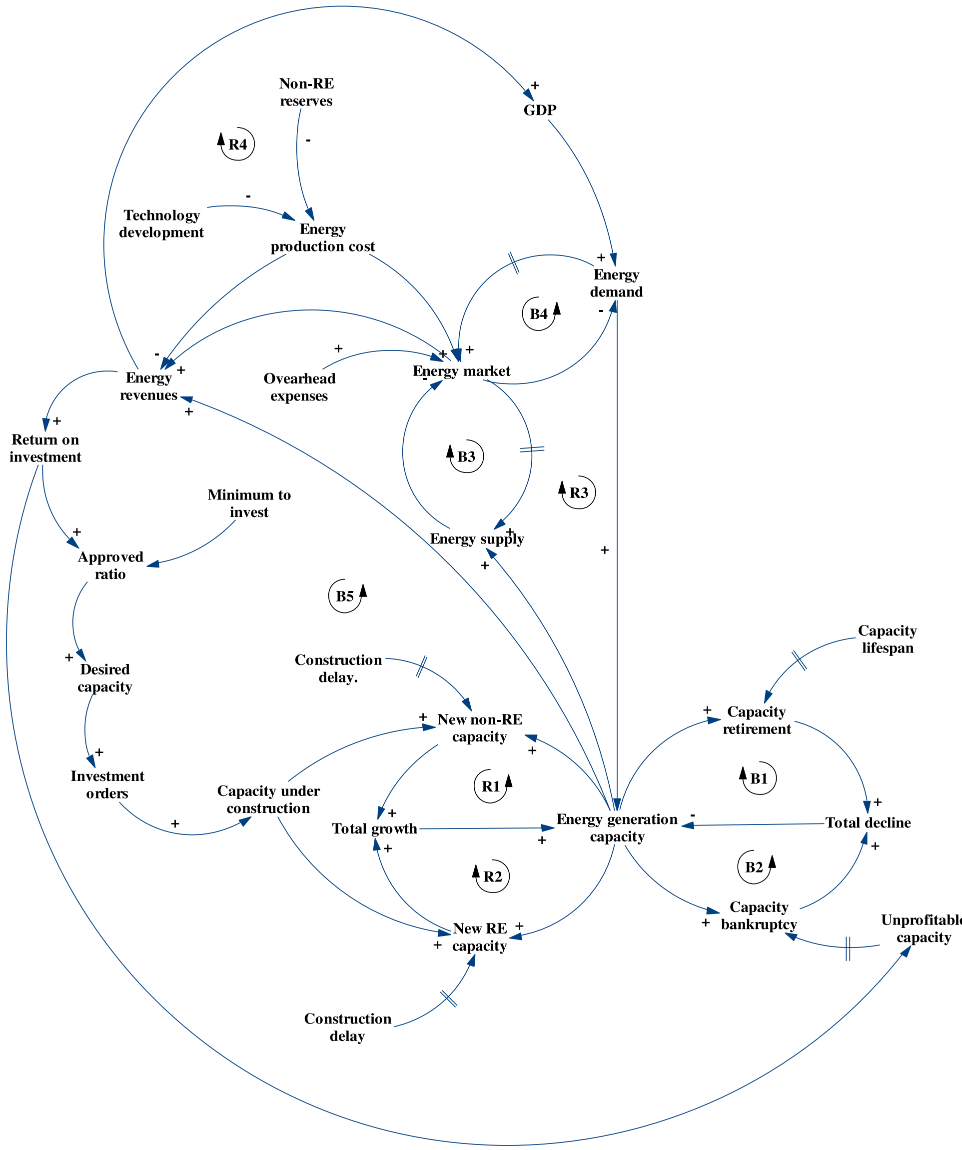

Fig. 5. Energy production capacity-economic loops.

3.2.4. Energy production capacity-energy policy developments loops

It is generally accepted that growing energy demand increases energy dependency, and thus decreases energy security [68]. Energy dependency is the level of energy imports that the country depends on to fulfil its energy needs [69]. The growing dependency of Australia on other countries to meet its needs of liquid fuel (oil), which is the largest share of Australia's energy mix is a good example of energy dependency (Fig. 2). Australian energy policy defines energy security as sufficient energy with minimal disruptions at an affordable price across the electricity, gas and liquid fuel sectors [52]. However, energy security can be defined as the diversity of long-term national energy sources that are available, affordable, reliable, and accessible, for fulfilling future energy needs while observing environmental concerns and with the flexibility to respond quickly to disruptions. Energy security is a key indicator of sustainable development [70].

Based on the experts' consultation, energy security was one of the most significant variables focused on through the interviews, and they mentioned many factors that may influence energy security. The factors that may decrease energy security in Australia are: misleading information, especially on energy demand; excessive natural resource exports; political instability; and the threat of natural disaster; as well as energy dependency. On the other hand, there are many factors that may increase energy security: exploration of new sources, demand management, access to new technology, diversification of energy sources, community awareness and engagement, reliability of supply, dispatchable generation from a number of sources, regionalization of energy markets, storage capacity and nuclear power. In a volatile world (politically, economically and environmentally), reducing energy dependency and increasing energy security should be priorities for any country.

In response, energy policies are continually reviewed and amended by the government to meet demand and support the energy sector (Fig. 8). Government support may come in different forms: mandates (e.g. renewable fuels standards), non-mandatory targets, subsidies and incentives [71]. This in turn increases the investment in energy efficiency (loop B12), thus lowering energy demand/consumption. Lowering energy demand means lowering supply to keep the balance of energy demand-supply. Lowering supply will save natural resources and thus mitigate emissions. Saving natural resources and lowering supply and demand will reduce energy dependency, as a result, improving energy security which makes investment in energy efficiency a crucial parameter for a sustainable energy future.

With investments in energy efficiency, the government is enabled to attract investments in new capacities (loop B10) to fulfill the growing

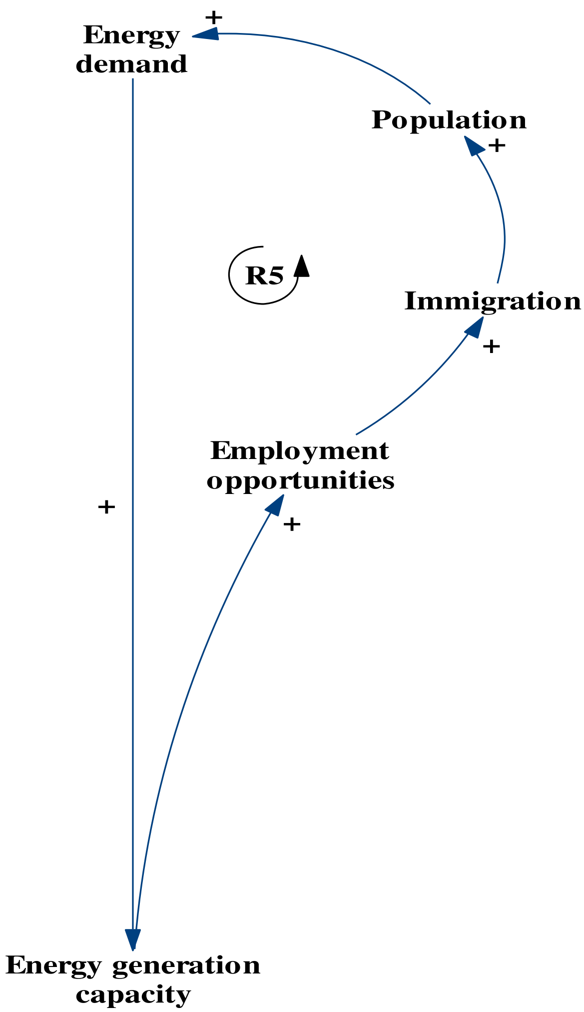

Fig. 6. Energy production capacity-social loop.

demand. Consequently, it will increase energy production capacity and competition, and thus should reduce energy prices and improve reliability and security. Investments in energy efficiency and new RE and non-RE capacities will improve the national security of Australia. The former reduces demand, and the latter guarantees supply. However, without a consistent, effective, and stable energy policy development, energy policy may become an impediment in itself and investments cannot be attracted.

On the other hand, it is important for Australia to meet liquid fuel needs (loop B8), and to increase gas supply (B9) to fulfil domestic and export needs. Liquid fuel generates 98% of transport needs [72]. However, Australia has only three weeks of liquid fuel reserves which constitutes a breach of international obligations which recommend storing a net stockpile of 90 days of liquid fuels [73]. With the continuing growth of dependency on imported liquid fuel predicted to reach 100% in the near future, the Australian liquid fuel sector is not secure and this could cause a serious domestic supply catastrophe. In regard to gas, it is projected that gas supplies will rise in terms of gas exports (loop R8) which in turn will increase domestic gas prices as the export of gas reduces the domestic share, making it more expensive. High gas prices will impact electricity's price, increasing it, as gas is one of the energy mixes that is used to generate electricity. Furthermore, excessive exports of gas will affect the gas reserves (loops R9 and B11), especially as Australia is the top exporter of natural gas globally in 2020 [57].

3.3. System archetypes

The first system archetype that appears in the model of Australia's energy sector is LGA composed of reinforcing (R1 and R2) and a balancing loop (B2) as shown in Fig. 9 (a). In the case of Australia, energy production growth is driven by the total growth of RE and non-RE sources as shown in loops R1and R2 (Fig. 9 (a)). Energy revenues motivate investors to invest in additional capacities. However, there is a limit for this growth, as shown in loop B2, so reaching this limit leads to overcapacity and potential price collapse. It could lead to reduced energy revenues causing bankruptcy and disinvestment in unprofitable capacity, and thus as a result, declining capacity. Capacity bankruptcy occurs when the energy market price is lower than its cost of energy production for a period of time. This is the case for many Australian coal plants, for example, that exited as market prices fell below production costs [74]. Reducing the limiting factor (unprofitable capacity) in loop B2, by controlling fluctuations in supply-demand puts the system in equilibrium situation and controls excessive losses. Misleading information around capacity of energy production to satisfy demand increases fluctuations between energy supply-demand.

The second SA that can be noticed in the model is FFA. In Australia, as in other countries, energy insecurity is a crucial problem for sustainable energy. The quick fix used by the government is to increase liquid fuel supply to meet short-term needs (represented in loop B8, Fig. 10 (a)). However, one unintended consequence associated with this intervention has been increased energy insecurity in the long term (represented in loop R8, Fig. 10 (a)), in this turn, this intervention increases the risk of supply disruptions caused by increased liquid fuel dependency. Similarly, the short-term intervention in the gas industry is represented by increasing gas supply to meet growing domestic and export demand (represented in loop B9, Fig. 10 (b)). However, there are many unintended consequences related to this action, one being that it has resulted in increased gas insecurity in the long-term. Gas export commitments may force up the more fluid domestic gas price, which may increase energy insecurity (represented by loop R8, Fig. 10 (b)). Furthermore, increasing gas supply domestically and internationally will impact gas reserves, which in turn decreases energy security in the long term (loop R9, Fig. 10 (b)).

Another FFA is linked to GHG emissions. As mentioned in Section 2.1, Australian per capita emissions are among the highest globally, and the energy sector contributes the largest CO_2 emissions in the country [75]. To alleviate CO_2 emissions, the government invests in RE (represented by loop B6, Fig. 10 (c)), mainly in renewable electricity. Although investing in RE is crucial to alleviate CO_2 emissions, uncertainty in supply and meeting demand growth may lead to further use of non-RE sources to fulfill the growing demand, which as a consequence will increase the CO_2 emissions (loop R6).

Clearly, the quick fix of increasing liquid fuel and gas supply, and investing in RE alleviates the energy insecurity and mitigate CO_2 emissions in the near future. Nevertheless, the consequences of these actions over time, and after a delay, may increase energy insecurity and CO_2 emissions (Fig. 10 (c)) in the long-term.

4. Discussion

The sustainability of the energy sector is of paramount importance to ensure economic growth and societal development [76, 77]. It is agreed that policy makers and energy managers face more dynamic decision sets driven by complex interactions in systems, and uncertain environments with divergent stakeholder views on sustainable energy development. Nevertheless, often, these decisions are based on a single part of a whole, but not the entirety of the complex energy system [23–26]. In addition, decisions current mental models that are based on assumptions to evaluate the current situation, predict possible outcomes, and decide how to influence the future, may not always deliver desired sustainable outcomes. To succeed in building sustainability of the energy sector, it is

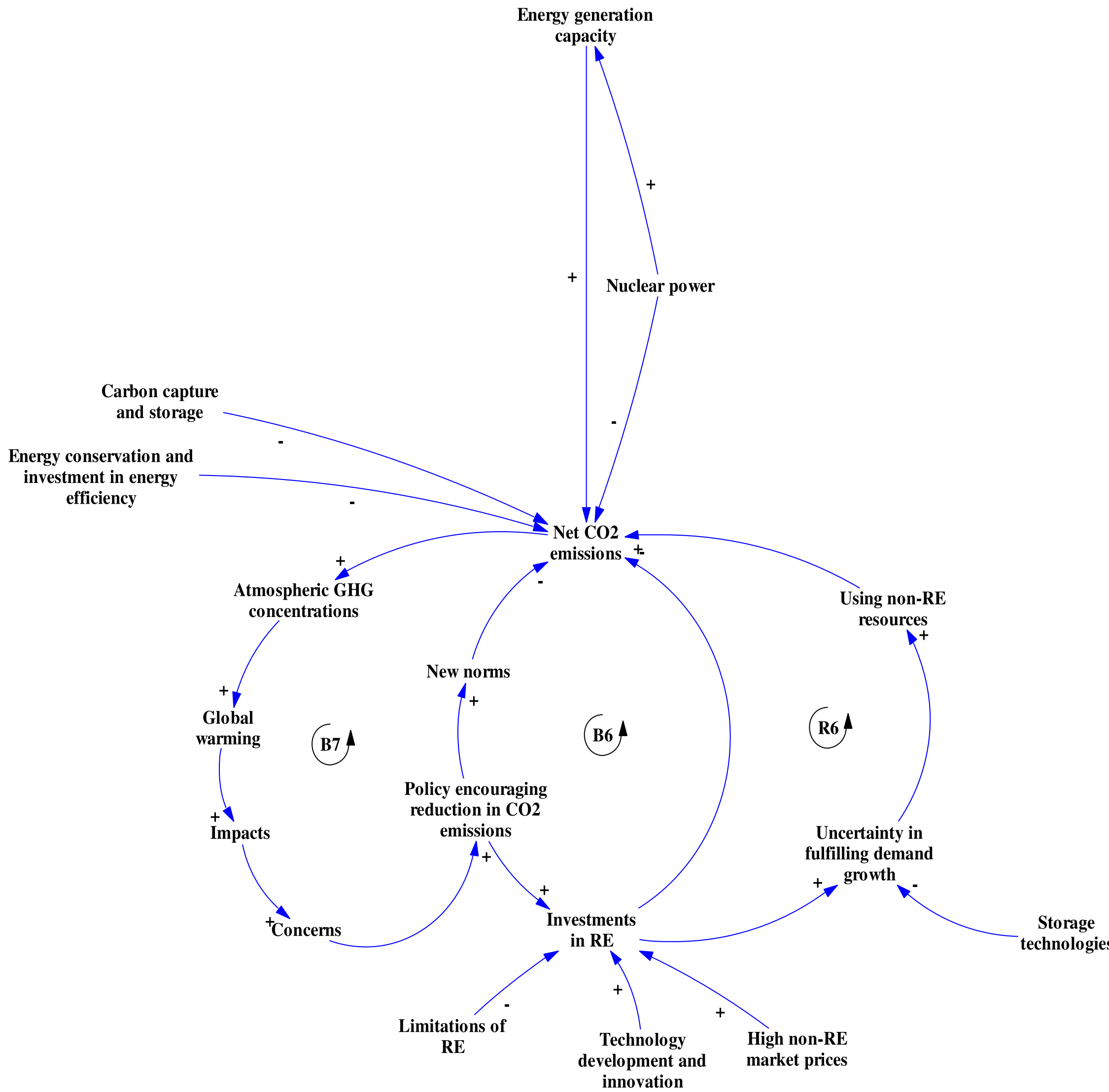

Fig. 7. Energy production capacity-emissions loops.

crucially important to align stakeholders' views and to equip decision makers and energy managers with the required abilities and skills to make proper decisions.

One of the pitfalls of oversimplifying a problem and ignoring the value of interconnection between components of the energy sector is the possible failure to provide the desired sustainable outcomes. Through the application of systems thinking, we have constructed a synthesis of qualitative modelling tools (CLDs and SAs); the perception they provide may help broad-spectrum of decision makers and stakeholders in relation to the challenges facing the sector in terms of sustainability.

The CLD presents the 'bigger picture" of the energy sector, outlining how factors affecting the sector are not isolated and independent but are dynamically linked. The bigger picture illustrates how the different factors cause growth or decline in each other as well as in other key areas of the energy sector. Thus, CLD provides valuable features concerning the energy sector (e.g., structure, feedback loops, loop dominance, and time delays between variables). It can therefore serve as a reliable tool to establish a common understanding of the issues that influence sustainability of the energy sector, and to provide opportunities for varied stakeholders to share learning and vision planning.

As mentioned in Section 2.1, growing energy dependency, depletion of energy sources, and high GHG emissions are some of the biggest challenges to the Australian energy sector. This is becoming more challenging to the sector as the Government ratified the Kyoto Protocol agreeing to reduce GHG emissions by 60 percent on 2000 levels by 2050 [78]. To ensure sustainable future energy for the country, the Australian Government is committed to encourage RE and energy efficiency [75]. However, LGA and FFA in Figs. 8 and 9 point out that there are significant risks in setting policies associated with energy security. Specifically, investing in liquid fuel and gas industry (quick fix policies) are effective in the short-term, but have unintended long-term consequences (more energy dependency), that require even more use of the same quick fix. Policy volatility has created distortion in the energy market, and has particularly affected climate change policies (carbon pricing policy and RET policy), and increased energy prices due to engaging in inadequate investments and unplanned closures [74]. Understanding these archetypes would help policy makers and energy managers to predict problematic behaviour and take necessary measures in a timely manner, thus contributing to a sustainable energy future.

To mitigate CO_2 emissions, some models have suggested that incorporating an energy mix of continuous and discontinuous RE and sources of fossil fuels that cause less CO_2 pollution can be the solution to combat increasing CO_2 emissions. For example, Saddler, Diesendorf [11] suggested that biofuels (28 %), wind (20%), solar (5%), and hydro (7%) with gas (30%), coal (9%), and oil (1%) will produce 100% of Australia's electricity needs by 2040. Blakers, Lu [25] went further when they

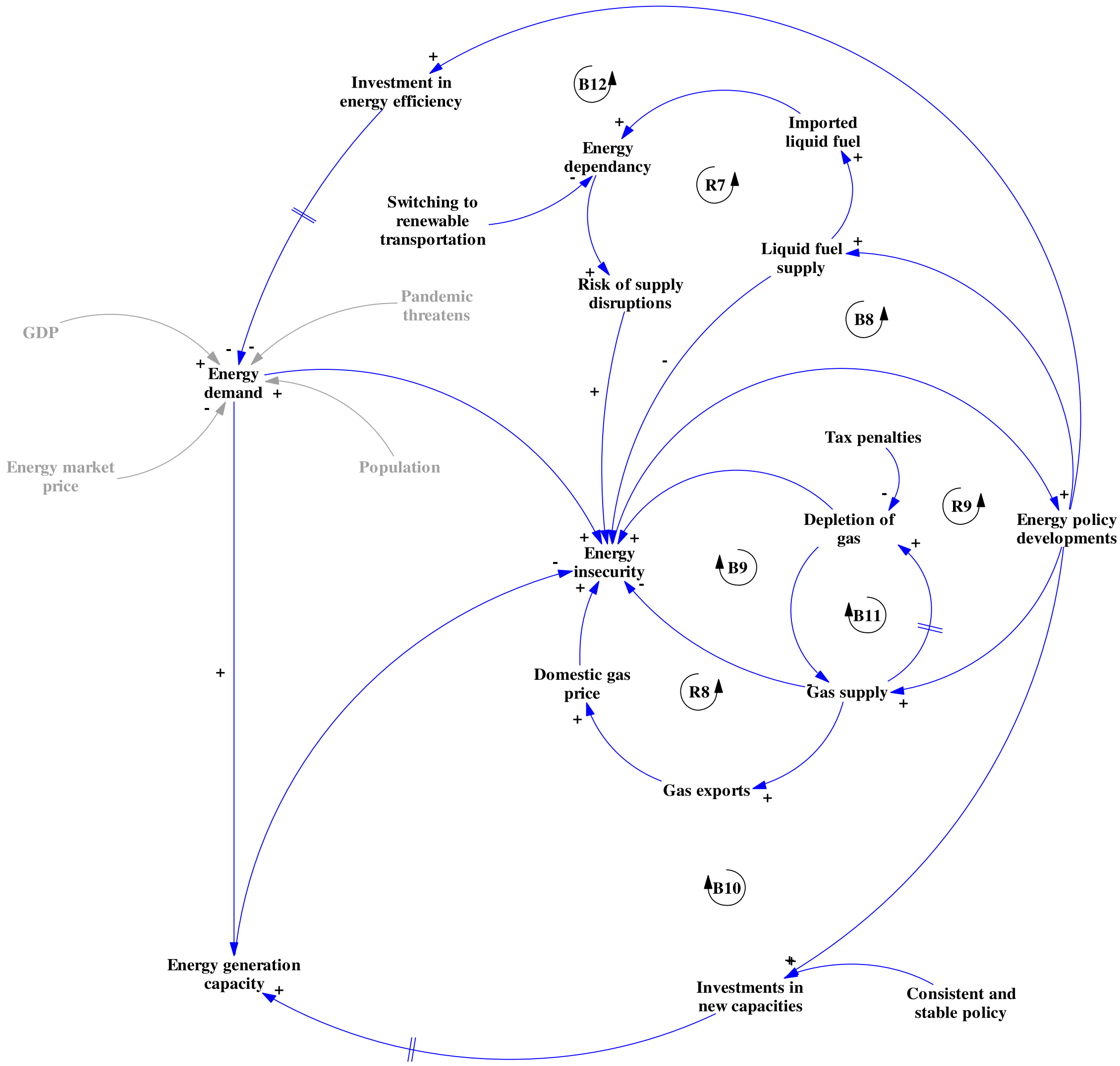

Fig. 8. Energy production capacity-energy policy developments loops.

suggested that 90% of wind and photovoltaics and 10% of hydroelectricity and biomass would contribute 100% of Australia's annual electricity needs.

However, the electricity supply sector accounted for only 26% of energy consumption in Australia in 2018/2019 [46], so heat and transport energy systems should also be a focus in the Australian RE policy, as in other countries. For example, Britain has taken a big step towards reducing its dependency on fossil fuel and mitigating CO_2 emissions by making a decision to ban the sale of all internal combustion engines and replace them completely with electric engines by 2040 [79]. Other countries (e.g. France, and India) are also speeding up the transition to ban petrol vehicles [80].

On the other hand, adopting a direct approach to RE may increase uncertainty in meeting supply and demand growth, and may create distortion in the energy market. This may then indirectly lead to increased use of non-RE sources to meet the growing demand in reliable sources. This may explain the increase in CO_2 emissions globally by 1.6% in 2017, although there is an extraordinary growth in RE [81]. That is the case in some countries that are leaders in RE like Germany, where CO_2 emissions are not declining although RE accounts for almost 30% of Germany's power mix in 2017.

Despite growth in RE, there is an increase in coal consumption by almost 30% [82]. Likewise, Australia's CO_2 emissions are not projected to fall with the current policy setting [83]. With the growing energy demand, focusing on the electricity sector and omitting other sectors (e.g., transportation and manufacturing sectors), and using fossil fuels as a backup power for RE may affect the share of RE, and consequently not achieve the desired goal of reducing CO_2 emissions. Considering using backup power in RE (solar and wind power), that can be obtained from energy storage systems (e.g., pumped hydropower batteries, megastore batteries) or other continuous sources of RE (e.g., hydrogen energy, biomass, hydropower), could make the future supply of RE more flexible and less uncertain.

Consistent and stable energy policy, along with technology development and innovation are crucial to attract investments in RE. Technology development and innovation will generally help to keep costs on a downward trend, which may create a stable environment for investment. Other options (such as nuclear power and CCS) have their own limitations. For example, CCS needs high energy inputs which causes a drop in plant thermal efficiency by up to 22.9%, which increases the cost of electricity generation, making it less competitive than other options [84]. Considering RE in other sectors, energy conservation and investment in energy efficiency, solving the intermittency problem in RE by using storage technologies, as well as adding new norms for the supply and demand sides (loop B7) are important to reduce CO_2 emissions significantly if nuclear power and CCS are not an option. Transitioning to a carbon-low economy requires understanding the risks and opportunities in the RE energy market, thus making markets more efficient,

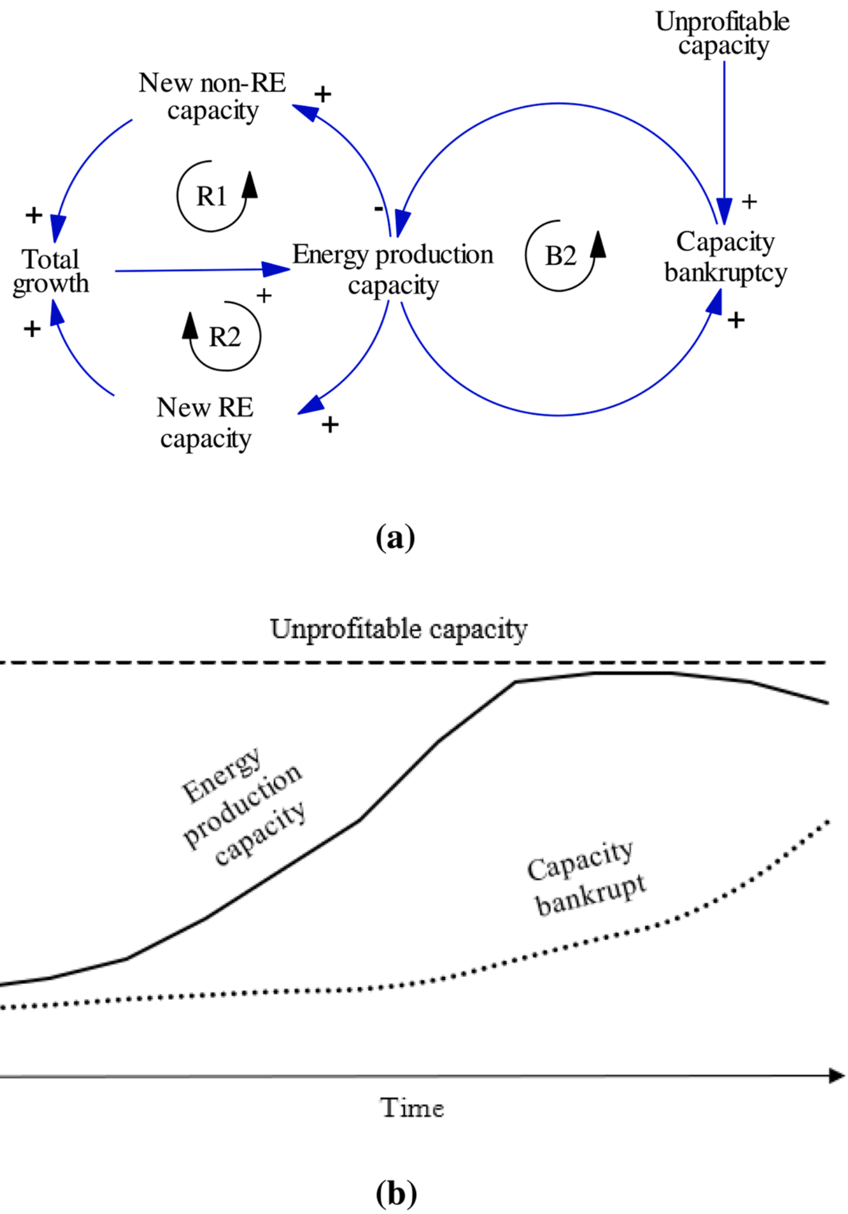

Fig. 9. The LGA for the Australian energy sector. Structure: (a). Behavioural graph: (b).

stable and resilient [85].

Australia is the worst performer among developed countries in terms of energy efficiency and performance indicators [86]; moreover, RE only accounted for 6% of Australia's energy mix in 2018/2019 [46]. Despite the rebound effects that are still controversial as a result of insufficient of empirical studies and bounded grasp about its effects [87, 88], there are real benefits to be gained by improving energy efficiency on the level of lowering energy bills, reducing emissions, improving health, welfare, and productivity, and increasing job and economic growth [89]. We consider that the rebound effect can be reduced by reducing dependency on fossil fuels and expanding the use of renewables. The rebound effect, in this case, can be seen as a welfare improvement.

Strengthening the feedback power of energy market signals, adding information flows to feedback loops, focusing on energy conservation, increasing investments in energy efficiency and RE, and technology development and innovation along with consistent and stable energy policy, are crucial factors to increase energy security and thus pave the road towards a sustainable energy sector.

5. Conclusion

The traditional linear thinking paradigm leads to just treating the symptoms by having quick fix solutions that fail to address the dynamics and complexity of sustainability challenges of the energy system. By focusing on the way that a system's constituent parts interrelate and how the system works overtime and within the context of larger systems, a systems thinking approach can assist policy makers and energy managers to comprehend the interactions among various interlinked subsystems of an energy system which drive its long-run dynamic behaviour. The advantages of systems thinking greatly outweigh traditional linear approaches that have been previously used in formulating strategic levels of energy management policies and plans.

In this paper, we have outlined the applications of a systems thinking approach to the Australian energy sector by implementing its fundamental steps in developing CLDs and SAs. These qualitative tools provide a valuable framework for investigating the dynamics and complexity of the energy sector. The CLDs assist in understanding a problem and recognising leverages in a dynamically complex system,

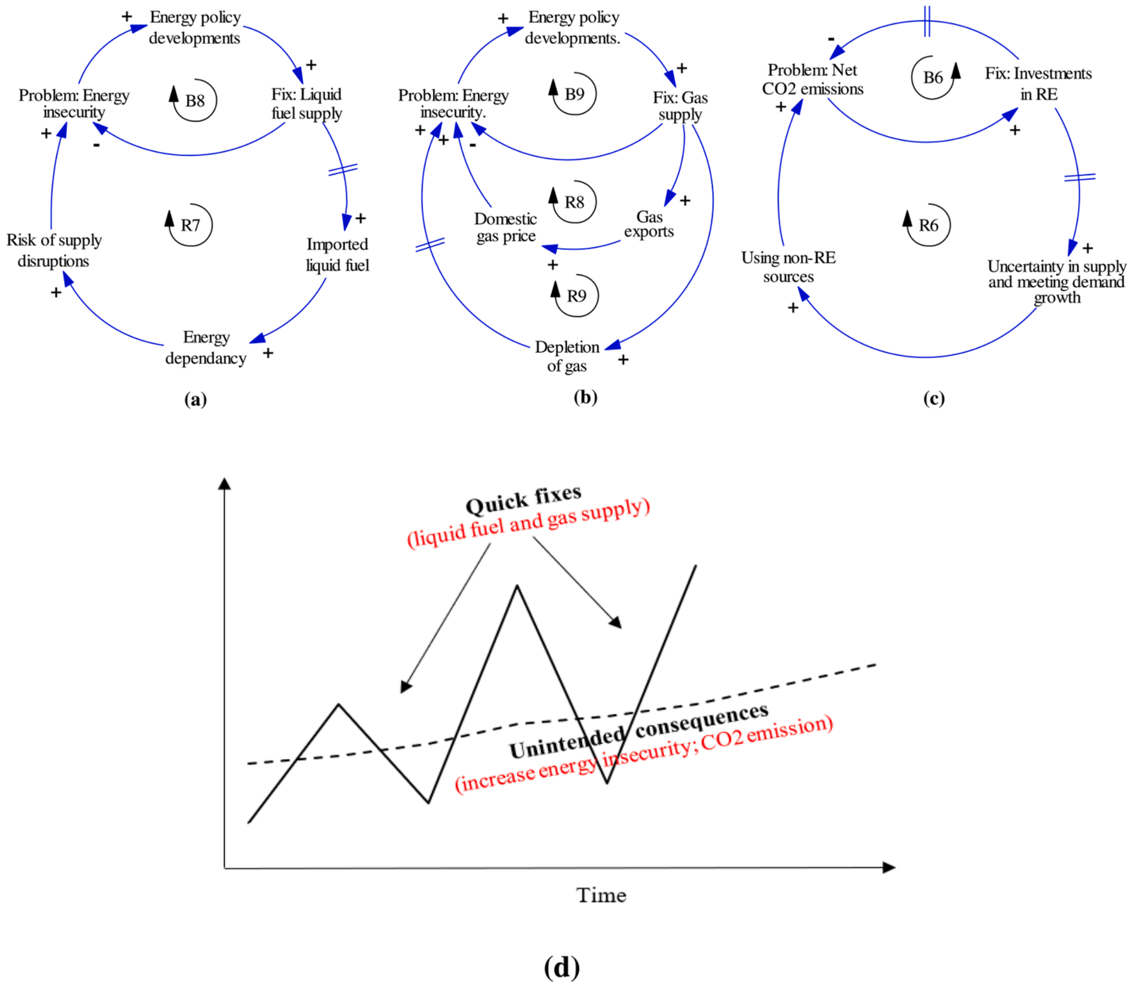

Fig. 10. The FFA for the Australian energy sector. Structure: (a, b and c). Long-term behaviour: (d).

while SAs enable policy makers and energy managers to reveal problematic trends and expect future issues. We conclude that common attempts to alleviate Australian energy-related problems have suffered from reliance on quick fixed solutions or short-term strategies. For the energy sector to meet sustainability challenges effectively, long-term thinking and strategies focused on key solutions must be carried out to better spot and reduce the unintended consequences that result from feedback of interventions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

[1 Hoogwijk, M.M., On the global and regional potential of renewable energy sources. 2004.
[2] U. GA, Transforming our world: the 2030 Agenda for Sustainable Development, Division for Sustainable Development Goals, New York, NY, USA, 2015.
[3] D. Nong, C. Wang, A.Q. Al-Amin, A critical review of energy resources, policies and scientific studies towards a cleaner and more sustainable economy in Vietnam, Renewable and Sustainable Energy Reviews 134 (2020), 110117.
[4] J.E. Holgaard, et al., Strategies for education for sustainable development–Danish and Australian perspectives, Journal of cleaner production 112 (2016) 3479–3491.
[5] M. Azzi, H. Duc, Q. Ha, Toward sustainable energy usage in the power generation and construction sectors—a case study of Australia, Automation in Construction 59 (2015) 122–127.
[6] N.V. Emodi, K.-J. Boo, Sustainable energy development in Nigeria: Current status and policy options, Renewable and Sustainable Energy Reviews 51 (2015) 356–381.
[7] M. Jefferson, Sustainable energy development: performance and prospects, Renewable energy 31 (5) (2006) 571–582.
[8] G. Morelli, M. Mele, Energy consumption, CO2 and economic growth nexus in Vietnam, International Journal of Energy Economics and Policy 10 (2) (2020) 443.
[9] M. Shahbaz, M. Bhattacharya, K. Ahmed, CO2 emissions in Australia: economic and non-economic drivers in the long-run, Applied Economics 49 (13) (2017) 1273–1286.
[10] A. Azad, et al., Energy scenario: production, consumption and prospect of renewable energy in Australia, Journal of power and Energy Engineering 2 (4) (2014) 19–25.
[11] H. Saddler, M. Diesendorf, R. Denniss, A clean energy future for Australia, Clean Energy Group, Sydney, WWF Australia, 2004 (see http://www. bioenergyaustralia.org/reports/Clean_Energy_Future_Report. pdf).
[12] N. Ralph, L. Hancock, Energy security, transnational politics, and renewable electricity exports in Australia and Southeast Asia, Energy Research & Social Science 49 (2019) 233–240.
[13] A. Cherp, J. Jewell, The concept of energy security: Beyond the four As, Energy policy 75 (2014) 415–421.
[14] B.K. Sovacool, M.A. Brown, Competing dimensions of energy security: an international perspective, Annual Review of Environment and Resources 35 (2010) 77–108.
[15] T. Fraser, A.J. Chapman, Drivers of social equity in renewable energy at the municipal level: the case of local Japanese energy policy and preferences, Journal of Environmental Policy & Planning (2020) 1–16.
[16] O. Johnson, et al., Assessing the Gender and Social Equity Dimensions of Energy Transitions, Stockholm Environment Institute, Stockholm, 2020.

[17] Sönnichsen, N. Global Energy Industry - Statistics & Facts. 2020 [cited 2021 8/1/2021]; Available from: https://www.statista.com/topics/6148/global-energy-industry/.
[18] X. Zhao, et al., The sustainable development of the economic-energy-environment (3E) system under the carbon trading (CT) mechanism: A Chinese case, Sustainability 10 (1) (2018) 98.
[19] E.G. Davies, S.P. Simonovic, Energy sector for the integrated system dynamics model for analyzing behaviour of the social-economic-climatic model, Department of Civil and Environmental Engineering, The University of Western …, 2009.
[20] D. MacKay, Sustainable Energy-without the hot air, UIT, cambridge, 2008.
[21] B. Warbroek, et al., The role of intermediaries in supporting local low-carbon energy initiatives, Sustainability 10 (7) (2018) 2450.
[22] S. Stagl, Multicriteria evaluation and public participation: the case of UK energy policy, Land use policy 23 (1) (2006) 53–62.
[23] P.K. Narayan, R. Smyth, Electricity consumption, employment and real income in Australia evidence from multivariate Granger causality tests, Energy policy 33 (9) (2005) 1109–1116.
[24] A. Finkel, et al., Inde-pendent Review into the Future Security of the National Electricity Market: Blueprint for the Future Commonwealth of Australia 2017, Commonwealth of Australia, 2017. Text.
[25] A. Blakers, B. Lu, M. Stocks, 100% renewable electricity in Australia, Energy 133 (2017) 471–482.
[26] B. Elliston, M. Diesendorf, I. MacGill, Simulations of scenarios with 100% renewable electricity in the Australian National Electricity Market, Energy Policy 45 (2012) 606–613.
[27] K. Fatai, L. Oxley, F.G. Scrimgeour, Modelling the causal relationship between energy consumption and GDP in New Zealand, Australia, India, Indonesia, The Philippines and Thailand, Mathematics and Computers in Simulation 64 (3-4) (2004) 431–445.
[28] R. Mahadevan, J. Asafu-Adjaye, Energy consumption, economic growth and prices: A reassessment using panel VECM for developed and developing countries, Energy policy 35 (4) (2007) 2481–2490.
[29] P.K. Narayan, S. Narayan, S. Popp, Energy consumption at the state level: the unit root null hypothesis from Australia, Applied Energy 87 (6) (2010) 1953–1962.
[30] M. Shahiduzzaman, K. Alam, Cointegration and causal relationships between energy consumption and output: Assessing the evidence from Australia, Energy Economics 34 (6) (2012) 2182–2188.
[31] J.C. Ciscar, et al., Vulnerability of the EU economy to oil shocks: A general equilibrium analysis with the GEM-E3 model, in: in 13th annual conference of the European Association of Environmental and Resource Economics, Citeseer, Budapest, Hungary, 2004.
[32] A. Syed, Australian energy projections to 2049–50, Bureau of Resources and Energy Economics, Canberra, 2012. December.
[33] R. Suppiah, et al., Australian climate change projections derived from simulations performed for the IPCC 4th Assessment Report, Australian Meteorological Magazine 56 (3) (2007) 131–152.
[34] DEE, Australia's emissions projections 2017, Commonwealth of Australia 2017. 2017.
[35] P.M. Senge, The fifth discipline: The art and practice of the learning organization, Currency, 2006.
[36] K. Maani, R.Y. Cavana, Systems thinking, system dynamics: Managing change and complexity, Prentice Hall, 2007.
[37] Meadows, D.H., Leverage points: Places to intervene in a system. 1999.
[38] T. Mai, et al., Defining flood risk management strategies: a systems approach, International journal of disaster risk reduction (2020), 101550.
[39] T. Van Mai, P.X. To, A systems thinking approach for achieving a better understanding of swidden cultivation in Vietnam, Human Ecology 43 (1) (2015) 169–178.
[40] T. Mai, C. Smith, Addressing the threats to tourism sustainability using systems thinking: A case study of Cat Ba Island, Vietnam, Journal of Sustainable Tourism 23 (10) (2015) 1504–1528.
[41] T. Mai, et al., A systems thinking approach to water trade: Finding leverage for sustainable development, Land Use Policy 82 (2019) 595–608.
[42] Y. Zuo, Y.-l. Shi, Y.-z. Zhang, Research on the sustainable development of an economic-energy-environment (3E) system based on system dynamics (SD): A case study of the Beijing-Tianjin-Hebei Region in China, Sustainability 9 (10) (2017) 1727.
[43] T. Wood, Australia's energy sector is in critical need of reform, The Conversation, 2016.
[44] M. Laimon, et al., Energy Sector Development: System Dynamics Analysis, Applied Sciences 10 (1) (2020) 134.
[45] Slezak, M. Climate change is a federal election issue for voters, so how do the policies stack up? 2019 [cited 2021 8/1/2021]; Available from: https://www.abc.net.au/news/2019-05-07/climate-change-federal-election-morrison-shorten-policies-votes/11084580?nw=0.
[46] DISER. Australian Energy Statistics. 2020 [cited 2021 8/1/2021]; Available from: https://www.energy.gov.au/government-priorities/energy-data/australian-energy-statistics.
[47] B. Dudley, BP statistical review of world energy, BP Statistical Review, London, UK 6 (2018) 2018, accessed Aug.
[48] K. Henry, The Australian collaboration: A Collaboration of national community organisations, A Multicultural Australia (2013).
[49] G. Australia, Australian Energy Resource Assessment, A.B.O. AGRICULTURAL, and R. ECONOMICS, Department of Resources. Energy and Tourism, 2010.
[50] Burck, J., et al., Climate Change Performance Index 2017. 2017: Germanwatch Nord-Süd Initiative eV.
[51] M. Stewart, Future of Australian Electricity Generation 2017, The, Future of Australian Electricity Generation (2017) 43. The, 2017.
[52] A. Yates, N. Greet, Energy Security for Australia: Crafting a Comprehensive Energy Security Policy, Energy Security for Australia: Crafting a Comprehensive Energy Security Policy (2014) 61.
[53] Eshkenazi, A. Australia's Fragile Energy Supply and Demand. 2017 [cited 2021 8/1/2021]; Available from: http://www.apics.org/sites/apics-blog/thinking-supply-chain-topic-search-result/thinking-supply-chain/2017/07/21/australia-s-fragile-energy-supply-and-demand.
[54] DISER. Australian Greenhouse Emissions Information System. 2019 [cited 2021 8/1/2021]; Available from: https://www.industry.gov.au/policies-and-initiatives/australias-climate-change-strategies/tracking-and-reporting-greenhouse-gas-emissions.
[55] Sterman, J., System Dynamics: systems thinking and modeling for a complex world. 2002.
[56] T. Yusaf, et al., Hydrogen Energy Demand Growth Prediction and Assessment (2021–2050) Using a System Thinking and System Dynamics Approach, Applied Sciences 12 (2) (2022) 781.
[57] Sönnichsen, N. Global liquefied natural gas exports by country 2020. 2021 [cited 2021; Available from: https://www.statista.com/statistics/274528/major-exporting-countries-of-lng/.
[58] Heakal, R., Economics basics: Supply and demand. Investopedia. accessed September, 2015. 28.
[59] J. Snow, Gas Pricing – where to from here? Brisbane. Australian Institute of Energy, 2017.
[60] A. Kaygusuz, Closed loop elastic demand control by dynamic energy pricing in smart grids, Energy 176 (2019) 596–603.
[61] M.T. Punzi, The impact of energy price uncertainty on macroeconomic variables, Energy Policy 129 (2019) 1306–1319.
[62] O. Publishing, OECD Green Growth Studies Energy, OECD publishing, 2012.
[63] K. Li, L. Fang, L. He, How population and energy price affect China's environmental pollution? Energy policy 129 (2019) 386–396.
[64] K. Dong, et al., CO2 emissions, economic and population growth, and renewable energy: Empirical evidence across regions, Energy Economics 75 (2018) 180–192.
[65] CEC, Progress and status of the renewable energy target. 2016.
[66] DISER. Renewables. 2022 [cited 2022 04/02/2022]; Available from: https://www.energy.gov.au/data/renewables#:~:text=In%202020%2C%2024%25%20of%20Australia's,recorded%20in%20the%20mid%2D1960s.
[67] S. Needham, The potential for renewable energy to provide baseload power in Australia, Parliamentary Library, 2008.
[68] A. Aslani, P. Helo, M. Naaranoja, Role of renewable energy policies in energy dependency in Finland: System dynamics approach, Applied energy 113 (2014) 758–765.
[69] A. Sözen, İ. Alp, Ü. İskender, An evaluation of Turkey's energy dependency, Energy Sources, Part B: Economics, Planning, and Policy 9 (4) (2014) 398–412.
[70] D. Štreimikienė, et al., Energy dependency and sustainable regional development in the Baltic states: A review, Geographica Pannonica 20 (2) (2016) 79–87.
[71] Bacon, R. and M. Kojima, Issues in estimating the employment generated by energy sector activities. 2011.
[72] DISER. Liquid fuel security review. 2019 [cited 2019; Available from: https://www.energy.gov.au/government-priorities/energy-security/energy-security-assessments/liquid-fuel-security-review.
[73] Hepburn, S. Australia's fuel stockpile is perilously low, and it may be too late for a refill. 2018 [cited 2019; Available from: https://theconversation.com/australias-fuel-stockpile-is-perilously-low-and-it-may-be-too-late-for-a-refill-96271.
[74] P. Simshauser, Garbage can theory and Australia's National Electricity Market: Decarbonisation in a hostile policy environment, Energy Policy 120 (2018) 697–713.
[75] A. Bahadori, et al., An overview of renewable energy potential and utilisation inAustralia, Renewable and sustainable energy reviews 21 (2013) 582–589.
[76] I. Vera, L. Langlois, Energy indicators for sustainable development, Energy 32 (6) (2007) 875–882.
[77] A. WE, United Nations Development Programme (UNDP, United Nations Department of Economic and Social Affairs (UNDESA) and World Energy Council (WEC), New York, USA, 2000.
[78] Jotzo, F., Australia's post–2020 emissions commitment: considerations and comparisons. 2015.
[79] A. Asthana, M. Taylor, Britain to ban sale of all diesel and petrol cars and vans from 2040, The Guardian, 2017.
[80] Slezak, M. As the UK plans to phase out petrol cars, is Australia being left behind? 2017 [cited 2019; Available from: https://www.theguardian.com/environment/2017/jul/30/as-other-countries-give-petrol-cars-an-end-date-is-australian-being-left-behind.
[81] S. Dale, Energy in 2017: two steps forward, one step back, BP, 2018.
[82] Conca, J. Why Aren't Renewables Decreasing Germany's Carbon Emissions? 2017 [cited 2019; Available from: https://www.forbes.com/sites/jamesconca/2017/10/10/why-arent-renewables-decreasing-germanys-carbon-emissions/?sh=77f0f2a168e1.
[83] A. Skarbek, Australia is not on track to reach 2030 Paris target (but the potential is there), The Conversation 6 (2018).
[84] S.D. Supekar, S.J. Skerlos, Reassessing the efficiency penalty from carbon capture in coal-fired power plants, Environmental science & technology 49 (20) (2015) 12576–12584.
[85] TCFD, Task force on climate-related financial disclosures: Status report. 2019.
[86] F. Castro-Alvarez, et al., The 2018 International Energy Efficiency Scorecard, American Council for an Energy-Efficient Economy (2018).

[87] M. Llorca, T. Jamasb, Energy efficiency and rebound effect in European road freight transport, Transportation Research Part A: Policy and Practice 101 (2017) 98–110.
[88] I.M. Azevedo, Consumer end-use energy efficiency and rebound effects, Annual Review of Environment and Resources 39 (2014) 393–418.
[89] IEA. Multiple Benefits of Energy Efficiency. 2019 [cited 2019; Available from: https://www.iea.org/reports/multiple-benefits-of-energy-efficiency.