SUSTAINABLE ENERGY SECTOR DEVELOPMENT USING SYSTEMS THINKING AND SYSTEM DYNAMICS ANALYSIS

A Thesis submitted by

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ABSTRACT

The energy sector is a dynamically-complex system, which comprises various interacting components and involves a diverse array of stakeholders. The development of the sector in a sustainable manner requires a comprehensive understanding of its components and their interactions. Previous efforts to improve energy systems mainly use silo approaches that focus on a particular system's components and neglect their interconnected nature. As a result, our ability to understand the system and/or mitigate undesirable outcomes is limited. We have adopted a systems-thinking approach to construct a conceptual model of the Australian energy sector as a case study. The model visualises energy systems as a whole and identifies feedback mechanisms likely to influence the behaviour of the sector. The conceptual model can serve as a common language for achieving a better understanding of the sector and alignment of stakeholder's view. It can also serve as a solid foundation to identify key leverage points for systematic intervention strategies towards the development of a sustainable energy sector. At this stage, systems thinking represents the qualitative tool.

To provide a complete analysis and test the feedback loops, empirical analysis and simulation modelling is required which represents the quantitative modelling that enables an in-depth investigation of the system dynamics of the energy sector. Thus, we have adopted a system dynamics approach to construct an integrated model for analysing the behaviour of the energy sector. Although the Australian energy sector is used as a case study, the model can be used in any country or the world as a whole and for any energy resource. Research findings indicate that there are significant risks in setting policies associated with energy security and environmental interventions in Australia. This is especially so in the case of oil and gas components, and the resulting CO_2 emissions of energy use. The current trajectory of the Australian energy sector is unsustainable and the growth is not being controlled. Limits to growth are not far due to excessive fossil fuel extraction, high emissions, and high energy dependency. With the current growth, Australia's global CO_2 emissions footprint will increase to unprecedented levels reaching 12% by 2030 (9.5% for exports and 2.5% for domestic). Oil dependency will account for 43% and 47% of total consumption by 2030 and 2050. By 2032, coal will be the only fossil fuel resource available in Australia. Expansion of investment in coal and gas production is a large risk. We have found that improving

only 1% of energy efficiency would result in 101k/331k GWh energy productivity (5% and 14% of total energy consumption) and reduce domestic CO_2 emissions by 15.3/50 Mt CO_2-e (4% and 10% of total domestic emissions) by 2030/2050. Switching to renewable energy for transportation and therefore saving 5% per year of current oil consumption may decrease dependency on oil to half by 2030 and to zero by 2050, and reduction in domestic CO_2 emissions by 74.1/198 Mt CO_2-e (18% and 41% of total domestic emissions). Switching to renewable electricity by 3% annually may lead to 60.8/129 Mt CO_2-e reduction in domestic CO_2 emissions (15% and 27% of total domestic emissions) by 2030/2050. Electrification of other sectors, mainly the manufacturing sector, using renewable energy by 4% annually may lead to 43.3/106 Mt CO_2-e reduction in domestic CO_2 emissions (11% and 22% of total domestic emissions) by 2030/2050. Improving energy efficiency, switching to renewable energy for transportation, switching to renewable electricity, electrification of sectors that do not run on electricity by renewable energy could achieve zero domestic CO_2 emissions by 2050 while energy consumption stays almost stable (0.5%/year). This process may be accelerated by improving energy efficiency by more than 1%.

CERTIFICATION OF THESIS

This Thesis is the work of Mohamd Omar Laimon except where otherwise acknowledged, with the majority of the authorship of the papers presented as a Thesis by Publication undertaken by the Student. The work is original and has not previously been submitted for any other award, except where acknowledged.

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Student and supervisors signatures of endorsement are held at the University.

STATEMENT OF CONTRIBUTION

The following detail is the agreed share of contribution for candidate and co-authors in the presented publications in this thesis:

- **Article I:** Laimon, M, Mai, T, Goh, S & Yusaf, T 2019, 'A Systems-Thinking Approach to Address Sustainability Challenges to the Energy Sector', *Manuscript submitted for publication. Renewable and Sustainable Energy Reviews.* (Q1 journal; impact factor: 10.556 (2018)).

  The overall contribution of ***Mohamd Laimon*** was 60% to the concept development, data collection, development of methodology, analysis, drafting and revising the final submission; ***Thanh Mai*** contributed for 20% in editing and providing important technical inputs; ***Steven Goh*** and ***Talal Yusaf*** contributed the other 20% for reviewing and editing the manuscript.

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  The overall contribution of ***Mohamd Laimon*** was 60% to the concept development, data collection, development of methodology, analysis, drafting and revising the final submission; ***Thanh Mai*** contributed for 20% in editing and providing important technical inputs; ***Steven Goh*** and ***Talal Yusaf*** contributed the other 20% for reviewing and editing the manuscript.

- **Article III:** Laimon, M, Mai, T, Goh, S & Yusaf, T 2019, 'The Potential Impact of Improving Energy Efficiency and the Full Transition to Renewable Energy Systems on the Performance of the Energy Sector', *Manuscript submitted for publication. Energies.* (Q2 journal; impact factor: 2.707 (2018)).

  The overall contribution of ***Mohamd Laimon*** was 70% to the concept development, data collection, development of methodology, analysis, drafting and revising the final submission; ***Thanh Mai, Steven Goh*** and ***Talal Yusaf*** contributed the other 30% for reviewing and editing the manuscript.

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ABBREVIATIONS

DEE: Department of the Environment and Energy

CCPI: Climate Change Performance Index

GHG: Green House Gases

AGEIS: Australian Greenhouse Emissions Information System

CLD: Causal Loop Diagram

SAs: System Archetypes

INDCs: Intended Nationally Determined Contributions

CCS: Carbon Capture and Storage

RET: Renewable Energy Target

CEC: Clean Energy Council

CER: Clean Energy Regulator

ATIC: Australian Trade and Investment Commission

SFM: Stock Flow Model

IPCC: Intergovernmental Panel on Climate Change

ISO 50001: International Organization for Standardization 50001

CHAPTER 1: INTRODUCTION

1. Background

Energy is essential for the development of countries and it is the cornerstone of modern life. Energy that is secure, environmentally-friendly, and produced and used efficiently is essential for sustainable development. The need for a sustainable energy sector is becoming more important with declining fossil energy resources and while the world's population is growing, energy demand is increasing even faster. Therefore, concerns such as growing energy demands, limitations of fossil fuels, threats of carbon dioxide (CO_2) emissions and global warming have drawn scientists, decision makers, and governments to develop sustainable energy sectors in their energy studies and policies. A sustainable energy sector not only meets energy needs and enhances national economies, but also achieves environmental sustainability, as well as addressing social needs (e.g. creating employment) (Sachs et al. 2019).

The energy sector is a dynamic and complex system that contains many interacting components that interact in a nonlinear behaviour (Zhao et al. 2018). It also consists of diverse supply sources, complex utilisation, and multiple stakeholder involvement with different interests. In addition, it can be influenced by internal factors (e.g. demand fluctuations, energy policy developments, socio-economic-ecological systems) and external factors (e.g. political instability, natural disaster, energy dependency). The combination of all these factors means that the energy sector is a dynamic and complex system.

Despite the dynamically-complex nature of the energy sector, previous efforts to improve it have primarily focused on addressing constituent parts of the sector. For example, Finkel et al. (2017) focus mainly on the electricity sector, while Blakers et al. (2017) emphasise the importance of renewable electricity technologies. Many energy models that have been used to plan for the energy sector are generally forecasting models and largely based on historical data, such as time series models (Hunt et al. 2003; Narayan & Smyth 2005; Narayan et al. 2010), Autoregressive Integration Moving Average (ARIMA) (Kankal et al. 2011; Pao & Tsai 2011; Barak & Sadegh 2016), Neural Network (NN) (Kalogirou 2000; Sözen et al. 2005; Geem & Roper 2009), and Grey prediction (Pi et al. 2010; Lin et al. 2011; Tsai 2016). Other common energy models are the subsystems energy models (Top-down models, Bottom-up models, and Hybrid models) such as GEM-E3 model (Ciscar et al. 2004); E4cast model (Arif 2014); and GCM model (Suppiah et al. 2007). Traditional techniques rely on historical data to predict future trends or outcomes with the assumption that the future will be very much like the past, neglecting the volatility of complex systems. Subsystem energy models lack the characteristics of the integrated system, so cannot explain the total connections of a system and thus have limitations, so the development an integrated model for energy-economy-society-environment systems is the trend of energy complex system modelling and analysis in the future (Wei et al. 2005). In addition, they are in many cases extremely complicated (Davies & Simonovic 2009). In a dynamically-integrated complex system such as the energy system, conditions are often prone to change rapidly, making these methods unreliable. In addition, most studies are skewed in favour of renewable energy without addressing other interrelated issues such as: the enormous accumulated energy reserves; the significant investments that have been spent on the non-RE sector; the limits to growth of energy capacities; and how to balance actions to address climate change with energy security (MacKay 2008). In other words, the argument reaches only halfway.

To achieve a comprehensive understanding of the dynamically-complex nature of energy systems, there is a need for a holistic approach to unlock insights into the causes of the system's behaviour and to determine leverage points, where a small shift can produce big changes that lead to enduring improvements in the whole system (Meadows 1999). We have adopted a systems-thinking approach to develop a dynamic hypothesis or conceptual model for a better understanding the dynamic complexity of the energy sector; and to suggest interventions to improve the performance of the energy sector more in line with sustainable development. To do this, we first constructed a conceptual model of the energy sector in Australia. We then used this model to identify leverage points and suggest intervention strategies towards sustainable energy development.

Then to provide a complete analysis and test the feedback loops of the energy sector, we adopted a system dynamics approach to construct an integrated model for analysing the behaviour of the energy sector. The system dynamics approach is not only about prediction, it is mainly about understanding the interactions among system components that impact system behaviour over time, and how intervention scenarios change system behaviour over time (Kelly et al. 2013). We use system dynamics for sustainable energy sector development to establish the balance of supply-demand, conservation of resources, and the reduction of energy dependency and emissions. The development of a sustainable energy sector is crucial to meet energy needs, to sustain economic development, and to achieve clean energy targets. Although the Australian energy sector is used as a case study, the model can be used in any country or throughout the world as a whole and for any energy resource.

Nowadays, systems thinking and system dynamics are widely used to address and manage sustainability challenges for many dynamically-complex issues, such as energy transitions and resources scarcity, environmental and ecological systems and safety and security (Pruyt 2013; Van Mai & To 2015; Turner et al. 2016). Understanding complex systems offers a new perspective on sustainability, stability, and the prevention of crises (Van Santen et al. 2010). Despite decades of research into the energy sector, there is a lack of adoption of this integrated approach on the relationship between energy structure, economics and the environment (Zuo et al. 2017).

This chapter is structured as follows: Section 2 provides an overview of the Australian energy sector. Section 3 highlights the research methods. Section 4 illustrates the gap existing in the literature. Section 5 discusses research questions. Section 6 presents the aims of the study. Section 7 shows how the aims of the thesis have been addressed through the study's papers. Section 8 explains the structure of the thesis.

2. Overview of the Australian energy sector

The Australian economy and population grew by 2% and 1.7% to reach $1.7 trillion and 24.6 million, respectively in 2016-2017; with this growth, the energy consumption rose by 1.1% and production rose by 4%; energy exports grew by 4% and imports increased by 2% (DEE 2018). The country has substantial conventional energy resources including coal and natural gas, and is ranked in the world's top 10 for coal, gas, and uranium production and is endowed with abundant RE resources (e.g. solar, wind) (BP. 2018).

However, there are three crucial issues related to energy supply and use in Australia: (1) to ensure that there are enough accessible energy resources; (2) to assess the impact of future energy dependency and high oil prices; and (3) to reduce greenhouse gas emissions (Murphy 2012). In response, it is important to note that Australian resources of oil are finite; the country relies increasingly on imports to meet demand for transport fuels; and the other major fossil fuel resource (gas) is expected to last only for a number of decades (Sandu et al. 2010). Furthermore, Australia is very low-performing country in three of the CCPI's categories: GHG emissions, energy use, and climate policy, where it is one of the highest per-capita emissions countries in the world (Burck et al. 2018). Moreover, Australia is the worst among developed country in terms of energy efficiency and performance indicators (Castro-Alvarez et al. 2018). 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 influence Australia's future energy generation options, and create uncertainty; as a result, these uncertainties will be likely to discourage investment (Stewart 2017).

Energy policies driven by politics and not informed by scientific approaches may lead to an uncertain energy future. Recently, ABCNEWS (2017) conducted an extensive investigation regarding Australian energy policy. It started the investigation with a question, "How could a nation as rich as Australia, has found itself in the middle of an energy crisis". The investigation included: mining lobbyists; industry lobbyists; energy analysts; and manufacturers. The investigation concluded that there is a problem in the Australian energy policy and change is imperative.

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, including: growing dependency on other countries to meet its needs of liquid fuel as shown in Fig. 2. In particular, oil has accounted for the largest share of the Australian energy mix (38%) (DEE 2018), and it has 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 (Yates & Greet 2014); resource depletion, and domestic accessibility such as oil and gas in the foreseen future; and high emissions such as CO_2 emissions which cause deterioration of the environment (e.g. climate change). Fig. 1 shows the domestic CO_2 equivalent from 1990-2016 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 the economy and job creation. Investment in the energy sector seriously impacts economic growth and job creation. High energy prices affect manufacturing industry and the work force. The closure of Australia's largest aluminium manufacturing company and subsequent laying off of workers is a good example (Eshkenazi 2017). In addition, three quarters of Australia’s power stations will close or be replaced in the near future with a considerable impact on the economy (including electricity prices), environment, and workforces. Based on the above, the Australian energy sector is in line with unsustainable future.

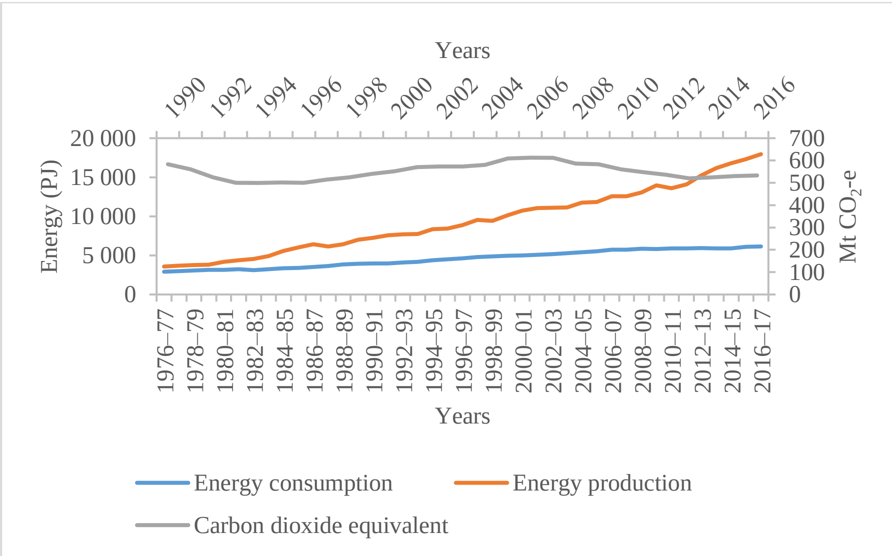

Fig. 1. Australian energy consumption, production, and carbon dioxide equivalent (DEE 2018).

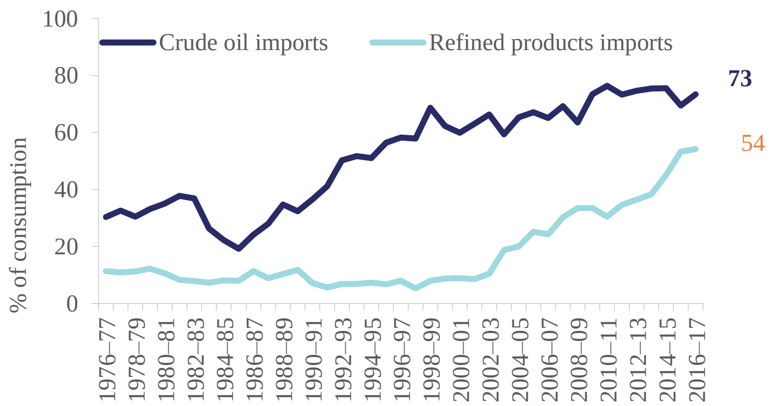

Fig. 2. Share of imports of crude and refined products in total consumption (DEE 2018).

3. Research methods

There are five main interrelated steps in applying systems thinking and system dynamics (Sterman 2000). The first two steps (problem articulation, and formulating dynamic hypotheses) focus on qualitative modelling, where the end goal is to develop a conceptual model that presents the dynamic interaction between system components. The remaining three steps (formulating a simulation model, validating/testing, and policy design and evaluation) emphasise quantitative modelling, where the end goal is to develop a computer-based simulation model to simulate the dynamic relationships between the components. Systems thinking represents qualitative modelling and system dynamics represents quantitative modelling.

A dynamic hypothesis, so-called a conceptual model for the Australian energy sector was constructed using a Causal Loop Diagram (CLD). A CLD consists of variables (words or phrases) and arrows that represent the causal relationships between pairs of variables. The arrows within a CLD links pairs of variables together to form either reinforcing (positive) or balancing (negative) feedback loops. Reinforcing feedback loops create exponential growth or exponential decline over time, while balancing feedback loops act to stabilise system behaviour over time.

The simulation model is developed based on the CLD. CLDs cannot be used for simulation as they are purely qualitative descriptions of system. Systems dynamics consists of stocks, flows, and auxiliary variables. The stock represents variable accumulation or depletion over time, stock change is through flow into or out of the stock. These mechanisms lead to feedback which can cause changes (accelerate or balance out); the feedback comes in two forms: positive (reinforcing feedback) arises when growth of a stock causes change leading to further growth of stock; negative (balancing feedback) arises when decline of a stock causes change leading to further changes to slow down. A stock changes by its flows, while stocks and auxiliary variables control the flows.

4. Research gaps

This study goes beyond filling a gap in the literature; it has a positive contribution represented by constructing a useful model which can be used by any country or for the whole world as a unit and for any energy resource, which puts it in a position to suggest ‘policy interventions’, to project into the future of the changing capacity mix and contributions to CO_2 emissions. From the above discussions, the research gaps can be identified as:

1. A lack of adoption of systems thinking and systems dynamics approaches on the relationship between energy structure, economics and the environment.
2. Previous studies to improve energy systems mainly use silo approaches that focus on a particular system’s components and neglect their interconnected nature.
3. Most studies use either traditional techniques that rely on historical data or subsystems energy models that lack the characteristics of the integrated system, so cannot explain the total connections of a system and thus have limitations.
4. No previous analyses have been done in the Australian context to analyse the behaviour of the energy sector using systems thinking and system dynamics methods.
5. To our knowledge no previous efforts dealt with the full transition to RE systems (electrification of everything using RE) in the Australian context.

5. Research questions

The main research questions that were addressed through this study are:

1. What are the influences of energy policies on energy dependency, energy security, CO_2 emissions, energy reserves, and energy prices within the Australian context?
2. What are the implications of energy scenarios on supply-demand balance, fossil fuels reserves, energy dependency, CO_2 emissions,

energy whole prices, and energy bankruptcy by 2050 within the Australian context?

3. What are the influences of improving energy efficiency and the full transition to renewable energy systems on energy productivity, domestic CO_2 emissions, oil dependency, and energy consumption by 2050 within the Australian context?

6. Aims of the study

The aims of this study are:

1. Using systems thinking to develop a dynamic hypothesis or conceptual model for a better understanding of the dynamic complexity of the energy sector; and to suggest interventions to improve the performance of the energy sector more in line with sustainable development.
2. Formulating and validating a system dynamics model of the energy sector.
3. Using the system dynamics model to develop possible development scenarios for the energy sector.
4. Using the system dynamics model to examine the influences of improving energy efficiency and the full transition to renewable energy systems on the performance of the energy sector.

7. Addressing thesis aims through publications

The first aim was accomplished, and the outcomes were presented in ***paper I***. A conceptual model of the Australian energy sector was constructed and used to identify leverage points and suggest intervention strategies towards sustainable energy sector development. The second and third aims were addressed in ***paper II***. A system dynamics model of the energy sector was constructed and validated. The model was used to develop possible development scenarios for the energy sector, and the implications of energy scenarios on supply-demand balance, fossil fuel reserves, energy dependency, CO_2 emissions, energy whole prices, and energy bankruptcy were clarified depending on the defined scenario. The fourth aim was addressed in ***paper III***. The influences of improving energy efficiency, switching to renewable energy for transportation, switching to renewable electricity, electrification of sectors that do not run on electricity by renewable energy on the performance of the energy sector were examined.

8. Thesis structure

Introduction

- Research background
- Research gaps
- Research aims

Paper I

Aim:

- A systems thinking approach was used to develop a dynamic hypothesis or conceptual model of the energy sector. This conceptual model was used to assess the potential consequences of current energy policy, and to suggest improvements of the policy towards sustainable development.

Summary results:

- Research findings indicated that there are significant risks in setting policies associated with energy security and environmental interventions in Australia. This is especially evident in the case of oil and gas components, and CO_2 emissions.

Paper II

Aim:

- We have formulated and validated a system dynamics model of the energy sector.
- We used system dynamics for the energy sector development and to examine trends through different possible scenarios. We established balance of supply-demand, and examined the implications on fossil fuel reserves, energy dependency, energy prices, energy bankruptcy, and CO_2 emissions.

Summary results:

- Research findings indicated that the current trajectory of the Australian energy sector is unsustainable and growth is not being controlled. Limits to growth are fast approaching due to excessive fossil fuel extraction, high emissions, and high energy dependency.

Paper III

Aim:

- We have used a system dynamics approach to examine the impact on the performance of the energy sector of improving energy efficiency and the full transition to renewable energy systems.

Summary results:

- Research findings indicated that both improving energy efficiency and full transition to RE systems are crucial for improving energy sector performance.

Conclusion

- Summary of key outcomes from all papers.
- Recommendations for future work detailed.

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CHAPTER 2: PAPER I

A SYSTEMS-THINKING APPROACH TO ADDRESS SUSTAINABILITY CHALLENGES TO THE ENERGY SECTOR

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A SYSTEMS-THINKING APPROACH TO ADDRESS SUSTAINABILITY CHALLENGES TO THE ENERGY SECTOR

Abstract

The energy sector is a dynamically-complex system, which comprises various interacting components and involves a diverse array of stakeholders. The development of the sector in a sustainable manner requires a comprehensive understanding of its components and their dynamic interactions. Previous efforts to improve energy systems have primarily used silo approaches that focus on a particular system's components and neglect their interconnected nature. These approaches limit our ability to understand the system and/or mitigate undesirable outcomes. This paper adopts a systems thinking approach to construct a systems model of the energy sector through the lens of a case study in Australia. The model visualises energy systems as a whole and identifies feedback mechanisms likely to influence the behaviour of the sector. The model can serve as a common language for achieving a better understanding of the sector and aligning stakeholders' views. It can also serve as a platform to identify key leverage points for systematic intervention strategies towards the development of a sustainable energy sector. Research findings indicate that there are significant risks in setting policies associated with energy security and environmental interventions in Australia. This is especially evident in the case of oil and gas components, and CO_2 emissions.

Keywords: Systems thinking; Sustainable development; Energy sector; Energy policy; Feedback loop; Energy security; CO_2 emissions.

1. Introduction

Energy has been and still is a significantly important topic that attracts a great deal of attention from policy makers and researchers throughout the world. The availability of energy is critically important to ensure economic growth and improve the quality of life (Hoogwijk 2004). The continuing growing imbalance between energy supply and demand due to rising population numbers, rapid economic development, and the negative impacts (e.g. CO_2 emissions) of the energy sector on climate change have encouraged many countries to develop sustainable energy systems (Asif & Muneer 2007). Sustainable energy systems not only meet energy needs and enhance national economies, but also achieve environmental sustainability, as well as addressing social needs (e.g. creating employment) (Mathiesen et al. 2011). Like other countries, Australia is looking forward to a sustainable energy future, but is still facing threats to energy sustainability, and is thus in critical need of reform to realise this goal (Wood 2016). Nowadays, energy, emissions and climate change are topical issues and there is a great deal of political debate on Renewable Energy (RE) and climate change in Australia, which signifies the need to take actions to mitigate emissions (Slezak 2019).

Studies have highlighted that the energy sector contains many interacting components. These can be in the form of energy production and supply, energy demand, and emissions, and a web of interactions between multiple dimensions of economic, social, and environmental aspects (Zhao et al. 2018). The system is also influenced by rapid changes, such as demand fluctuations (Davies & Simonovic 2009) and diverse supply sources and complex utilisation (MacKay 2008). In addition, the sector involves a diverse array of stakeholders (e.g. suppliers, intermediaries, and customers) (Warbroek et al. 2018), each of whom has different management objectives and interests that make convergence criteria for sustainable outcomes a complex task (Stagl 2006). The interaction of all these factors that control the energy sector is an intrinsically dynamic and complex system.

Despite the dynamically complex nature of the energy system, previous efforts to understand the practice and governmental policies and measures designed to improve it, tend to primarily focus on its specific parts and neglect the interconnected nature of the system. For example, Narayan and Smyth (2005) and Finkel et al. (2017)

focus mainly on electricity, while Blakers et al. (2017) emphasise the importance of renewable electricity technologies. In many cases, energy management, planning, and forecasting are mainly based on techniques that rely on historical data such as time series (Fatai et al. 2004; Mahadevan & Asafu-Adjaye 2007; Narayan et al. 2010; Shahiduzzaman & Alam 2012); or on subsystems energy models such as top-down models (e.g. GEM-E3) (Ciscar et al. 2004); bottom-up models (e.g. E4cast model) (Arif 2014); hybrid models (e.g. GCM model) (Suppiah et al. 2007); and a combination of top-down and bottom-up models (DEE 2017). These conventional approaches rely on historical data to predict future trends or outcomes with the assumption that the future will be very much like the past. However, in a dynamically complex system such as an energy system, conditions often change rapidly, making these techniques unreliable, and thus fail to achieve a comprehensive understanding of its complexity and underlying rationale.

Clearly, issues and challenges related to the sustainability of energy system are multiple and complex in nature. These problems and challenges cannot be addressed and solved in isolation and along single dimensions. Integrated approaches are essential to comprehensively understand the system and/or mitigate undesirable outcomes to create a sustainable energy sector. In contrast to the aforementioned linear (deterministic) approaches, systems thinking offers a holistic way of thinking based on the primacy of the whole system and interactions between its constituent parts (Senge 2006) and provides a framework for conceptualising the management of multifaceted or ‘wicked’ problems (Maani & Cavana 2007). Further, it facilitates greater understanding of where the leverage points are within the system—points where a small intervention can produce big changes leading to enduring improvements in the whole system (Meadows 1999). Importantly, systems thinking enables the outcomes of policy decisions, as well as the unintended consequences of intervention programs and strategies, to be forecast (Mai & Smith 2015; Van Mai & To 2015; Mai et al. 2019). Despite its rich history, applications of this innovative approach have been largely absent in the field of energy management (Zuo et al. 2017).

In this paper, we adopt a systems thinking approach to develop a dynamic hypothesis or conceptual model of the energy sector. We then use this conceptual model to assess the potential consequences of current energy policy, and to suggest improvements of the policy towards sustainable development. This is done through the lens of a case study of the Australian energy sector. Energy resources considered in this study are primary energy (RE and non-RE).

2. Research method

2.1. Overview of the energy sector in Australia

In 2016-2017, the Australian economy and population grew by 2% and 1.7% to reach $1.7 trillion and 24.6 million, respectively; with this growth, the energy consumption rose by 1.1% and production rose by 4%; energy exports grew by 4% and imports increased by 2% (DEE 2018). The country has substantial conventional energy resources including coal and natural gas, and is ranked in the world's top 10 for coal, gas, and uranium production and is endowed with abundant RE resources (e.g. solar, wind) (BP. 2018).

However, there are three crucial problems related to energy supply and use in Australia: (1) to ensure that there are enough accessible energy resources; (2) to assess the impact of future energy dependency and high oil prices; and (3) to reduce greenhouse gas emissions (Murphy 2012). In response, it is important to note that Australian resources of oil are finite; the country relies increasingly on imports to meet demand for transport fuels; and the other major fossil fuel resource (gas) is expected to last for only a number of decades (Sandu et al. 2010). Furthermore, Australia is very low-performing country in three of the CCPI's categories: GHG emissions, energy use, and climate policy, where it is one of the highest per-capita emissions countries in the world (Burck et al. 2018). 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 influence Australia's future energy generation options and create uncertainty; as a result uncertainties will be likely to discourage investment (Stewart 2017).

With growing energy demand over the last 40 years (1977-2017) as shown in Figure 1, due to growth in both population and economy, the Australian energy sector is facing many challenges, including: growing dependency on other countries to meet its needs of liquid fuel as shown in Figure 2. In particular, oil has accounted for the largest share of the Australian energy mix (38%) (DEE 2018), and it has caused crises in Australia like those that occurred in 1973 and 1979, driven by a curtailment of supply, and that from 2008 caused by soaring demand (Yates & Greet 2014); resource depletion, and domestic accessibility such as oil and gas in the foreseen future; high emissions such as CO_2 emissions which cause deterioration of the environment (e.g. climate change). Figure 1 shows the CO_2 equivalent from 1990-2016 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 the economy and job creation. Investment in the energy sector seriously impacts economic growth and job creation. High energy prices affect the manufacturing industry and the work force. The closure of Australia's largest aluminium manufacturing company and subsequent laying off of workers is a good example (Eshkenazi 2017). In addition, three quarters of Australia’s power stations will be closing or being replaced in the near future with a considerable impact on the economy, environment, workforces and electricity price. Based on the above, the Australian energy sector is regarded as unstable and is still far from being sustainable.

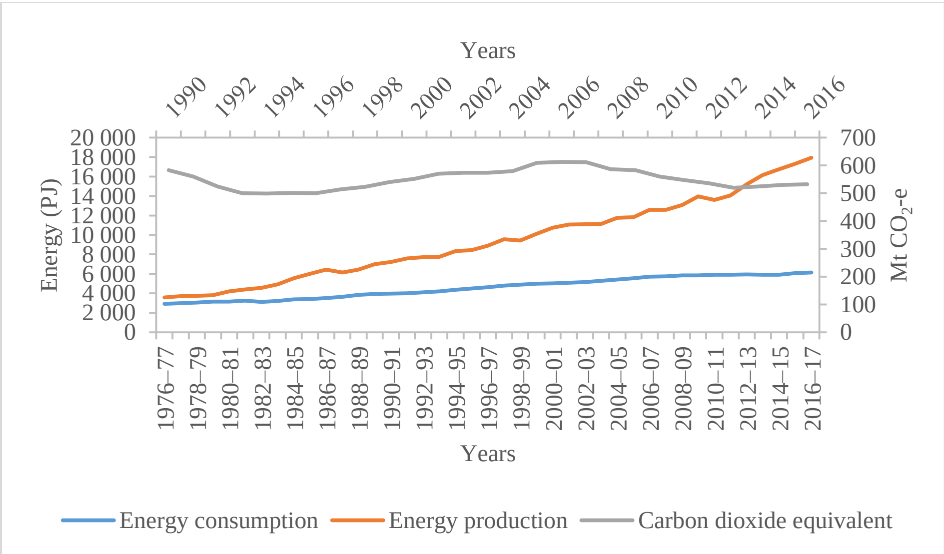


Figure 1. Australian energy consumption, production, and carbon dioxide equivalent (DEE 2018).

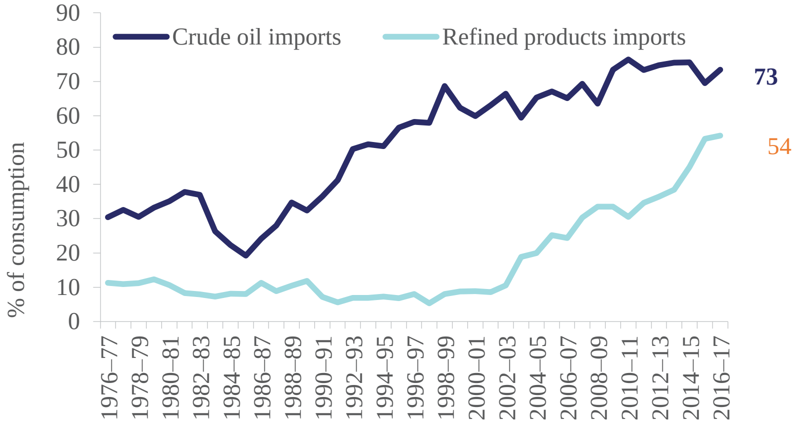


Figure 2. Share of imports of crude and refined products in total consumption (DEE 2018).

2.2. Formulation of a conceptual model for the Australian energy sector

There are five main interrelated steps in applying systems thinking and modelling (Sterman 2000). The first two steps focus on qualitative modelling, where the end goal is to develop a conceptual model that presents the dynamic interaction between system components. The remaining three steps emphasise quantitative modelling, where the end goal is to develop a computer-based simulation model to simulate the dynamic relationships between the components. In this paper, we adopted the first two steps (problem articulation, and formulating dynamic hypotheses) to understand the dynamic complexity of the Australian energy sector and to determine systemic intervention strategies for sustainable energy development in the country.

A dynamic hypothesis, or so-called conceptual model for the Australian energy sector was constructed using a Causal Loop Diagram (CLD). A CLD consists of variables (words or phrases) and arrows that represent the causal relationships between pairs of variables. The arrows within a CLD link pairs of variables together to form either reinforcing (positive) or balancing (negative) feedback loops. Reinforcing feedback loops create exponential growth or exponential decline over time, while balancing feedback loops act to stabilise system behaviour over time.

The development of the CLD in this study involved 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, we used these variables to develop a preliminary CLD by creating links, polarities and a time delay between the variables. In the third stage, the preliminary CLD was amended and validated through consulting with multiple experts in the Australian energy sector to produce a working CLD. During expert consultation, the preliminary CLD was split to feedback loops and the experts were asked to suggest modifications to variables and their associated links. The working CLD was again reviewed and any errors or inconsistencies identified in the model were corrected to produce the final CLD for the Australian energy sector.

2.3. Leverage points and intervention strategies

It is generally accepted that leverage points are not easily accessible. Meadows (1999) points out the possible places of high leverage points in the system: the rules and regulations of the system; the structure of information flows; the gain around reinforcing feedback loops; and the strength of balancing feedback loops. The rules of the system are designed by the government and the government has authority over them. The structure of information flows means delivering information to influence behaviour change. The gain associated with reinforcing feedback loops and the strength of balancing feedback loops will be discussed in the System Archetypes (SAs) section. SAs are diagrams resemble CLDs but in fact they are not the same, SAs show mechanisms and generic patterns of behaviour in isolation (Pruyt 2013), which simplifies the complexity of the CLD by identifying the core of system structure, and thus makes problems and leverage points in the system more obvious (Mai et al. 2019).

3. Results

3.1. The conceptual model of the Australian energy sector

The final CLD of the Australian energy sector is shown in Figure 3, which contains twenty one feedback loops including ten reinforcing loops (R1 to R10) and eleven balancing loops (B1 to B11). This CLD highlights the main components of the energy sector linked to Australia's energy policy including energy resources (loops R1 and R2); energy production, supply and demand (loops R3, B3 and B4); energy economics (loops B5 and R4); energy emissions and energy emissions policies (loops R6, B6 and B7); and energy policy developments (loops R7, B8, R8, B9, R9, B10, R10 and B11). These feedback loops are briefly described in the following section.

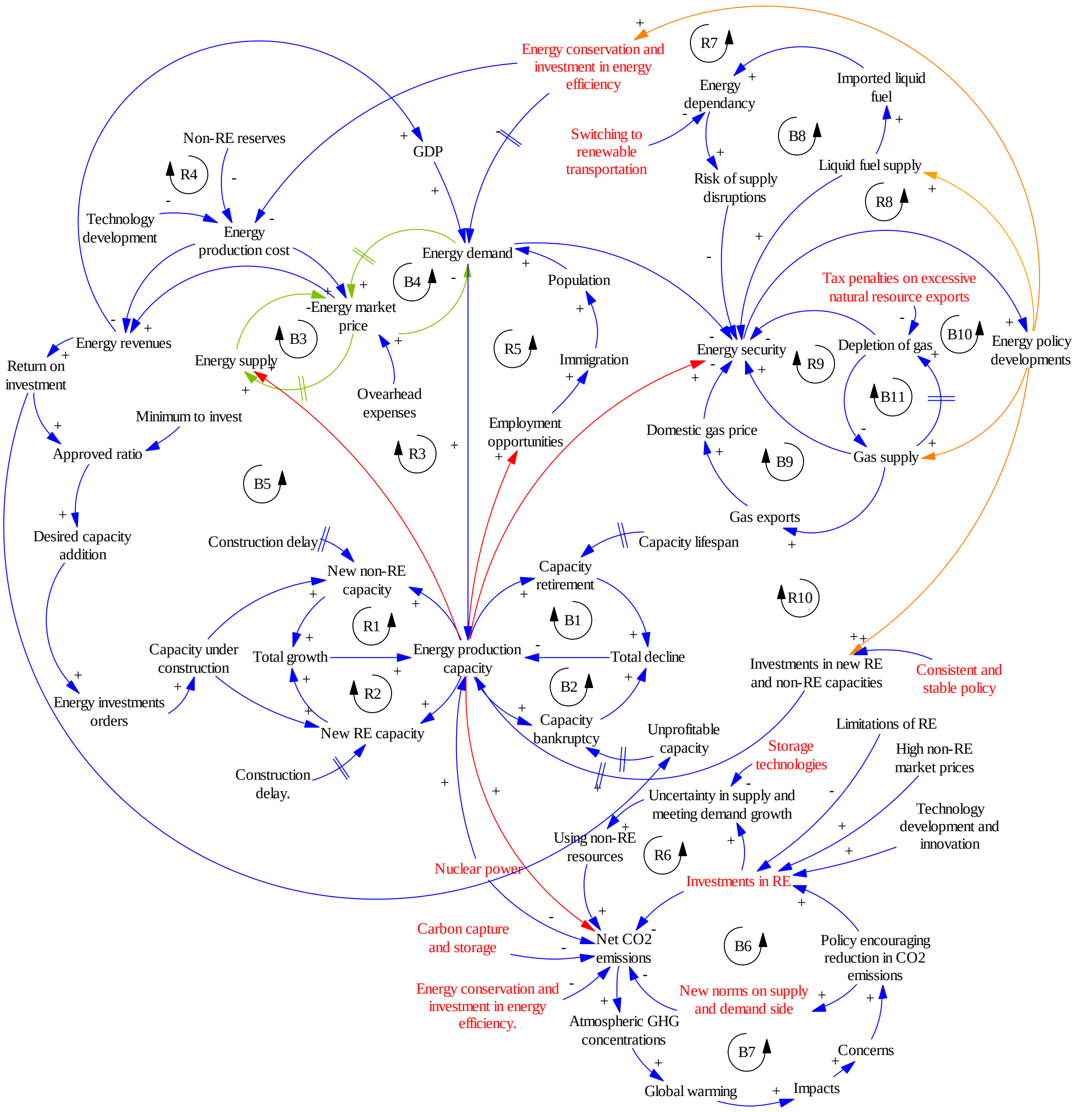


Figure 3. The CLD of the energy sector. Parameters in red colour are missing or poorly performing in the Australian context.

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) as shown in Figure 4. It includes energy resources construction pipeline loops (R1, R2, B1, B2 and B5); supply-demand balance loops (R3, B3 and B4); and GDP loop (R4).

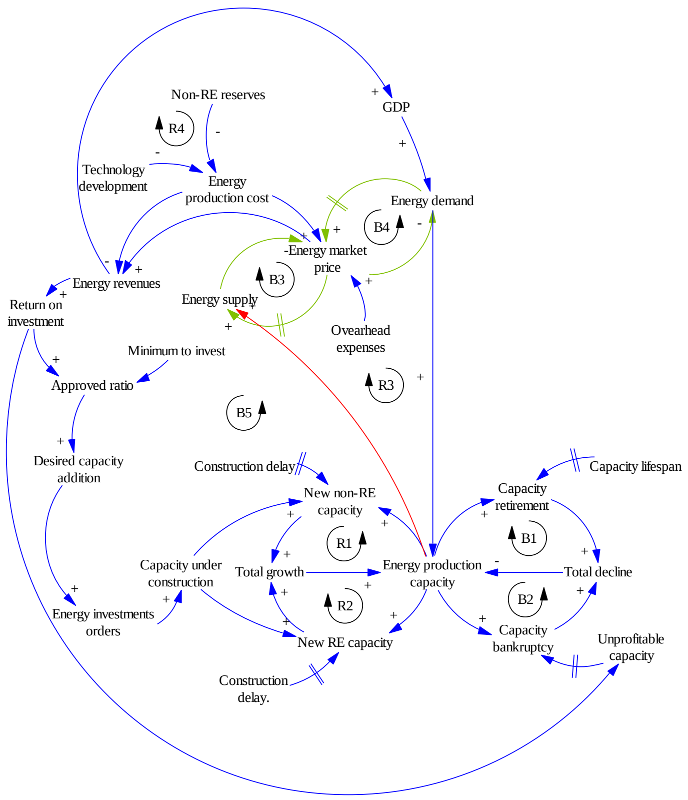


Figure 4. Energy production capacity-economic loops.

Energy resources construction pipeline loops contain two reinforcing loops (R1 and R2), and three balancing loops (B1, B2 and B5). These loops represent the construction and developmental pipelines of two major energy resources in Australia including RE and non-RE. Loops R1 and R2 reflect the total growth of RE and non-RE energy resources considering that both capacities require infrastructure construction delay. Loops B1 and B2 reflect the total decline of both capacities resulting from capacity bankruptcy and capacity 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 impede investment.

Supply-demand balance loops (R3, B3 and B4) show the relationship between energy price, energy supply, energy demand, and energy production capacity. The demand side includes transportation and non-transportation sectors (e.g. industry, household). The supply side includes RE (e.g. biomass, solar, wind) and non RE (coal, oil, and gas) resources. Non-RE (coal, oil and gas) accounted for 94% and RE only around 6% of Australia’s energy mix in 2016/2017 (DEE 2018). 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 keep supply-demand in balance (self-correction feedback balance). This is called the law of supply and demand (Heakal 2015). Energy price provides an incentive to supply more capacity; however this may lead to overcapacity which in turn leads to a decrease in price (loop B3). Loop B4 reflects the demand side; high energy demand means higher energy price, while low demand means lower energy price (Davies & Simonovic 2009; Snow 2017; Kaygusuz 2019; Punzi 2019). This supply-demand balance drives the energy production capacity as shown in Loop R3. GDP loop (R4) shows the role of energy revenues in increasing GDP. GDP positively affects energy demand (Shahiduzzaman & Alam 2012). Energy demand increases the energy market price which as a result, increases energy revenue and GDP.

3.2.2. Energy production capacity-social loop

This loop shows the interactions between energy production capacity and such diverse social issues (loop R5) as employment opportunities, immigration and population (Figure 5). It shows the role of energy production capacity in creating employment opportunities and how these new opportunities increase immigration and thus population. Population positively affects energy demand leading to increased energy production capacity (OECD & IEA 2011; Dong et al. 2018; Li et al. 2019).

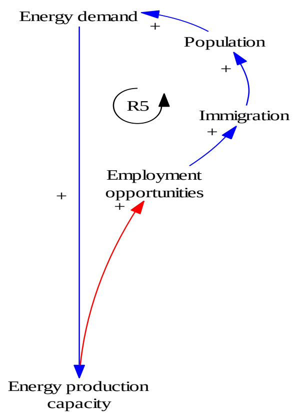


Figure 5. Energy production capacity-social loop.

3.2.3. Energy production capacity-emissions loops

Loops contained in Figure 6 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 (MacKay 2008). Following Intended Nationally Determined Contributions (INDCs), Australia seeks to reduce emissions 5% below 2000 levels by 2020 and 26-28% below 2005 levels by 2030 (DEE 2017). 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 on the supply and demand side (loop B7).

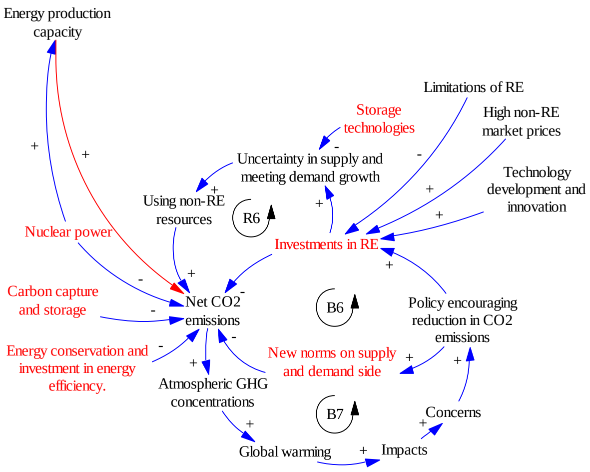


Figure 6. Energy production capacity-emissions loops.

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 RE supply. Australia's RET is a government policy that aims to generate at least 33,000 GWh of electricity from RE resources by 2020, and remain at that level until 2030. That represents more than 23.5% of Australia’s electricity (CEC 2016). The scheme is split into two parts. The first is the Large Scale Renewable Energy Target (LRET) which is a limited target that requires 33,000 GWh of new generation annually from large scale RE power plants, such as wind farms, solar plants and hydroelectric power stations by 2020. The second is the Small Scale Renewable Energy Scheme (SRES) which is an unlimited scheme to encourage small scale renewables, such as household rooftop solar, solar hot water, and heat pumps. The SRES is up to 100 KW. Systems over this size are considered for the LRET (CER 2018).

There are several factors that may increase investments in RE, such as non-RE market prices, technology development and innovation, and consistent and stable RE policy. Technology development and innovation 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 resources 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 resources of RE (e.g. biomass and geothermal energy) have the capability to provide reliable and continuous power; discontinuous resources of RE (e.g. solar, wind) with storage technologies have the capability to enhance flexibility of supply (Needham 2008).

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 (Aslani et al. 2014). Energy dependency is the level of energy imports that the country depends on to fulfil its energy needs (Sözen et al. 2014). 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 (Figure 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 (Yates & Greet 2014). However, energy security can be defined as the diversity of long-term national energy resources 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 considered one of the most important indicators of sustainable development (Štreimikienė et al. 2016).

Based on the experts' consultation, energy security is one of the most significant variables that the experts have 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 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 resources, demand management, access to new technology, diversification of energy resources, community awareness and engagement, reliability of supply, dispatchable generation from a number of resources, 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 a priority for any country.

In response, energy policies are reviewed and amended by the government to meet demand and support the energy sector (Figure 7). Government support may come in different forms: mandates (e.g. renewable fuels standards), non-mandatory targets, subsidies and incentives (Bacon & Kojima 2011). This in turn increases the investment in energy efficiency (loop R7) 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 resorts to attracting investments in new RE and non-RE capacities (loop R10) to meet the growing demand. As a result, 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.

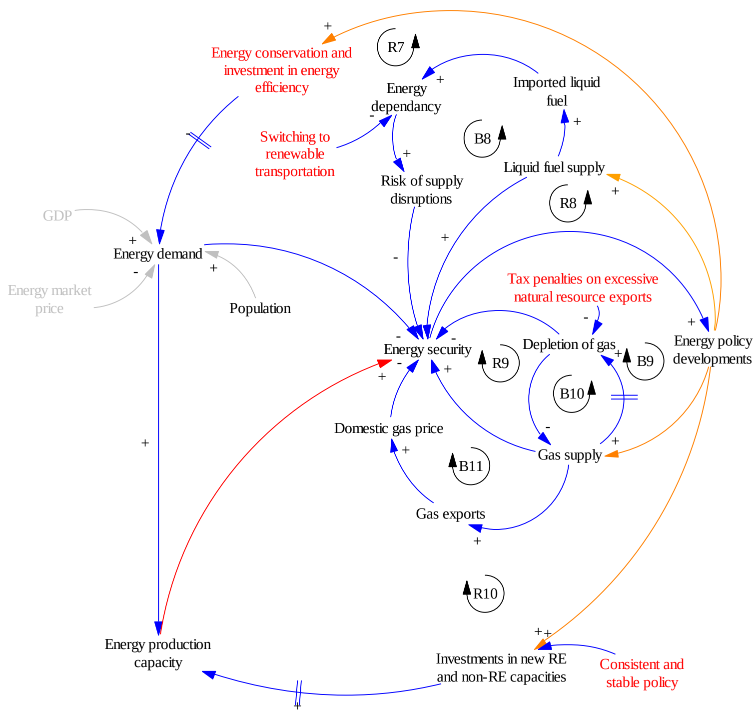


Figure 7. Energy production capacity-energy policy developments loops.

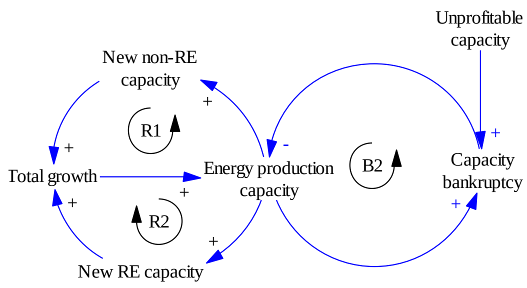
On the other hand, it is important for Australia to meet liquid fuel needs (loop R8), and increase gas supply (R9) to fulfil domestic and export needs. Liquid fuel generates 98% of transport needs (DEE 2019). However, Australia has only three weeks of liquid fuel reserves which constitutes a breach of international obligations which recommend storing a net stockpile of 90 days of liquid fuels (Hepburn 2018). 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. It is projected that gas supplies will rise in terms of gas exports (loop B9) 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 (B10), especially as Australia will be the world's largest exporter of natural gas by 2020 (ATIC 2019).

3.3. System archetypes

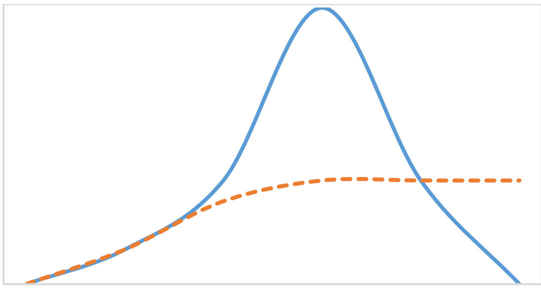
Two types of system archetypes have been identified in this study. These include: "Limits to Growth" and "Fixes that Fail".

3.3.1. Limits to Growth

'Limits to growth' relate to growth followed by stagnation or possibly collapse when reaching its limit (Pruyt 2013) as shown in Figure 8 (b). Energy production growth in Australia is driven by the total growth of RE and non-RE resources as shown in loops R1and R2 (Figure 8 (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 less than energy production cost for a period of time. 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 fluctuation between energy supply-demand.



(a)



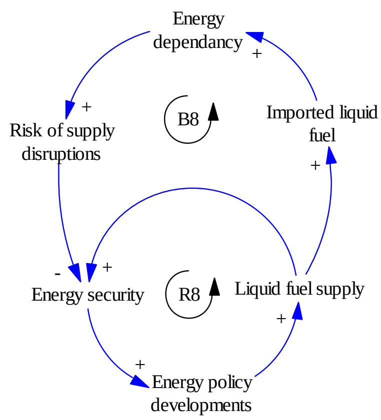
(b)

Figure 8. Structure (a) and the two possible behaviours (b) of Limits to Growth archetype (after reaching a limit). The solid line represents growth followed by collapse while the dashed line represents growth followed by stagnation.

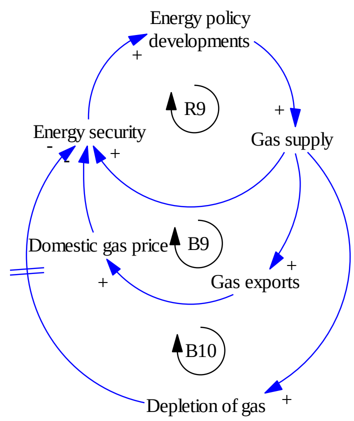
3.3.2. Fixes that Fail

'Fixes that Fail' indicate fixes that result in unintentional and undesirable consequences following well-intentioned actions (Maani & Cavana 2007). In the case of the Australian energy sector or any other country, energy security is crucial for a sustainable energy future. Energy security needs to be enhanced especially in oil and gas sectors as they are in a vulnerable position. The government's intervention to meet the growing demand of liquid fuel is only by increasing liquid fuel supply to meet short term needs (loop R8, Figure 9 (a)). However, this intervention cannot guarantee energy security in terms of liquid fuel in the long term, as it will increase liquid fuel dependency. This in turn increases the risk of supply disruptions, and thus decreases energy security (loop B8).

Similarly, the intervention in the gas sector is represented by increasing gas supply to meet growing domestic and export demand, which will increase gas security in the short term (loop R9, Figure 9 (b)). However, gas export commitments will force up the more fluid domestic gas price, which in turn decreases energy security (loop B9). Furthermore, increasing gas supply domestically and internationally will impact gas reserves, which in turn decreases energy security in the long term (loop B10).



(a)



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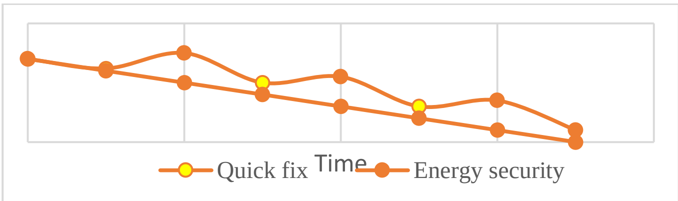

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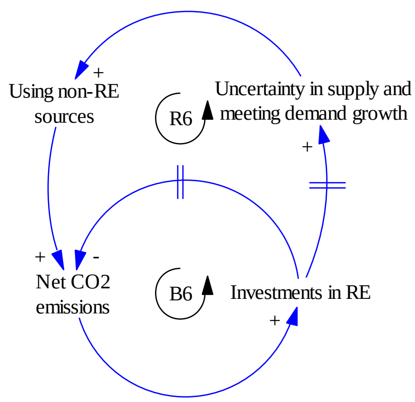
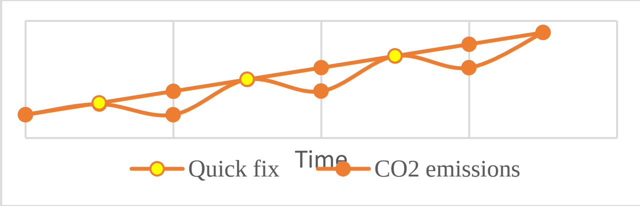


(d)



(e)

Figure 9. Structure (a, b and d) and long-term behaviour (c and e) of the Fixes that Fail archetype.

On the other hand, energy security is inversely related to energy emissions; the more energy emissions, the less energy security achieved. In this regard, the government is intervening to mitigate CO_2 by investing in RE (B6, Figure 9 (d)), mainly in renewable electricity. While investing in RE is important to mitigate CO_2 emissions, uncertainty in supply and meeting demand growth may lead to further use of non-RE resources to meet the growing demand, which in turn will increase the net of CO_2 emissions (loop R6). Loop B6 needs to be strengthened by focusing on other sectors (e.g. transport), as focusing purely on the electricity consumption sector may not achieve the desired goal of reducing CO_2 emissions. 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 (Supekar & Skerlos 2015). Considering RE in other sectors, energy conservation and investment in energy efficiency, solving the intermittency problem in RE by using storage technologies to convert RE (wind and sun) from non dispatchable to dispatchable power, as well as adding new norms on supply and demand side (loop B7) are important to reduce CO_2 emissions significantly if nuclear power and CCS are not an option.

4. Discussion

The research findings indicate that there are significant risks in setting policies associated with energy security and environmental interventions in the Australian energy sector. Energy security is regarded as a fundamental requirement for a sustainable energy future. It is connected directly with national economic security in particular and national security in general, food and water security, sustainable development and environmental security, social stability and energy stress (Yates & Greet 2014). In some ways, the sustainable energy future is about energy security. Energy security is about establishing the balance of supply-demand, and reducing emissions. Supply-demand balance and reducing emissions are about energy conservation and investments in new capacities. Investments in new capacities are about offering consistent and stable energy policies, and technology development and innovation.

In the case of the Australian energy sector, the main source of energy policy failure is policy volatility. This is the main source of uncertainty which impedes growth and investment in the energy sector. We suggest the following strategies: strengthening the feedback ability of energy market signals, and engaging the market to find the most effective solutions in the form of technological innovation and adoption; adding missing feedback loops (information flow feedback) to the Australian energy sector to influence behaviour change; adding optional or compelling feedback information, in particular on energy consumption and emissions to improve the energy system. For example, using devices with high efficiency factors and smart digital control technologies to improve the energy system in terms of energy demand/consumption (Palensky & Dietrich 2011). Monitoring consumption through a digital control device is just one of many simple examples that may alter behaviour and reduce consumption. Another example is in reporting emissions to the public which may improve the behaviour of high-emission industries and reduce emissions. Setting compelling tax penalties on excessive natural resource exports to keep natural resources from unsustainable depletion, as well as will help to keep domestic consumption in balance with export prices. A missing feedback loop is one of the most common causes of system failure (Meadows 1999). These feedback loops improve the energy sector stockholders' behaviour, and inform and control energy policy decision making. In the case of stockholders' behaviour, optional and compelling feedback loops should be taken into consideration to improve their behaviour in particular on energy consumption, emissions, and exports of natural resources. In the case of energy policy makers, an accountability feedback loop should be considered to take responsibility of their decisions. These missing feedback loops can be considered as new norms that need to be activated in the Australian energy sector (B7). Engaging human factor and information flows into the loop may impact the behaviour and thus improve the energy system.

In order to mitigate CO_2 emissions, some models have suggested that incorporating an energy mix of continuous and discontinuous RE and resources of fossil fuel that cause less CO_2 pollution can be the solution to combat increasing CO_2 emissions. For example, Saddler et al. (2004) 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 et al. (2017) went further when they suggested that 90% of wind and photovoltaics and 10% of hydroelectricity and biomass will contribute 100% of annual Australia's electricity.

However, the electricity supply sector accounted for only 28% of energy consumption in Australia in 2016/2017 (DEE 2018), 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 gasoline and diesel vehicles and replace them completely with electric vehicles by 2040 (Asthana & Taylor 2017). Other countries (e.g. France, India) are also speeding up the transition to ban petrol vehicles (Slezak 2017).

On the other hand, adopting a direct approach to RE may increase uncertainty in meeting supply and demand growth, and create distortion in the energy market. This may then indirectly lead to an increase in the use of non-RE resources to meet growing demand in reliable resources. This may explain the increase in CO_2 emissions globally by 1.6% in 2017, although there is an extraordinary growth in RE (Dale 2018). 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% (Conca 2017). Likewise, Australia's CO_2 emissions are not projected to fall with the current policy setting (Skarbek 2018). With the growing energy demand, focusing on the electricity sector and omission 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 (wind and sun), which may come from mass storage batteries (e.g. off-river pumped hydro battery, mega battery) or other dispatchable RE resources (e.g. bio mass, hydropower) that will enhance flexibility and solve uncertainty in the future supply of RE. Focusing on energy conservation and increasing investments in energy efficiency and RE with storage technologies to include other large energy consuming sectors (besides electricity sector generation) will accelerate CO_2 emissions reduction. Australia is the worst performer among developed countries in terms of energy efficiency and performance indicators (Castro-Alvarez et al. 2018), as well as RE only accounted for 6% of Australia's energy mix in 2016/2017 (DEE 2018).

Despite the rebound effects that are still controversial due to the lack of empirical studies and limited understanding about its effects (Azevedo 2014; Llorca & Jamasb 2017), there are real benefits of improving energy efficiency on the level of lowering energy bills, reducing emissions, improving health, welfare, and productivity, increasing job and economic growth (IEA 2019). We consider that the rebound effect can be reduced by reducing dependency on fossil fuel and accelerating the transition to full renewable systems. 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 development of a sustainable energy sector requires a comprehensive understanding of the energy sector's components and their interrelationships. The findings of this study highlight these components, identify the leverage points (red parameters in the CLD) in the system, and suggest intervention strategies towards the development of a sustainable energy future which is crucial to meet energy needs, to sustain economic development, and to achieve clean energy targets. We have used a systems thinking approach to understand the structure of the energy system and its complex dynamic behaviour, and considered Australia as a case study. Given the increasing need for effective strategies to better handle energy sector challenges, the application of such an approach may enable more effective decisions/policy changes to get much better outcomes and avoid undesirable ones.

The research findings indicate that the current situation of the Australian energy sector is unstable and far from being sustainable, driven by an Australian energy policy context that is volatile and inconsistent. The government's intervention to meet the growing demand of energy is likely to lead to high energy dependency, high energy prices, high CO_2 emissions, and unsustainable fossil fuel extraction.

The conceptual model of the Australian energy sector designed and proposed in this study can effectively assist in developing a pathway towards a sustainable energy sector. However, the conceptual model remains a qualitative tool, and the feedback loops remain hypotheses that need to be tested. Therefore, to provide a complete analysis and test the feedback loops to balance the system, empirical analysis and simulation modelling will need to be constructed in the second paper, which represents the quantitative modelling to enable an in-depth investigation of the system dynamics of the Australian energy sector. This simulation model will be developed based on the conceptual model of the Australian energy sector designed and proposed in this paper.

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CHAPTER 3: PAPER II

Laimon, M.; Mai, T.; Goh, S.; Yusaf, T. Energy Sector Development: System Dynamics Analysis. Appl. Sci. 2020, 10, 134.

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Article

Energy Sector Development: System Dynamics Analysis

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Abstract: The development of a complex and dynamic system such as the energy sector requires a comprehensive understanding of its constituent components and their interactions, and thus requires approaches that can adapt to the dynamic complexity in systems. Previous efforts mainly used reductionist approaches, which examine the components of the system in isolation, neglecting their interdependent nature. Such approaches reduce our ability to understand the system and/or mitigate undesirable outcomes. We adopt a system dynamics approach to construct an integrated model for analysing the behaviour of the energy sector. Although the Australian energy sector is used as a case study, the model can be applied in other context elsewhere around the world The results indicate that the current trajectory of the Australian energy sector is unsustainable and growth is not being controlled. Limits to growth are fast approaching due to excessive fossil fuel extraction, high emissions and high energy dependency. With the current growth, Australia's global CO_2 emissions footprint will increase to unprecedented levels reaching 12% by 2030 (9.5% for exports and 2.5% for domestic). Oil dependency will account for 43% and 47% of total consumption by 2030 and 2050. By 2032, coal will be the only fossil fuel resource available in Australia. Expansion of investment in coal and gas production is a large risk.

Keywords: complexity; dynamic modelling; energy modelling; energy policy; energy security; energy dependency; CO_2 emissions

1. Introduction

The energy sector is an inherently dynamic and complex system, as it contains many components that have complex cause-effect relationships generated through multiple feedback loops. The system also consists of diverse supply sources, complex utilisation and the involvement of multiple stakeholders with different management objectives and interests. Furthermore, it is influenced by various internal (e.g., demand fluctuations, energy policy developments and socio-economic-ecological systems) and external (e.g., political instability, natural disaster and energy dependency) factors. The combination of all these factors means that energy managers and planners have to make decisions under uncertain environments, and thus the development of the sector in a sustainable manner faces many challenges. These include growing energy demand, depletion of fossil fuels, threats of pollution from energy emissions and global warming. The high energy dependency, lack of energy efficiency development and uncertain policy towards the development of renewable energy (RE) are other key challenges [1].

Despite a growing sense of uncertainty in the energy sector, energy management and planning largely rely on forecasting models that are mainly based on historical data, such as time series models [2–4], autoregressive integration moving average (ARIMA) [5–7], neural network (NN) [8–10] and grey prediction [11–13]. These models neglect the interconnected nature of the energy system. In many cases, subsystem energy models (e.g., top-down models, bottom-up models and hybrid models) are used, such as GEM-E3 model [14]; E4cast model [15]; and GCM model [16]. Similar to the aforementioned forecasting models, these subsystem models focus on constituent parts of the energy system and disregard the interconnected nature of the sector [17]. In addition, they are relatively complicated to use [18]. Obviously, future energy management and planning cannot be relied on aforementioned models. As such, a holistic or integrated approach is required.

Recognition of the behaviour of dynamically complex systems is controlled not by the number of their components, but by the interactions among them via feedback loops embed in the systems [19]. However, many feedback loops are often latent and remote from the triggering events [20,21]. This means the future behaviour of complex systems can change as latent feedback loops become active due to system shocks. With its emphasis on capturing the causal structure (by means of causal loop diagram) and formulating equations (in a quantitative model) for each cause and effect relationship [22–24], system dynamics approach would benefit to study the dynamics and complexity of energy sector.

System dynamics are widely used to manage many dynamically complex issues, such as energy transitions and resource scarcity, environmental and ecological systems, safety and security [25]. Despite considerable research efforts into the energy sector, there is a lack of adoption of this fresh approach in determining the relationship between energy structure, economics and the environment [26]. This study goes beyond filling a gap in the literature; it has a positive contribution represented by constructing a useful model that can be used by elsewhere around the world, which puts it in a position to suggest 'policy interventions', to project into the future of the changing capacity mix and contributions to CO_2 emissions.

The aims of the paper are to (1) formulate a system dynamics model of the energy sector; (2) develop possible development scenarios for the energy sector in the Australian context; and (3) use the system dynamics model to evaluate the scenarios to identify the best plausible one.

2. Research Method

2.1. Formulating a Simulation Model

A system dynamics model of the Australian energy sector is developed based on the causal loop diagram (CLD) designed in Laimon et al. [1]. In this research, CLD was used to describe the dynamics underlying interactions between constituent components of the sector.

The limitation of this powerful qualitative tool is that it cannot be used to quantitatively simulate the dynamics of the energy sector over time. We have developed a stock-flow model (SFM) of the energy sector that enables an in-depth investigation of the dynamics of the Australian energy sector. The key components of the SFM are stocks, flows and auxiliary variables. The stocks represent variable accumulation or depletion over time, stock change is through flow into or out of the stock, and these mechanisms lead to feedback which can cause changes (accelerate or balance out); the feedback comes in two forms: positive (reinforcing feedback) arises when growth of a stock causes change leading to further growth of stock; negative (balancing feedback) arises when decline of a stock causes change leading to further changes to slow down. Stocks change by the flows, while stocks and auxiliary variables control the flows.

Feedback loops in Figure 1a are taken from Laimon et al. [1], which contains two reinforcing loops (R1 and R2), and two balancing loops (B1, B2). Loops R1 and R2 are the inflows; they represent the rate at which new capacity—after a construction delay—comes on-stream. This adds to the total energy production capacity of the Australian energy sector. Loops B1 and B2 are the outflows, reflecting the total decline of both capacities resulted from capacity bankruptcy and capacity retirement. These outflows eliminate unprofitable and retired capacity from the total energy production capacity of the Australian energy sector. Figure 1b is an SFM that translated from CLD Figure 1a. In this example, energy production capacity is the stock; new renewable energy (RE) capacity and new non-RE capacity are the inflows; capacity retirement and capacity bankruptcy are the outflows; construction delay, unprofitable capacity and capacity lifespan are the auxiliary variables.

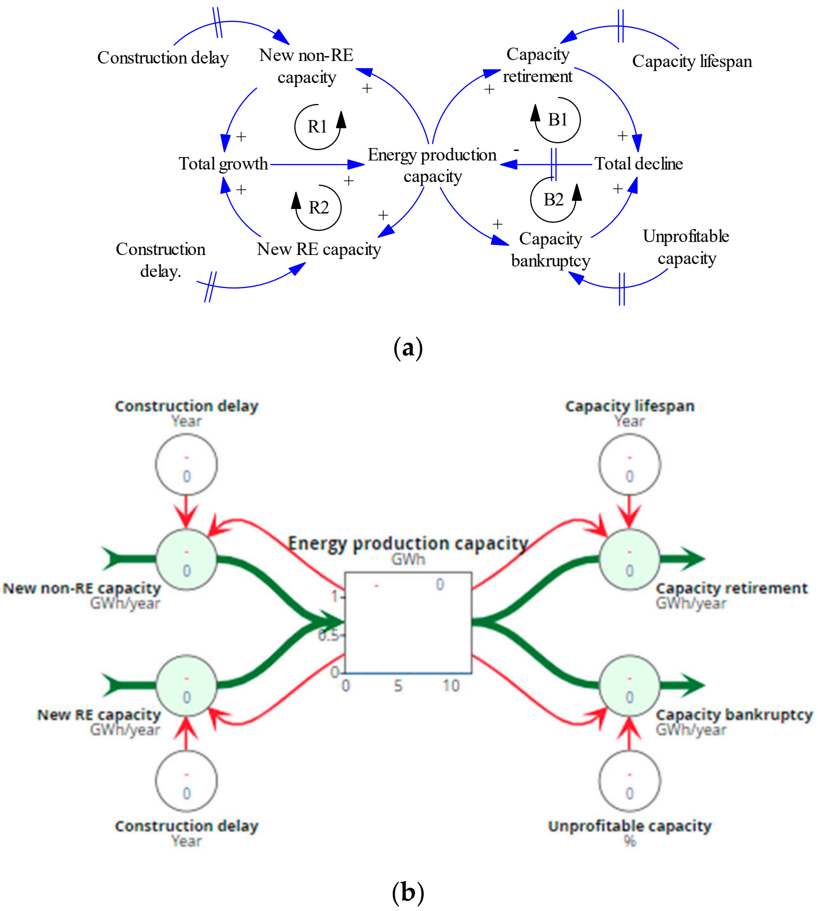


Figure 1. Feedback loops (**a**) and stock-flow model (**b**).

The translation of other feedback loops to SFMs that were contained in Laimon et al. [1] went through the same process. However, not all feedback loops were translated due to data unavailability. Only feedback loops that are highlighted in Figure 2 were converted to our SFM.

Our SFM was run during the period 1990–2050 (a 61-year time period), and the following parameter values are required to run simulations. These values include initial (e.g., initial energy production capacity) and constants (e.g., construction delay). Equations were also used to parametrise variables in the SFM (e.g., capacity retirement = energy production capacity/capacity lifespan). Furthermore, what if functions were used (e.g., if "surplus or shortfall" > 0 then "energy production capacity" * (1 -"surplus or shortfall"/100) else "energy production capacity").

The different forms of energy were put into the same unit: gigawatt-hour (GWh), in which one gigawatt is one billion watts. It is a unit that represents the energy used or the energy production capacity, and we used it to express all energy resources. This is used by many sources and it is the scientific way to compare and summarize energies [27]. In addition, Australian Energy Update, the Commonwealth of Australia annual report uses the same unit (PJ) for different forms of energy production, consumption and trade. It is important to remember that, after all, fossil fuels run out, GWh will be the dominant energy unit.

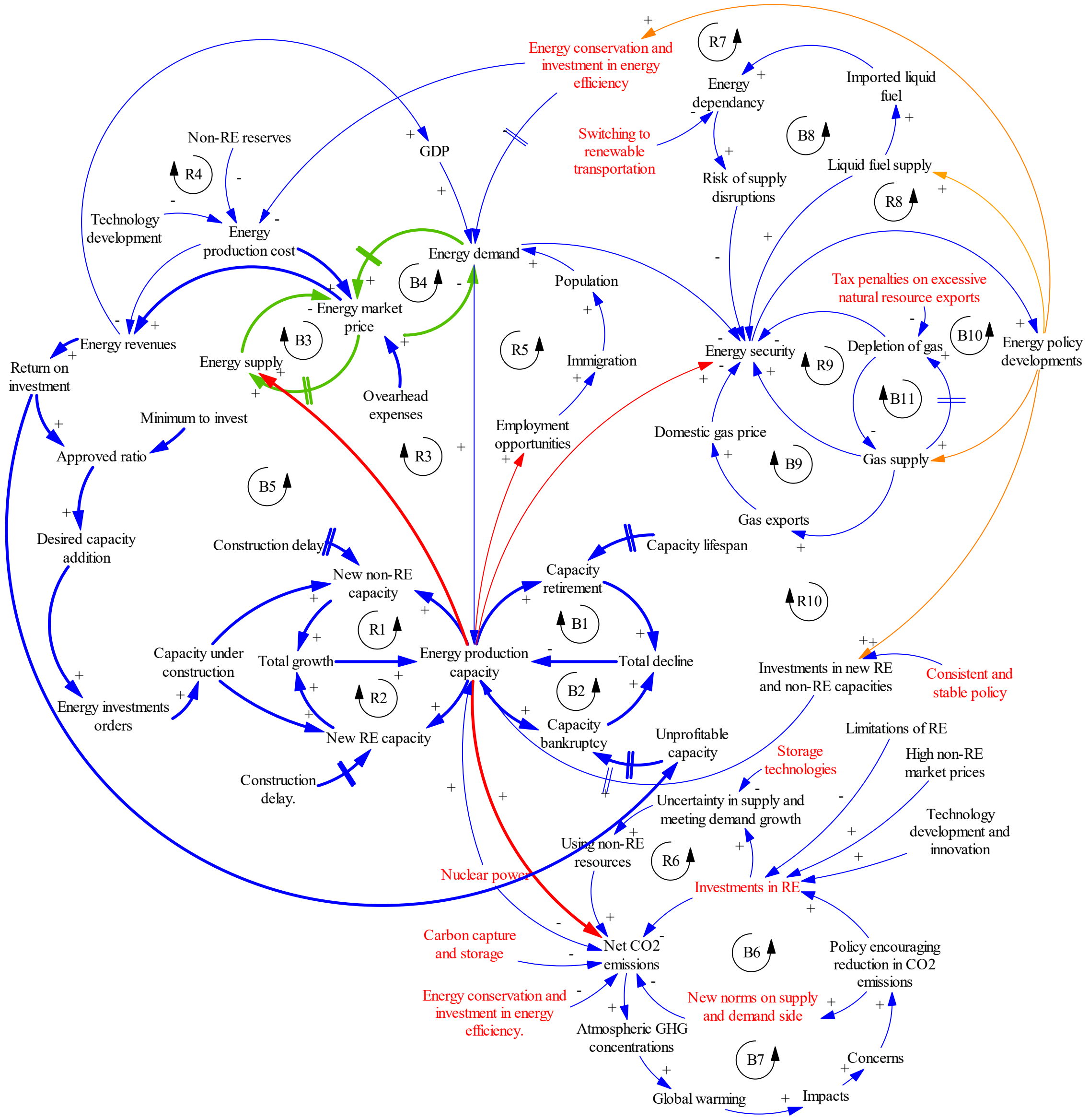


Figure 2. Feedback loops from Laimon et al. [1] causal loop diagram (CLD) replicated in the stock-flow model (indicated in bold). The CLD contains 21 feedback loops including ten reinforcing loops (R1 to R10) and eleven balancing loops (B1 to B11). This CLD highlights the main components of the energy sector linked to Australia's energy policy including energy resources (loops R1 and R2); energy production, supply and demand (loops R3, B3 and B4); energy economics (loops B5 and R4); energy emissions and energy emissions policies (loops R6, B6 and B7); and energy policy developments (loops R7, B8, R8, B9, R9, B10, R10 and B11). Parameters in red are missing or poorly performing in the Australian context.

In this study, we divide energy resources into dispatchable resources (continuous resources) (coal, oil, gas, hydropower, biopower) and non-dispatchable resources (discontinuous resources) (wind and solar). The models for dispatchable and non-dispatchable resources are almost similar, as resource extraction must be ordered, built and installed, which introduces a construction delay. The main differences are that non-dispatchable resources need backup power to tackle the inherent intermittency problem, therefore a backup power parameter is added to the model. On the other hand, some dispatchable resources (e.g., coal, oil and gas) are finite, and thus their reserves decline with time. So, the model includes a sub-model for reserves. In addition, there is a sub-model for CO_2 emissions.

Delimitations

In our modelling, we make the following delimitations:

- Nuclear power is excluded because it is not included in total Australian energy production. It is only produced for export and it seems unlikely to be used to generate power in the near future due to public opposition and high capital cost.
- Oil is excluded as Australia's oil production already reached its peak in 2000, and reserves are declining with time [28]. In addition, most of Australia's oil production is exported because the characteristics of Australian oil are not suited to Australia's refineries [29]. However, CO_2 emissions resulting from imported and exported oil are considered in the model.
- LPG is excluded as it depends on oil production, which is already excluded, and on natural gas production, which is already included.
- Solar hot water is excluded from the total supply of solar power due to slow growth and small capacities. Strong growth has been demonstrated for photovoltaic cells, which are included in the model.
- Biogas and biofuels are excluded from the total supply of biopower due to slow growth and small capacities. Strong growth and big amounts are only available for wood, wood waste and bagasse, which are included in the model. Although biomass releases CO_2 emissions resulting from burning, it is excluded from the CO_2 emissions model, as they are carbon-neutral energy resources. In other words, they captured already a nearly equivalent amount of CO_2 through photosynthesis during their lifecycle.
- Geothermal is excluded as there has been no growth since 2004 with very small generated energy (0.5 GWh) since that time.
- Due to the data availability and small capacities of wind and solar power, historical data started from 2005, 2010 for wind and solar, respectively.

2.2. Model Validating/Testing

The validating of system dynamics models commonly involves structural and behavioural tests. Structural tests assess whether the structure of the model represents the real system. Behavioural tests assess whether the model provides a reasonable output behaviour [30].

In relation to structural tests, the following tests have been applied: dependency and unit consistency test, feedback loop test, laws of conservation and accumulation test, and negative stock test. Dependency and check unit consistency was performed using the "dependency tracking" feature in the software used (Sysdea) [31] to check the relationship between parameters and thus track their units. The feedback loop test was used to check the behaviour of feedback loops, as reinforcing loops should follow reinforcing behaviour and balancing loops should follow balancing behaviour. The stock and flow test implies that the value of the stock must equal the sum of inflows minus the sum of outflows. The negative stock test implies that the stock can go to zero, but cannot go below zero.

In regard to the behavioural tests, the following points are important: the model should include a number of historical time-periods. The current study used a historical time series consisting of 28 years from 1990–2017 for most resources. The simulated values calculated by the model (blue line) should match these real-world values (red line). This matching can be given a value from 0 (perfect predictions) to 1 (worst predictions) called the discrepancy coefficient. Values between 0.4–0.7 indicate good to average models [32]. This test has been used for energy production capacity for every resource, total energy consumption, total energy production and CO_2 emissions to compare modelled with historical trends between 1990 and 2017 for most resources and between 2007 and 2017 for CO_2 emissions due to data availability.

Extreme conditions tests were used to assess the robustness of the SFM under different extreme conditions. For example, (1) the gross demand growth rate was set to (0%, 0%) (no growth) for coal and wind respectively, (2) base case scenario with gross demand growth rate was set to (0, 3.25%) and

(3) gross demand growth rate was set to (10.3%, 52.4%) (maximum), to determine their influence on energy production capacity, capacity under construction, wholesale price, total supply cost, capital employed, capex (capital expenditure) and reserves depletion. In addition, we conducted three extreme condition tests for total CO_2 emissions for black coal, brown coal, gas and oil. The test scenarios were as follows: (1) gross demand growth rate set to 0% (no growth) for black coal, brown coal, gas and oil, (2) gross demand growth rate set to (0%, −8%, 22.7%, 2%) (current trend) for black coal, brown coal, gas and oil, respectively, (3) gross demand growth rate set to (10.3%, 13.8%, 27.3%, 7.5%) (maximum) for black coal, brown coal, gas and oil, respectively.

2.3. Policy Design and Evaluation

Three possible scenarios for energy development in Australia were identified. These scenarios were (1) a no-growth scenario, (2) a base case scenario and (3) a likely to happen scenario as described in Table 1. These scenarios were identified based on the results of a sensitivity analysis. The sensitivity analysis was done by adjusting model parameters by ± 20% to identify the most influential parameters in energy production capacity. The most influential parameter was the gross demand growth rate parameter.

Table 1. Energy sector development scenarios.

Model Parameters	Scenario 1 (No Growth)	Scenario 2 (Base Case)	Scenario 3 (Likely Happen)
Black coal demand growth rate	0%	0%	3.9%
Brown coal demand growth rate	0%	−8%	−0.02%
Gas demand growth rate	0%	22.7%	9.4%
Wind power demand growth rate	0%	3.25%	16.9%
Solar demand growth rate	0%	18%	59.2%
Hydropower demand growth rate	0%	6.3%	3.4%
Bio demand growth rate	0%	4.71%	0.65%

3. Results

3.1. The Simulation Model

The structure of the system dynamics model consists of two linked main models: energy resources extraction pipeline model (Figures 3 and 4), and CO_2 emissions model (Figure 5). Energy resources extraction pipeline model is almost similar in all energy resources, but a stock of reserves is added to fossil fuel resources, thus representing energy reserves and extraction, and backup power cost is added to non-dispatchable resources (wind and solar). To evaluate the above scenarios, we used the model to produce behaviour over time from 1990 to 2050 and from 2007 to 2050 for key performance indicators, including energy supply/demand and CO_2 emissions. A summary of the parameters, equations and functions used for each variable in the model is provided in Appendix A.

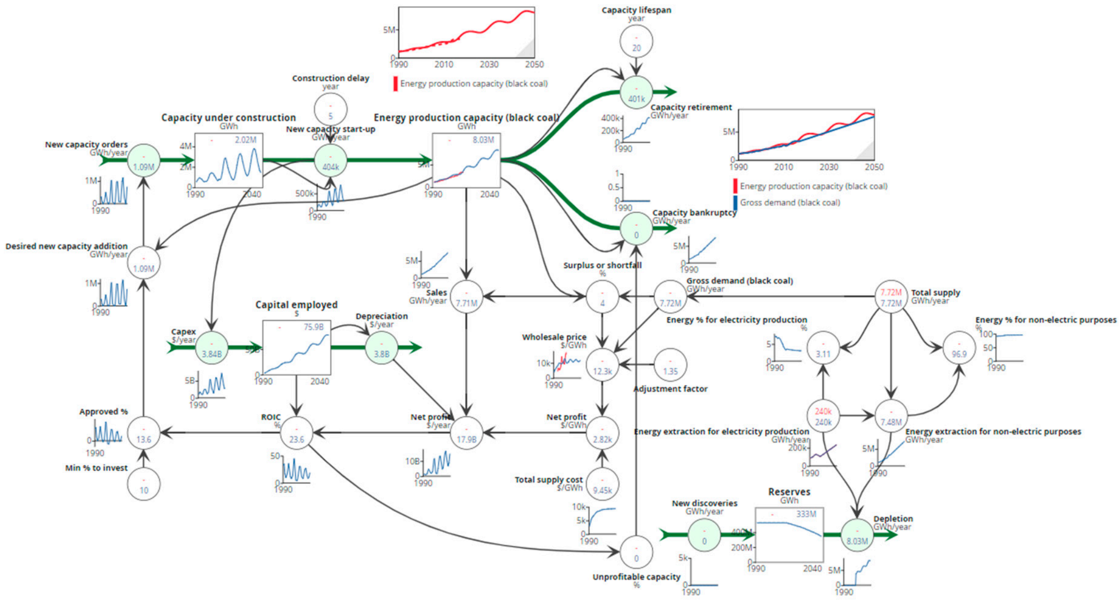


Figure 3. Energy resources extraction pipeline model for dispatchable resources.

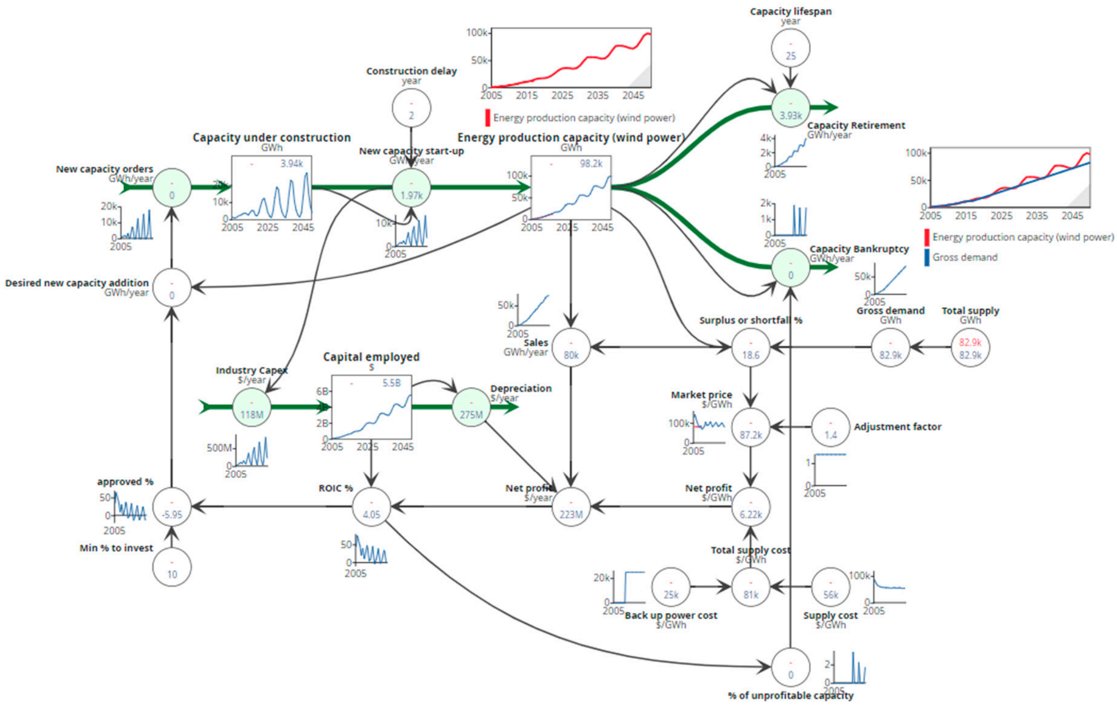


Figure 4. Energy resources extraction pipeline model for non-dispatchable resources.

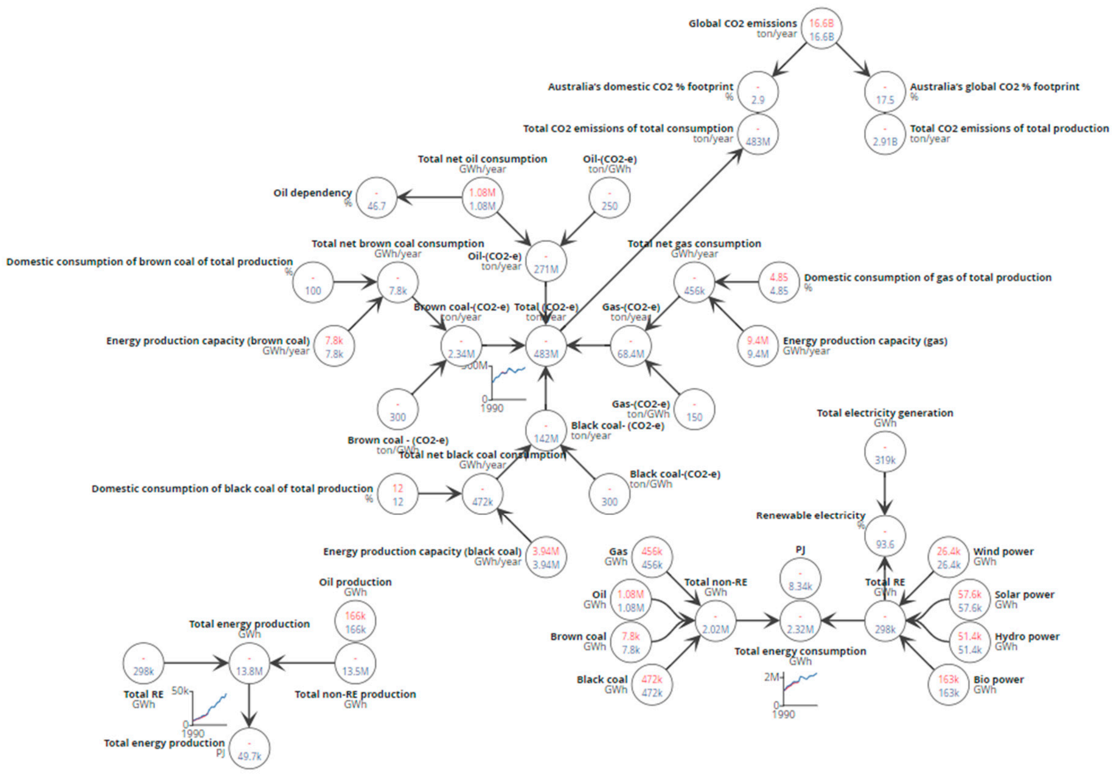


Figure 5. CO_2 emissions model.

3.1.1. Energy Resources Extraction Pipeline Model (Dispatchable Resources)

The representation of the energy resources extraction pipeline has four stocks and eight flows, as shown in Figure 3 (black coal model). The four stocks are (1) reserves stock, (2) capital employed stock, (3) capacity under construction stock and (4) energy production capacity stock. The eight flows are (1) new discoveries inflow, (2) depletion outflow, (3) capex inflow, (4) depreciation outflow, (5) new capacity order inflow, (6) new capacity start-up inflow and outflow, (7) capacity retirement outflow and (8) capacity bankruptcy outflow. Reserves are the proved reserves which are economically feasible for extraction. The initial value of reserves is the current reserve of the resource of the country. Capital employed is the current financial value of the capacity and this depreciates over many years. The initial value of capital employed was set to be in line with the cost of the initial capacity. Capacity under construction is the quantity of capacity that is currently under construction (GWh/year) that comes on-stream after some construction time. The initial value of capital under construction results from model calibration. Energy production capacity (GWh/year) is the quantity of capacity that is currently operating (GWh/year). The initial value of energy production capacity results from the historical data (real data).

Capex refers to capex costs AU$ per GWh/year of capacity and was set to balance the average historical price of the resource. New capacity order is the rate at which companies start building new capacity (GWh/year). This reflects their current profitability, with some delay for building confidence for future profitability. When confidence in future profitability is high, new capacity is ordered, and the higher confidence becomes, the more new capacity is started. New capacity start-up is the rate at which new capacity—whose construction was started some time ago—comes on-stream (GWh/year). This immediately adds to the total operating capacity. Capacity retirement is linked to the lifespan of the project. Capacity bankruptcy is the rate at which companies close capacity that is already operating (GWh/year). This reflects the profitability the capacity is currently achieving. The lower this profitability, the faster companies close capacity down. All other dispatchable resources (e.g., gas) have experienced the same model, but for dispatchable and renewable resources (hydro, bioenergy), the reserves sub-model is not considered as they are renewable resources.

There are many variables in the model. For example, (1) gross demand, (2) surplus or shortfall, (3) wholesale price, (4) adjustment factor and (5) total supply cost. Gross demand is based on the desired resource production, which we have assumed to equal historical production. Surplus or shortfall is the percentage by which capacity exceeds market demand. The higher this surplus, the lower prices fall. A negative value indicates a shortage, leading to high prices. Wholesale price is based on the total supply cost and on the energy demand/production ratio. The adjustment factor is the overhead expenses factor; its value ranges from 1.2 to 1.4 depending on the energy resource, which is an important factor in matching supply with demand. Total supply cost includes production costs (variable and fixed costs).

3.1.2. Energy Resources Extraction Pipeline Model (Non-Dispatchable Resources)

As mentioned previously, the model for dispatchable and non-dispatchable resources are almost similar. For non-dispatchable resources (wind, sun), backup power cost is considered as they are discontinuous resources and the reserves sub-model is excluded as they are renewable resources, as shown in Figure 4 (wind), for example. The backup power value is AU$25,000/GWh, which is in line with the additional cost of balancing RE supply/demand (AU$25/MWh) that is used in Blakers et al. [33]. Solar power has experienced the same model.

3.1.3. CO_2 Emissions Model

The CO_2 emissions model is linked with every energy production capacity resource after achieving supply–demand balance. It represents the consequences of energy production, both domestic and exported, as shown in Figure 5. In addition, many variables such as total energy production, total energy consumption are represented. Variables are connected together by the black arrows; however, we can delete arrows while keeping the connection between variables. This feature is useful to ease congestion of arrows.

3.2. Model Testing and Validation

3.2.1. Structural Tests

All feedback loops displayed their expected behaviour. All stocks passed laws of conservation and the accumulation test and negative stock test, as illustrated in Figures 3–5, for example.

3.2.2. Behavioural Tests

The behavioural tests we applied were comparisons of simulated values with actual values (historical) and extreme conditions tests. The model was able to generate behaviour patterns similar to actual behaviour with discrepancy coefficients below 0.4 for most parameters, as shown in Figure 6.

The extreme condition test results (Figures 7–9) show that the pattern of modelled behaviour did not dramatically change. with energy production capacity, wholesale price, capital employed, capex, reserve depletion and CO_2 emissions. This reflects the robustness of the model behaviour and shows that it follows limits to growth.

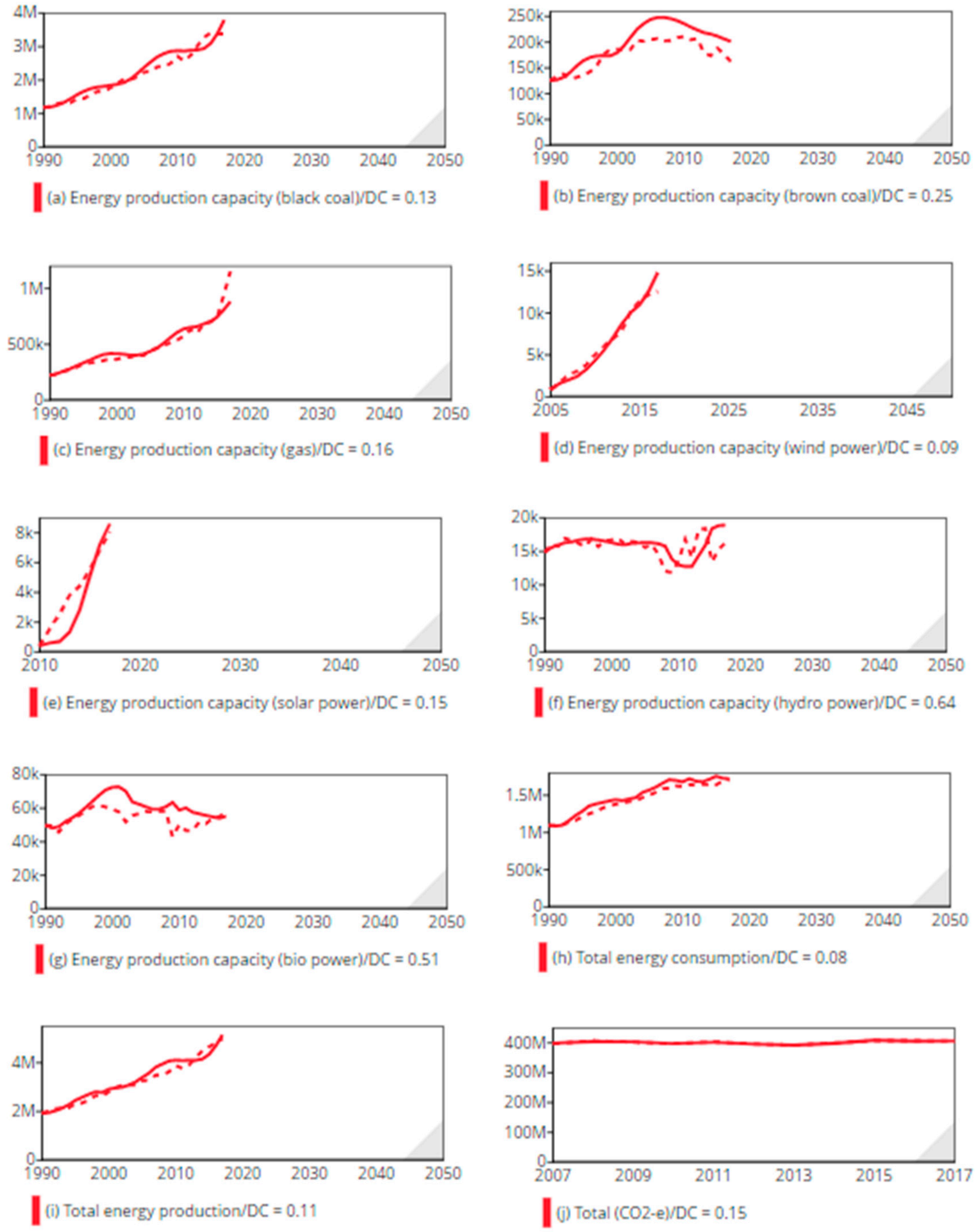


Figure 6. Comparison of real historical trends (dotted lines) and simulated trends (solid lines) for (**a**) energy production capacity of black coal, (**b**) energy production capacity of brown coal, (**c**) energy production capacity of gas, (**d**) energy production capacity of wind power, (**e**) energy production capacity of solar power, (**f**) energy production capacity of hydropower, (**g**) energy production capacity of biopower, (**h**) total energy consumption, (**i**) total energy production and (**j**) total (CO_2-e) (ton). Production and consumption in GWh. CO_2 emissions in tons.

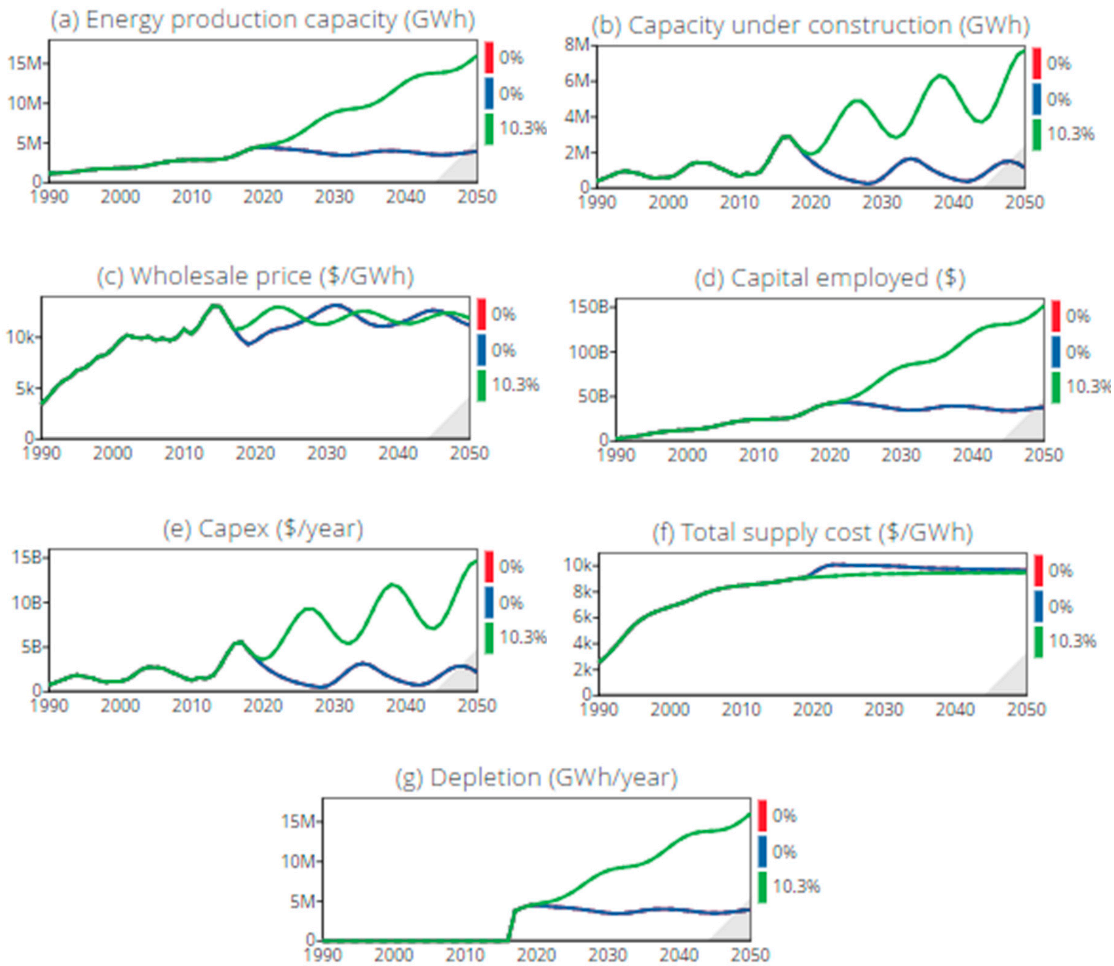


Figure 7. Extreme condition test results for black coal for (**a**) production capacity, (**b**) capacity under construction, (**c**) wholesale price, (**d**) capital employed, (**e**) capex, (**f**) total supply cost and (**g**) reserves depletion. The coloured lines on each graph represents (1) gross demand growth rate set to 0% (no growth), (2) base case scenario with gross demand growth rate set to 0% (current trend) per year for 2017 and (3) gross demand growth rate set to 10.3% (maximum).

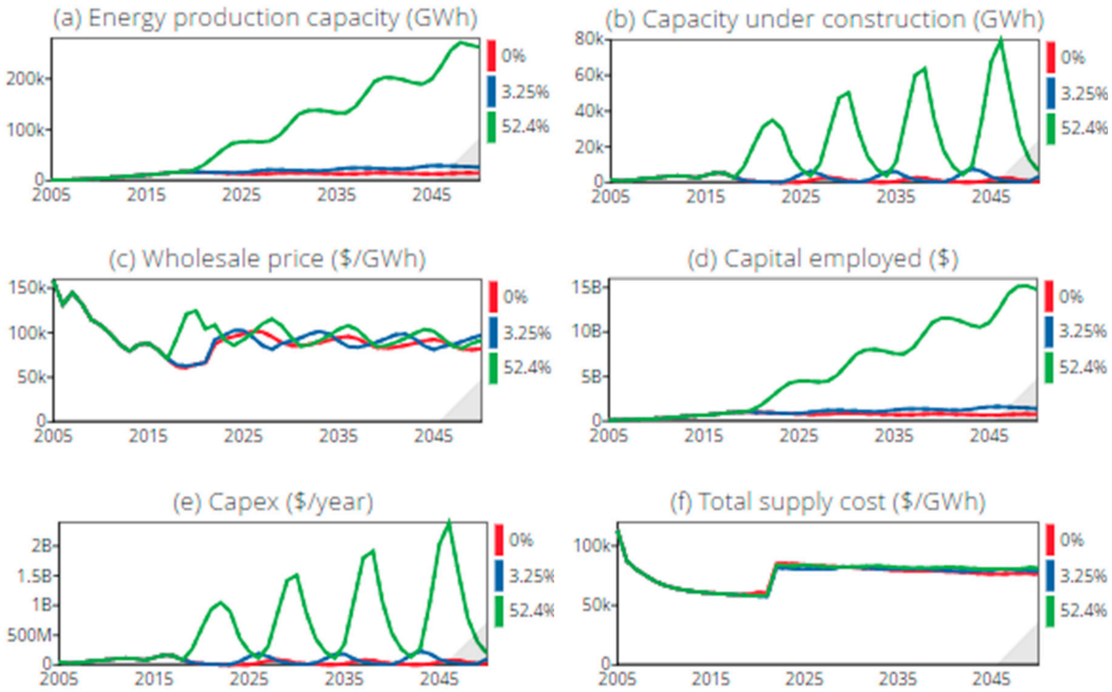


Figure 8. Extreme condition test results for wind for (**a**) production capacity, (**b**) capacity under construction, (**c**) wholesale price, (**d**) capital employed, (**e**) capex and (**f**) total supply. The coloured lines on each graph represents (1) gross demand growth rate set to 0% (no growth), (2) base case scenario with gross demand growth rate set to 3.25% (current trend) per year for 2017, (3) gross demand growth rate set to 52.4% (maximum).

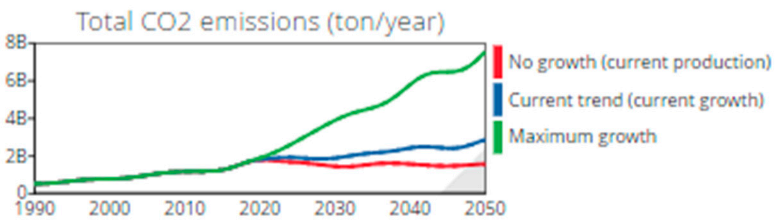
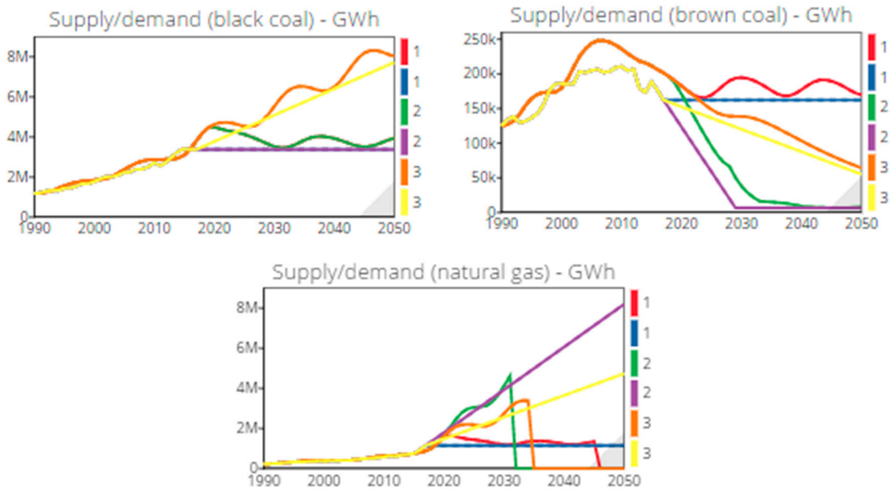


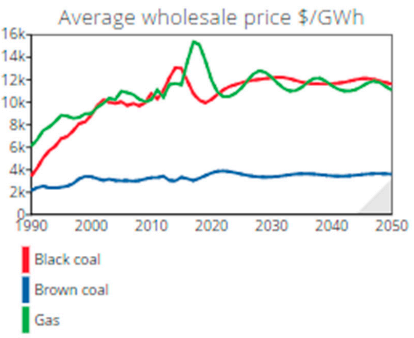
Figure 9. Extreme condition test results for total CO_2 emissions. The coloured lines on the graph represents (1) gross demand growth rate set to 0% (no growth) for black coal, brown coal, gas and oil, (2) gross growth rate set to (0%, −8%, 22.7%, 2%) (current trend) for black coal, brown coal, gas and oil respectively, (3) gross demand growth rate set to (10.3%, 13.8%, 27.3%, 7.5%) (maximum) for black coal, brown coal, gas and oil respectively.

3.3. Policy Design and Evaluation

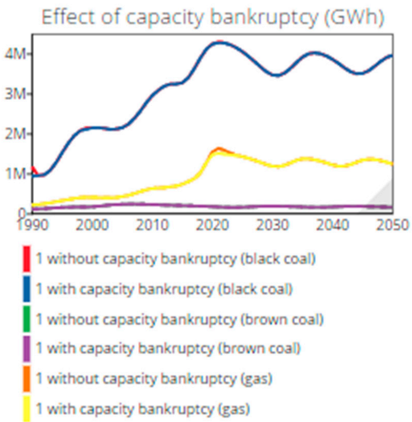
The possible scenarios are as follows: (1) a no-growth scenario that represents current production with no further growth, (2) a base case scenario that represents the current trend (current growth), and no dramatic changes assumed and (3) a likely to happen scenario based on average growth over the last ten years, as described in Table 1. More scenarios could make the analysis unclear. The results of all scenarios are summarised in Figure 10, Figure 11 and Table 2.



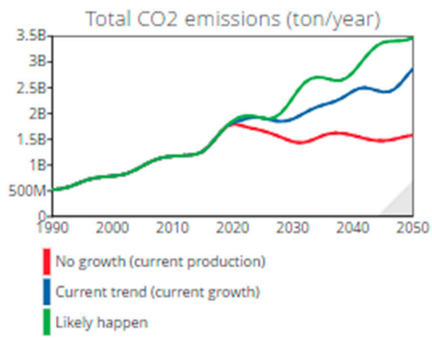
(a)



(b)



(c)



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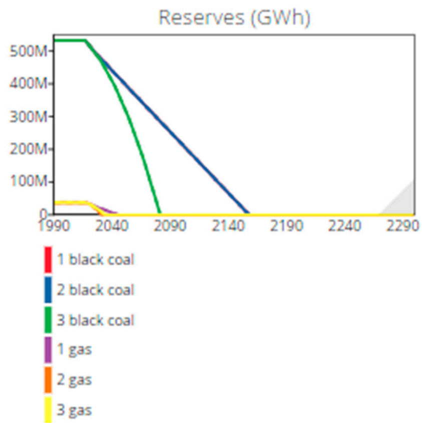
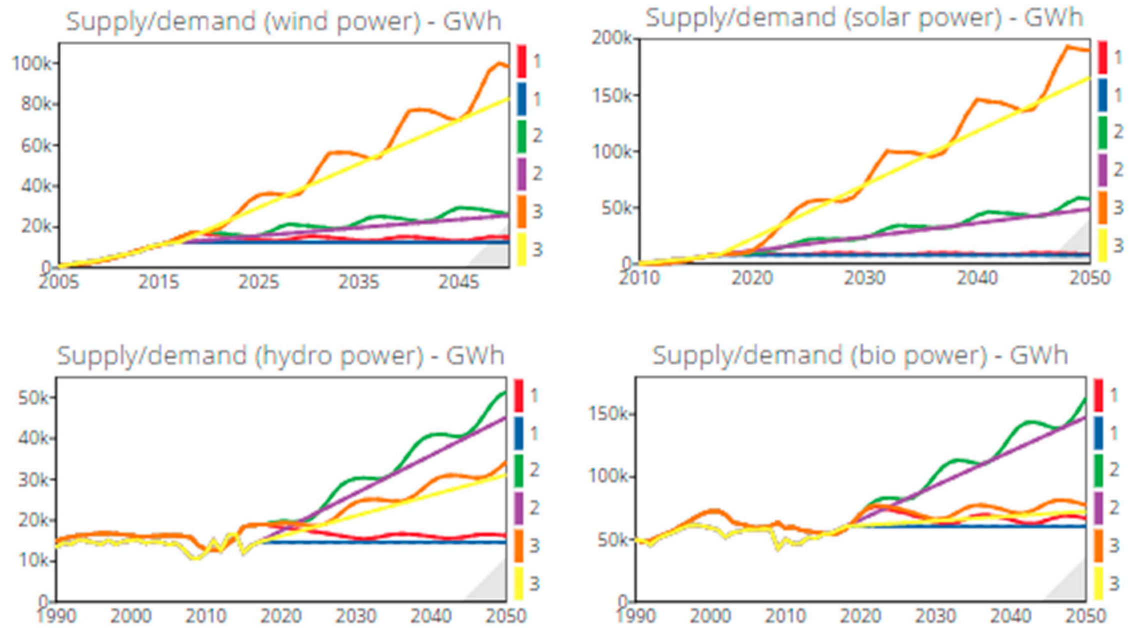
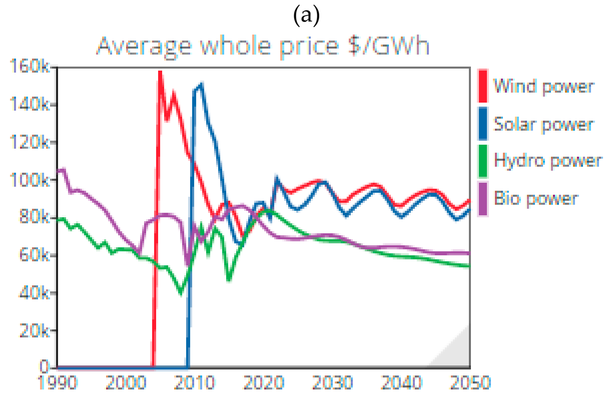


(e)

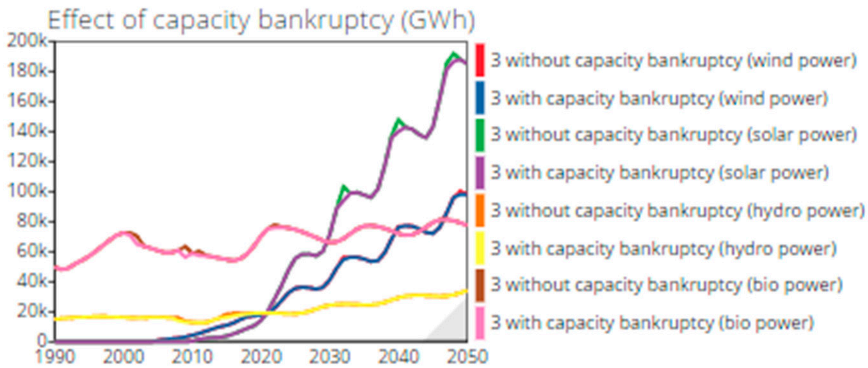
Figure 10. Behaviour over time produced by each development scenario until 2050 for (**a**) energy supply/demand, (**b**) average wholesale price, (**c**) bankruptcy, (**d**) CO_2 emissions and (**e**) reserves. The numbers on each colour represent (1) no growth scenario, (2) base case/current scenario and (3) likely to happen scenario, as described in Table 1.



(a)



(**b**)



(**c**)

Figure 11. Behaviour over time produced by each development scenario until 2050 for (**a**) energy supply/demand, (**b**) average wholesale price and (**c**) bankruptcy. The numbers on each colour represent (1) no growth scenario, (2) base case/current scenario and (3) likely to happen scenario, as described in Table 1.

Table 2. Comparison of all energy sector development scenarios relative to the base case scenario.

Scenarios	Oil Dependency		Australia's Global CO_2 Footprint	Australia's Domestic CO_2 Footprint	Reserves (Black Coal/Gas)	Renewable Electricity	
Year	2030	2050	2030	2030		2030	2050
Scenario 1	34%	28%	9%	2.5%	2158/2046	37%	33.5%
Scenario 2	43%	47%	12%	2.5%	2158/2032	62.5%	93.5%
Scenario 3	40%	41%	14%	2.5%	2082/2035	72%	125%

4. Discussion

Our results indicate that the current trend (scenario 2) of the Australian energy sector is likely to lead to high CO_2 emissions, high energy dependency and unsustainable fossil fuel extraction. This destination is in line with an unsustainable future for the energy sector.

With the current trend and under the scenario of the Intergovernmental Panel on Climate Change (IPCC) 1.5 °C (a 45% reduction by 2030 from 2010 CO_2 emission levels), Australia's global CO_2 emissions footprint will increase to unprecedented levels reaching 12% by 2030 (9.5% for exports and 2.5% for domestic). This result is compatible with a recent report from Climate Analytics [34]. Australia's oil dependency with the current trend will account for 43% and 47% of total consumption by 2030 and 2050; oil dependency accounted for the largest share of energy consumption in 2017 (38%). By 2032, with excessive fossil fuel extraction, coal will be the only fossil fuel resource that Australia totally relies on (Figure 10e). Australia is now the world's largest gas exporter [35]. Although brown coal can last for a long time, it is not an option for Australia, as brown coal is not as efficient as black coal, it has less heat content and more moisture than black coal, so it produces 30% more emissions than black coal, and it is not fit for export as it is too heavy, unstable and low in heat value. This explains why it is only used domestically with a continuous decline in annual growth: −8% for the current trend and −0.02% for the average last 10 years (Figure 10a).

In regard to RE, the current trend is heading to 298k GWh by 2050. Although it will account for 94% of expected electricity generation (319k) as we expect by 2050, supply should exceed demand to cover the peak demand, the likely to happen scenario (3) is ideal for this situation. In addition, the development of dispatchable wind and solar systems is still insufficient. Moreover, a stable RE policy is missing. We found that using backup power in RE (wind and sun), which may come from mass storage batteries (e.g., off-river pumped hydro battery, mega battery) or other dispatchable RE resources (e.g., biomass, hydropower) will enhance flexibility and solve uncertainty in the future supply of RE. With affordable prices and clean energy, RE can compete with fossil fuel; for example, the average whole price for electricity generated from gas in Australia was $100/MWh [36]. If wind and solar are available on-demand with a backup power the wholesale price will be around $93/MWh by 2030 (Figure 11b). Other dispatchable RE resources (hydropower and biopower) will be $68 and $71/MWh respectively. These prices are for primary electricity generated by RE and are different from fossil fuel primary energy prices in Figure 10b. We found the effect of bankruptcy is not considerable in black coal and gas (Figures 10c and 11c). Scenarios 1 and 3 have been taken as examples. The largest bankruptcy was for brown coal from 2017 to 2026 and from 2027 to 2032 for the current trend and this may explain the recent closures of several brown coal plants (e.g., Hazelwood in Victoria, and Northern in South Australia).

The expansion of investment in coal and gas production is a large risk, as keeping global warming less than 2 °C requires a sharp decline in international demand for fossil fuels under the Paris Agreement [34,37,38]. Because of that, we suggest no more growth in fossil fuel production.

5. Conclusions

Developing the energy sector requires a comprehensive understanding of its components and their interactions that impact system behaviour over time, and how intervention scenarios change system behaviour. This is the domain of system dynamics. We used system dynamics for the energy sector development and to examine trends through different possible scenarios. We established a balance of supply–demand, and examined the implications on fossil fuel reserves, energy dependency, energy prices, energy bankruptcy and CO_2 emissions. For a sustainable energy future, establishing the balance of supply–demand, conservation of resources and reducing energy dependency and emissions is crucial. Furthermore, a supply–demand balance ensures sustained economic growth and fulfils energy needs; reducing emissions implies reduced dependency on fossil fuels. We found that the current trend of the Australian energy sector is in line with unsustainable future and the growth is not being controlled. Our modelling shows that limits to growth are approaching due to excessive fossil fuel extraction, high emissions and high energy dependency. Therefore, the current scenario could be one of the worst scenarios for the Australian energy sector. On the other hand, reducing dependency on fossil fuel and accelerating the transition to full renewable systems could be the best scenario. That implies improving energy efficiency, switching to renewable transportation, switching to renewable electricity, electrification of sectors that do not run on electricity by RE. However, more research is required to examine the potential impact of such improvements on the energy sector, which is the topic of the next paper.

Author Contributions: Conceptualization, M.L.; methodology, M.L. and T.M.; software, M.L.; validation, M.L. and T.M.; formal analysis, M.L.; investigation, M.L.; resources, M.L.; data curation, M.L.; writing—original draft preparation, M.L.; writing—review and editing, M.L., T.M., S.G. and T.Y.; visualization, M.L. and T.Y.; supervision T.M., S.G. and T.Y.; project administration, S.G. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Parameters used for stocks (the parameter value column represents initial values).

Variable Name	Units	Parameter Value	References
Reserves (black coal)	GWh	532,415,833.75	[39]
Capital employed (black coal)	$	3,000,000,000	
Capacity under construction (black coal)	GWh	400,000	
Energy production capacity (black coal)	GWh	1,176,111.11	
Reserves (brown coal)	GWh	209,681,944.61	[39]
Capital employed (brown coal)	$	200,000,000	
Capacity under construction (brown coal)	GWh	40,000	
Energy production capacity (brown coal)	GWh	125,194.44	
Reserves (gas)	GWh	37,420,833.36	[39]
Capital employed (gas)	$	1,000,000,000	
Capacity under construction (gas)	GWh	80,000	
Energy production capacity (gas)	GWh	221,472.22	
Capital employed (wind power)	$	100,000,000	
Capacity under construction (wind power)	GWh	500	
Energy production capacity (wind power)	GWh	885	
Capital employed (solar power)	$	50,000,000	
Capacity under construction (solar power)	GWh	400	
Energy production capacity (solar power)	GWh	425	
Capital employed (hydropower)	$	1,000,000,000	
Capacity under construction (hydropower)	GWh	3,000	
Energy production capacity (hydropower)	GWh	14,880	
Capital employed (biopower)	$	4,000,000,000	
Capacity under construction (biopower)	GWh	1000	
Energy production capacity (biopower)	GWh	49,833.32	

Table A2. Parameters used for flows.

Variable Name	Units	Parameter Value
New discoveries	GWh/year	0
Depletion	GWh/year	(pulse ("Energy extraction for electricity production"+"Energy extraction for non-electric purposes",2017,1)) * ("Energy production capacity"/"Gross demand")
Capex	$/year	"Capex costs" * "New capacity start-up"
Depreciation	$/year	"Capital employed"/20
New capacity orders	GWh/year	"Desired new capacity addition"
New capacity start-up	GWh/year	"Capacity under construction"/"Construction delay"
Capacity retirement	GWh/year	"Energy production capacity"/"Capacity lifespan"
Capacity bankruptcy	GWh/year	"Energy production capacity" * "Unprofitable capacity "/100

Table A3. Parameters used for auxiliary variables.

Variable Name	Units	Parameter Value
Capacity lifespan	year	20 (coal and gas), 25 (wind and solar power), 50 (hydropower), 30 (biopower)
Construction delay	year	5 (coal), 3 (gas), 2 (wind and solar power), 3 (hydro and biopower)
Desired new capacity addition	GWh/year	max (0,"Energy production capacity" * "Approved %"/100)
Approved %	%	"ROIC" - "Min% to invest"
Min % to invest	%	10
ROIC	%	("Net profit"/"Capital employed") * 100
Net profit	$/year	("Sales" * "Net profit") − "Depreciation"
Sales	GWh/year	if "Surplus or shortfall" > 0 then "Energy production capacity"*(1-"Surplus or shortfall"/100) else "Energy production capacity"
Net profit	$/GWh	"Wholesale price" - "Total supply cost"
Total supply cost	$/GWh	"Capital employed"/"Energy production capacity"
Wholesale price	$/GWh	"Adjustment factor" * "Total supply cost" * ("Gross demand"/"Energy production capacity") + (("Surplus or shortfall"/10)^3)
Adjustment factor		1.35 (coal and gas), 1.4 (wind power), 1.25 (solar power), 1.3 (hydro and biopower)
Surplus or shortfall	%	("Energy production capacity"/"Gross demand"-1) * 100
Gross demand	GWh/year	"Total supply"
Energy extraction for non-electric purposes	GWh/year	"Total supply"-"Energy extraction for electricity production"
Energy % for electricity production	%	"Energy extraction for electricity production"/"Total supply" * 100
Energy % for non-electric purposes	%	"Energy extraction for non-electric purposes"/"Total supply"*100
Total (CO_2-e)	ton/year	"Black coal (CO_2-e)" + "Brown coal (CO_2-e)" + "Gas (CO_2-e)" + "Oil (CO_2-e)"

Table A3. *Cont.*

Variable Name	Units	Parameter Value
(CO_2-e)	ton/GWh	300 (coal), 250 (oil), 150 (gas)
(CO_2-e)	ton/year	"Total net consumption" * "(CO_2-e)"
Total net consumption	GWh/year	"Energy production capacity" * "Domestic consumption of total production"/100
Australia's domestic CO_2 % footprint	%	"Total CO_2 emissions of total consumption"/"Global CO_2 emissions" * 100
Australia's global CO_2 % footprint	%	"Total CO_2 emissions of total production"/"Global CO_2 emissions" * 100
Total CO_2 emissions of total production	ton/year	("Energy production capacity (black coal)" * "Black coal-(CO_2-e)") + ("Energy production capacity (brown coal)" * "Brown coal-(CO_2-e)") + ("Total net oil consumption" * "Oil-(CO_2-e)") + ("Energy production capacity (gas)" * "Gas-(CO_2-e)") + ("Oil production"*250)
Oil dependency	%	"Total net oil consumption"/"Total energy consumption" * 100
Total energy production	GWh	"Total non-RE production" + "Total RE"
Total non-RE production	GWh	"Oil production" + "Energy production capacity (black coal)" + "Production Capacity (brown coal)" + "Energy Production Capacity (gas)"
Renewable electricity	%	"Total RE"/"Total electricity generation" * 100
Total energy consumption	GWh	("Total non-RE" + "Total RE")

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THE POTENTIAL IMPACT OF IMPROVING ENERGY EFFICIENCY AND THE FULL TRANSITION TO RENEWABLE ENERGY SYSTEMS ON THE PERFORMANCE OF THE ENERGY SECTOR

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THE POTENTIAL IMPACT OF IMPROVING ENERGY EFFICIENCY AND THE FULL TRANSITION TO RENEWABLE ENERGY SYSTEMS ON THE PERFORMANCE OF THE ENERGY SECTOR

Abstract

The energy sector is large, complex, and dynamic. The development of such a sector requires a comprehensive understanding of its components and their interactions. We have adopted a system dynamics approach to examine the impact on the performance of the energy sector of improving energy efficiency and the full transition to renewable energy systems. Unlike previous studies that use silo approaches that focus on a particular system's components and neglect their interconnected nature, the system dynamics approach gives the opportunity to understand the interactions among system components that affect system behaviour over time, and how intervention scenarios change system behaviour. Although, the Australian energy sector is used as a case study, the model can be used in any country or for the whole world as a unit and for any energy resource. We found that improving only 1% of energy efficiency would result in 101k/331k GWh energy productivity (5% and 14% of total energy consumption) and reduce domestic CO_2 emissions by 15.3/50 Mt CO_2-e (4% and 10% of total domestic emissions) by 2030/2050. Switching to renewable energy for transportation and therefore saving 5% per year of current oil consumption may decrease dependency on oil to half by 2030 and to zero by 2050, and reduction in domestic CO_2 emissions by 74.1/198 Mt CO_2-e (18% and 41% of total domestic emissions). Switching to renewable electricity by 3% annually may lead to 60.8/129 Mt CO_2-e reduction in domestic CO_2 emissions (15% and 27% of total domestic emissions) by 2030/2050. Electrification of other sectors, mainly the manufacturing sector, using renewable energy by 4% annually may lead to 43.3/106 Mt CO_2-e reduction in domestic CO_2 emissions (11% and 22% of total domestic emissions) by 2030/2050. Improving energy efficiency, switching to renewable energy for transportation, switching to renewable electricity, electrification of sectors that do not run on electricity using renewable energy could achieve zero domestic CO_2 emissions by 2050 while energy consumption stay almost stable (0.5%/year). This process may be accelerated by improving energy efficiency by more than 1%.

Keywords: Energy modelling; Energy policy; System dynamics; Energy sector; Energy security; Energy dependency; Energy efficiency; renewable energy systems, CO_2 emissions.

1. Introduction

Growing energy demand, depletion of fossil fuels, threats of pollution from energy emissions and global warming are key challenges that the world faces. Despite the temporary economic benefits of fossil fuels resources, they are finite resources and have polluting effects. Therefore, thinking and acting beyond fossil fuels is inevitable. Full transition to Renewable Energy (RE) systems may give a lasting solution to energy challenges (Creutzig et al. 2014; Sgouridis et al. 2016; Breyer et al. 2017; García-Olivares et al. 2018) as well as improving energy efficiency which has a major role in reducing energy costs, maintaining energy security, reducing emissions, and creating economic growth and jobs (Murray-Leach 2019). Energy efficiency and RE systems are the core elements of energy transition (Gielen et al. 2019). However, it is not easy to examine the impact of RE and energy efficiency separately, as they work together in many cases (e.g. electric vehicles). To simplify this, we have divided the energy sector into three main-areas: transportation, electricity and other sectors, mainly manufacturing. We have only examined the impact of improving energy efficiency in the manufacturing sector, and these improvements may include: using modern technology for production, application of energy management systems (e.g. ISO 50001), and using materials efficiency technology (e.g. recycling). Energy efficiency and full transition to renewable energy systems can address not only the symptoms but also the causes of energy challenges.

The current Australian energy sector is unsustainable and faces many challenges due to excessive fossil fuel extraction, high emissions, high energy dependency, lack of energy efficiency development and unstable policy towards development of the RE sector. With the existing trends for future energy, Australia's global CO_2 emissions footprint will increase to high levels, reaching 12% by 2030 (9.5% for exports and 2.5% for domestic). Oil dependency will account for 43% and 47% of total consumption by 2030 and 2050. Coal will be the only fossil fuel resource available in Australia by 2032 (Laimon et al. 2019a). Australia is the worst among developed countries in terms of energy efficiency and performance indicators (Castro-

Alvarez et al. 2018). These issues are interconnected with the continuing growth of the economy and population, and they add to other challenges such as the uncertainty in energy policy.

The aim of this study is to use a system dynamics approach to examine the influences of improving energy efficiency, switching to full renewable electricity and transportation systems on energy productivity, domestic CO_2 emissions, oil dependency, and energy consumption. We use the case of the Australian energy sector (Laimon et al. 2019b). Unlike previous studies that have used silo approaches that focus on components a particular system and neglect their interconnected nature, a system dynamics approach gives the opportunity to understand both the interactions among system components that impact system behaviour over time, and the way intervention scenarios change system behaviour over time (Kelly et al. 2013).

2. Research method

There are five interrelated steps of a system dynamics approach: problem articulation, formulating dynamic hypotheses, formulating a simulation model, validating/testing, and policy design and evaluation (Sterman 2001). We have already implemented all of these steps on the Australian energy sector in (Laimon et al. 2019b) and (Laimon et al. 2019a). At this stage we extended the above studies to include sub models for the following key parameters: energy efficiency factor, energy productivity, electrification of sectors that do not run on electricity, switching to renewable electricity, and switching to RE transportation, as shown in Fig. 3 in the result section.

3. Results

The model is linked with every energy production capacity resources after achieving supply-demand balance for dispatchable and non dispatchable resources as shown in Fig. 1 and Fig. 2. It represents the consequences of energy production, both domestic and exported, as shown in Fig. 3 and also includes many variables such as total energy production, total energy consumption (percent of total production), electricity generation by RE and non-RE, (CO2-e) reduction due to; switching to RE transportation, switching to RE electricity, and electrification of other sectors, energy productivity, and energy efficiency factor. Energy efficiency factor is an exogenous factor to moderate the rate of consumption growth. It means getting the same output while using less energy. Energy productivity is a measure of energy efficiency.

The different forms of energy are expressed by the same unit (GWh), which is the scientific way to compare and summarize energies (MacKay 2008). Variables are connected together by the black arrows; however arrows can be deleted while keeping the connection between variables. This feature is useful to ease congestion of arrows, thus making the model clearer.

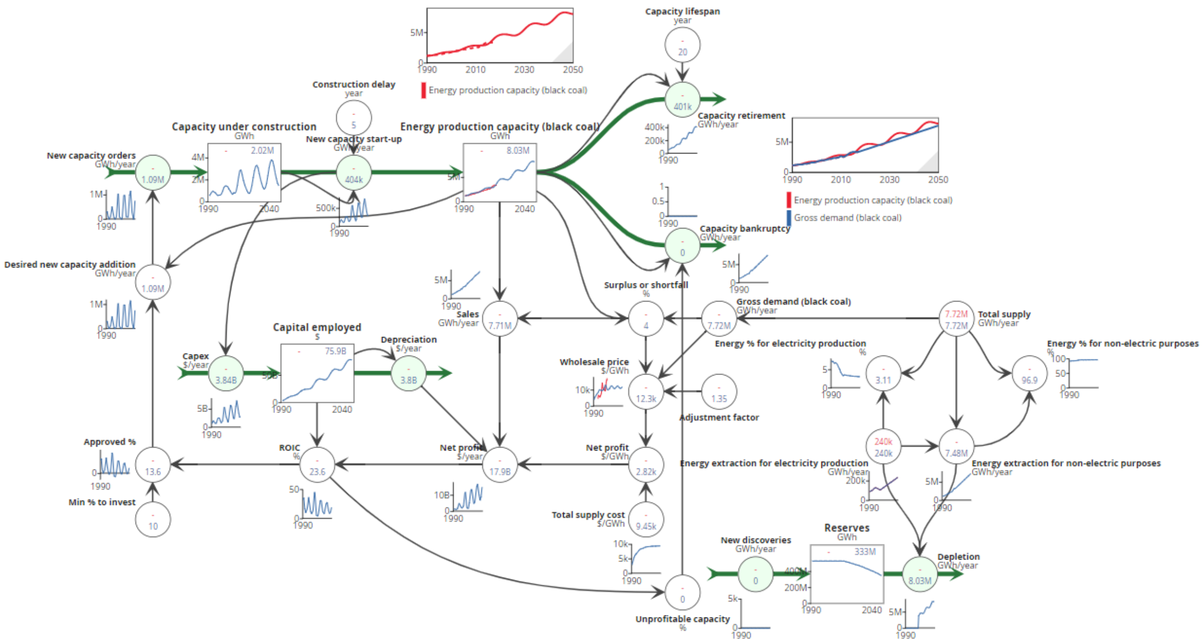

Fig. 1. Energy resources extraction pipeline model for dispatchable resources constructed by Laimon et al. (2019a).

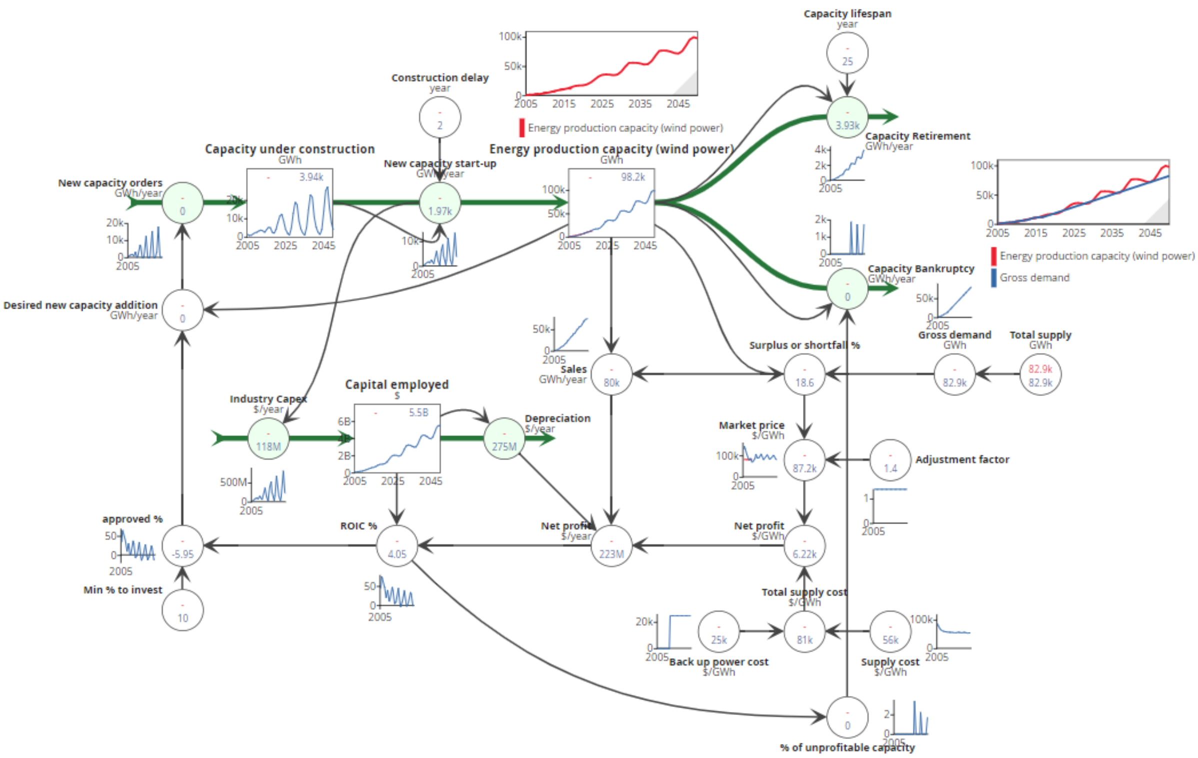

Fig. 2. Energy resources extraction pipeline model for non-dispatchable resources constructed by (Laimon et al. 2019a).

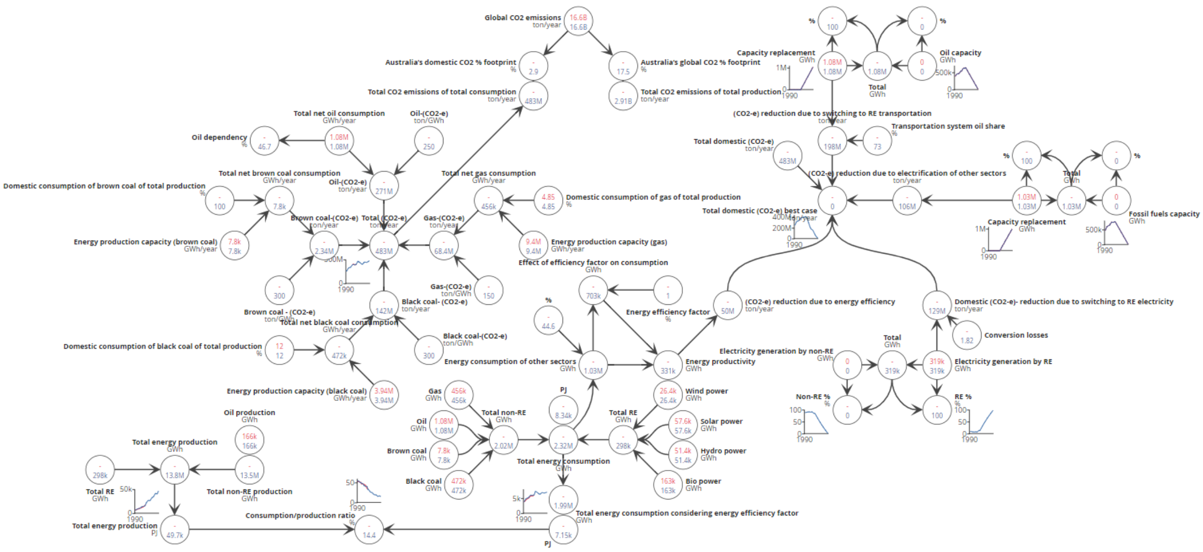

Fig. 3. The study's model.

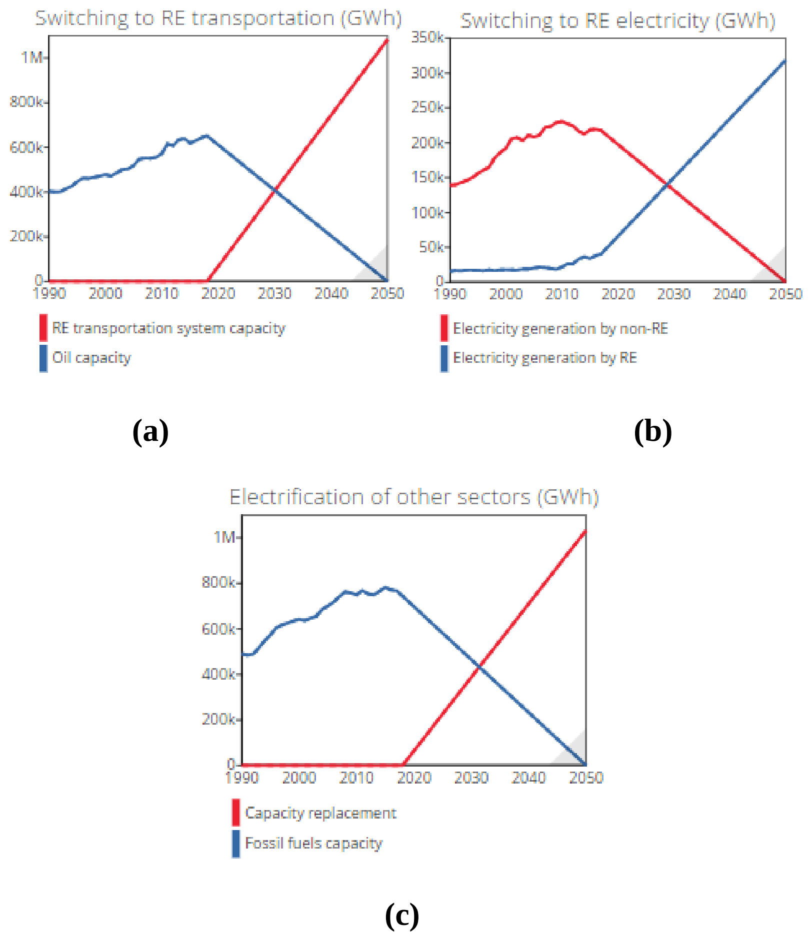

Fig. 4. Behaviour over time for (a) switching to renewable transportation, (b) switching to renewable electricity, and (c) electrification of other sectors.

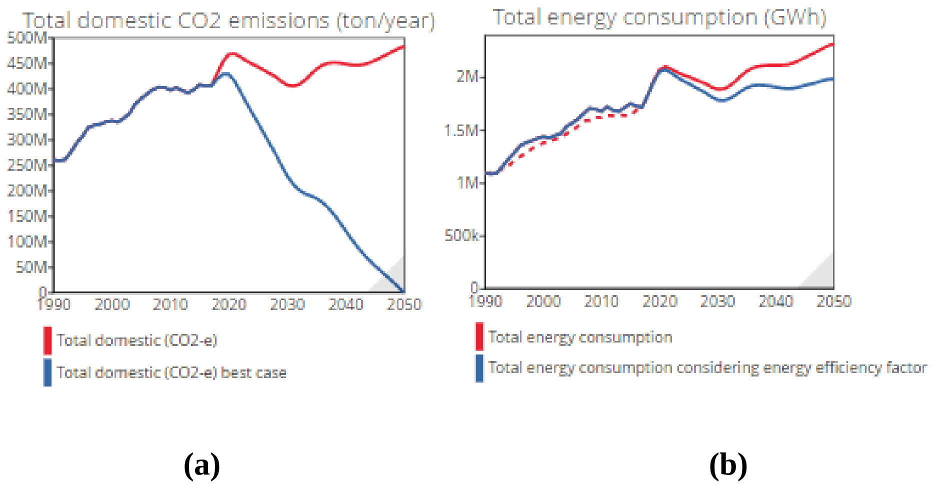

Fig. 5. Behaviour over time for (a) total domestic CO_2 emissions (current scenario and best case), best case implies considering energy efficiency factor and full transition to RE systems, (b) total energy consumption (current scenario and considering energy efficiency factor case). Historical trends (dotted line) and simulated trends (solid line).

4. Discussion

Our results indicate that energy efficiency has an important role in increasing energy productivity and thus in increasing energy security and reducing emissions. Improving energy efficiency by only 1% resulted in 101k/331k GWh energy productivity (5% and 14% of total energy consumption) and reduced domestic CO_2 emissions by 15.3/50 Mt CO_2-e (4% and 10% of total domestic emissions) by 2030 and 2050 respectively. Improving energy efficiency should be the first step to ensure that supply and demand sides are integrated (Murray-Leach 2019). Such improvements can be implemented in transport, building, manufacturing, and appliances.

Despite the rebound effects that are still controversial due to the lack of empirical studies and limited understanding about its effects (Azevedo 2014; Llorca & Jamasb 2017), improving energy efficiency brings benefits such as lowering energy bills, reducing emissions, improving health, welfare, and productivity, and increasing job and economic growth (IEA 2019). We think that the impact of rebound can be reduced by reducing dependency on fossil fuels and accelerating the transition to full RE systems. The bounce effect in this case can be considered as an improvement of well-being.

We found switching to renewable transportation by 5% of current oil consumption may decrease oil dependency to half by 2030 and 0% by 2050 (Fig. 4a), reduction in domestic CO_2 emissions by 74.1/198 Mt CO_2-e (18% and 41% of total domestic emissions) by 2030/2050. While considering that the freight transportation and aviation sectors are not easy to electrify with the current technology, other RE (e.g. hydrogen cells, and biofuels) can play an important role in that transition (García-Olivares et al. 2018), and switching to electric vehicles alone can decrease 80% of oil dependency. Internal combustion vehicles waste around 70% of energy as heat loss and cause environmental deterioration (Arefin et al. 2017).

Switching to renewable electricity by 3% annually may lead to a 60.8/129Mt CO_2-e reduction in domestic CO_2 emissions (15% and 27% of total domestic emissions) based on 399k GWh expected to be generated by RE in 2050. This capacity can cover the expected electricity demand in 2050 (319k GWh) (Fig. 4b), with an increase of 25% to cover peak demand. Considering backup power in RE (wind and sun), which may come from mass storage batteries (e.g. off-river pumped hydro battery, mega battery) or other dispatchable RE sources (e.g. bio mass, hydropower) may solve uncertainty in the future supply of RE. RE is now able to compete with fossil fuels and will replace fossil fuels eventually (Laimon et al. 2019a).

Electrification of other sectors, mainly the manufacturing sector, by 4% annually may lead to 43.3/106 Mt CO_2-e reduction in domestic CO_2 emissions (11% and 22% of total domestic emissions) by 2030/2050. This result is seen after considering energy efficiency improvement by 1% in other sectors (e.g. manufacturing, mining, and construction) other than transport and electricity sectors as they are already considered in the model. The amount of CO_2 emissions reduction resulting from energy efficiency was subtracted from the total CO_2 emissions reduction resulting from electrification of other sectors to prevent duplication. The electricity supply, transport and manufacturing sectors accounted for 73% (27.5%, 27.5%, and 18% respectively) of Australian energy consumption in 2016/17 (DEE 2018). Electrification of all sectors using RE is possible by 2050 (Hansen et al. 2019; Ram et al. 2019).

Improving energy efficiency, switching to renewable transportation, changing to renewable electricity, and electrification of other sectors by RE could achieve zero emissions by 2050 and allow energy consumption to stay almost stable (Fig. 5ab), this process can be accelerated by improving energy efficiency by more than 1%.

5. Conclusion

We used a system dynamics approach to examine the impact of improving energy efficiency, switching to full renewable electricity and transportation systems on energy productivity, domestic CO_2 emissions, oil dependency, and energy consumption. System dynamics goes beyond prediction; it is mainly about understanding the interactions among system components that impact system behaviour over time, and how intervention scenarios change system behaviour over time.

We have used the Australian energy sector as a case study, and the results indicate that both improving energy efficiency and full transition to RE systems are crucial for improving energy sector performance. This improvement in energy sector performance implies an improvement in energy productivity, cutting fossil fuel emissions, cutting oil dependency, and maintaining stable energy consumption. Thus, synergies between energy efficiency and RE are crucial as they can support and accelerate the full transition to renewable energy systems.

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CHAPTER 5: CONCLUSION

PUBLICATION OUTCOMES SUMMARY AND FUTURE RECOMMENDATIONS

We have used systems thinking and system dynamics approaches towards the development of a sustainable energy sector. The study was conducted in eight phases:

1. We highlighted key issues of the Australian energy sector, so-called variables.
2. We used these variables to develop a preliminary causal loop diagram (CLD) by creating links, polarities and a time delay between the variables.
3. The preliminary CLD was amended and validated through consulting with multiple experts in the Australian energy sector to produce a working CLD.
4. The working CLD was again reviewed and any errors or inconsistencies identified in the model were corrected to produce the final CLD for the Australian energy sector used in this study, which represents the qualitative modelling.
5. Long and intense training on system dynamics through Sysdea Corporation, UK were implemented.
6. A stock flow model was developed into a fully formulated system dynamics approach based on the final CLD of the Australian energy sector, which represents the quantitative modelling.
7. The model was operated during the period (1990-2050) and the results were analysed.
8. The results were concluded to inform policy development.

In ***paper I***, we were able to visualise energy systems as a whole and to identify feedback mechanisms likely to influence the behaviour of the sector to better understanding of the sector and to identify key leverage points for systematic intervention strategies towards the development of a sustainable energy sector. This represents the first aim of the study, which led to answer the first question: “What are the influences of energy policies on energy dependency, energy security, CO_2

emissions, energy reserves, and energy prices within the Australian context?" The findings indicated that there are significant risks in setting policies associated with energy security and environmental interventions in Australia, especially, in the oil and gas components, and CO_2 emissions.

In ***paper II***, we were seeking to establish balance of supply-demand, and thus the implications on fossil fuel reserves, energy dependency, energy prices, energy bankruptcy, and CO_2 emissions. Establishing the balance of supply-demand, conservation of resources, and reducing energy dependency and emissions are crucial for a sustainable energy future. Furthermore, supply-demand balance ensures sustain economic growth and fulfils energy needs; reducing emissions implies reduced dependency on fossil fuel. Through ***paper II*** we were able to achieve the second and the third aims, as we have formulated and validated a system dynamics model of the energy sector, and used the system dynamics model to develop possible development scenarios for the energy sector. Moreover, we were able to answer the second questions of the study "What are the implications of energy scenarios on supply-demand balance, fossil fuels reserves, energy dependency, CO_2 emissions, energy whole prices, and energy bankruptcy by 2050 within the Australian context?".

The model was run during the period 1990-2050, and the findings were compatible with ***paper I***. We have found that the current trend of the Australian energy sector is in line with unsustainable future and the growth is not being controlled. Our modelling shows that limits to growth are approaching fast due to excessive fossil fuel extraction, high emissions, and high energy dependency. Therefore, the current scenario (base case scenario) could be one of the worst scenarios for the Australian energy sector. On the other hand, reducing dependency on fossil fuel and accelerating the transition to full renewable systems could be the best scenario. That implies improving energy efficiency, switching to renewable transportation, switching to renewable electricity, and using RE for electrification of sectors that do not run on electricity. However, more research is required to examine the potential impact of such improvements on the energy sector, which was the topic of ***paper III***.

In paper III we were able to use a system dynamics approach to examine the influences of improving energy efficiency and the full transition to renewable energy systems on energy productivity, domestic CO_2 emissions, oil dependency, and energy consumption. This represents the fourth aim and the third question of the study. The results indicated that both improving energy efficiency and full transition to RE systems are crucial for improving energy sector performance. This improvement in energy sector performance implies an improvement in energy productivity, cutting fossil fuel emissions, cutting oil dependency, and maintaining stable energy consumption.

This study has made an important contribution to both the literature and practice. This study goes beyond filling a gap in the literature; it has a positive contribution represented by constructing a useful SD model which can be used by any country or for the whole world as a unit and for any energy resource. As the model deals with energy resources. Resource extraction must be ordered, built and installed, which is the procedure in any country. This study has also added to the literature by developing a conceptual model for energy-economy-society-environment systems which is the trend of energy complex system modelling and analysis in the future (Wei et al. 2005). For practice, this study provides insights and information on how to take advantage of energy policy to resolve the world’s most pressing energy problems, such as CO_2 emissions and global warming, and energy dependency. The proposed model will assist policy decision makers to test their scenarios related to energy policies in their countries, as the proposed model can be carried out by any other country. Given the increasing need for effective strategies to better handle energy sector challenges, the application of systems thinking and system dynamics approaches may enable more effective decisions/policy changes to get much better outcomes and avoid undesirable ones. Which makes such approaches suitable to manage dynamically complex issues.

However, there are some challenges and limitations associated with the construction and application of the model. Defining each component or subsystem is a very time-consuming job and required significant planning. Data availability and systems understanding for users are other challenges. In regard to limitations, energy demand growth has been taken as an exogenous variable. Other studies may take it as an indigenous variable. Moderating the rate of demand growth can be considered in other studies by linking price to investment in energy efficiency. Furthermore, any research faces multiple options and this study is no exception. This study focuses on the Australian context, so future studies can implement the created system dynamics model in other countries and the result can be compared with the current work. There are huge expected benefits of improving energy efficiency and the full transition to renewable energy systems, such as cutting emissions thus improving air quality and human health; maintaining the quality and quantity of water; ending energy dependency on other countries thus saving billions of dollars; providing a way of avoiding the risk of supply disruption; and creating millions of new jobs. However, the cost of this transition should be a focus in other studies. More studies need to be done on freight transportation and aviation sectors. With the current technology, these sectors are difficult to electrify. However, hydrogen cells or biofuels are promising sources of power in the future.

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Appendix A. Parameters used in the energy sector development simulation model

Table A1

Parameters used for stocks (the parameter value column represents initial values)

Variable Name	Units	Parameter Value	References
Reserves (black coal)	GWh	532,415,833.75	(BP. 2018)
Capital employed (black coal)	$	3,000,000,000	
Capacity under construction (black coal)	GWh	400,000	
Energy production capacity (black coal)	GWh	1,176,111.11	
Reserves (brown coal)	GWh	209,681,944.61	(BP. 2018)
Capital employed (brown coal)	$	200,000,000	
Capacity under construction (brown coal)	GWh	40000	
Energy production capacity (brown coal)	GWh	125194.44	
Reserves (gas)	GWh	37,420,833.36	(BP. 2018)
Capital employed (gas)	$	1,000,000,000	
Capacity under construction (gas)	GWh	80000	
Energy production capacity (gas)	GWh	221,472.22	
Capital employed (wind power)	$	100,000,000	
Capacity under construction (wind power)	GWh	500	

Energy production capacity (wind power)	GWh	885
Capital employed (solar power)	$	50,000,000
Capacity under construction (solar power)	GWh	400
Energy production capacity (solar power)	GWh	425
Capital employed (hydro power)	$	1,000,000,000
Capacity under construction (hydro power)	GWh	3,000
Energy production capacity (hydro power)	GWh	14,880
Capital employed (bio power)	$	4,000,000,000
Capacity under construction (bio power)	GWh	1000
Energy production capacity (bio power)	GWh	49833.32

Table A2

Parameters used for flows

Variable Name	Units	Parameter Value
New discoveries	GWh/year	0
Depletion	GWh/year	(pulse ("Energy extraction for electricity production"+"Energy extraction for non-electric purposes",2017,1))*("Energy production capacity"/"Gross demand")

Capex	$/year	"Capex costs"*"New capacity start-up"
Depreciation	$/year	"Capital employed"/20
New capacity orders	GWh/year	"Desired new capacity addition"
New capacity start-up	GWh/year	"Capacity under construction"/"Construction delay"
Capacity retirement	GWh/year	"Energy production capacity"/"Capacity lifespan"
Capacity bankruptcy	GWh/year	"Energy production capacity"*" Unprofitable capacity"/100

Table A3

Parameters used for auxiliary variables

Variable Name	Units	Parameter Value
Capacity lifespan	year	20 (coal and gas) ,25 (wind and solar power), 50 (hydro power), 30 (bio power)
Construction delay	year	5 (coal), 3 (gas), 2 (wind and solar power), 3 (hydro and bio power)
Desired new capacity addition	GWh/year	max (0,"Energy production capacity"*"Approved %"/100)
Approved %	%	"ROIC"–"Min % to invest"
Min % to invest	%	10
ROIC	%	("Net profit"/"Capital employed")*100
Net profit	$/year	("Sales"*"Net profit")-"Depreciation"
Sales	GWh/year	if "Surplus or shortfall" > 0 then "Energy production capacity"*(1 – "Surplus or shortfall"/100) else "Energy production capacity"
Net profit	$/GWh	"Wholesale price"-"Total supply cost"
Total supply cost	$/GWh	"Capital employed"/"Energy production capacity"

Wholesale price	\$/GWh	“Adjustment factor”*“Total supply cost”*(“Gross demand”/“Energy production capacity”)+((“Surplus or shortfall”/10)^3)
Adjustment factor		1.35 (coal and gas), 1.4 (wind power), 1.25 (solar power), 1.3 (hydro and bio power)
Surplus or shortfall	%	(“Energy production capacity”/“Gross demand”1)*100
Gross demand	GWh/year	“Total supply”
Energy extraction for non-electric purposes	GWh/year	“Total supply”-“Energy extraction for electricity production”
Energy % for electricity production	%	“Energy extraction for electricity production”/“Total supply”*100
Energy % for non-electric purposes	%	“Energy extraction for non-electric purposes”/“Total supply”*100
Total (CO_2-e)	ton/year	“Black coal (CO_2-e)”+“Brown coal (CO_2-e)”+ “Gas (CO_2-e)”+“Oil (CO_2-e)”
(CO_2-e)	ton/GWh	300 (coal), 250 (oil), 150 (gas)
(CO_2-e)	ton/year	“Total net consumption”*“(CO_2-e)”
Total net consumption	GWh/year	“Energy production capacity”*“Domestic consumption of total production”/100
Australia’s domestic CO_2 % footprint	%	“Total CO_2 emissions of total consumption”/“Global CO_2 emissions”*100
Australia’s global CO_2 % footprint	%	“Total CO_2 emissions of total production”/“Global CO_2 emissions”*100
Total CO_2 emissions of total production	ton/year	(“Energy production capacity (black coal)”*“Black coal-(CO_2-e)”)+(“Energy production capacity (brown coal)”*“Brown coal - (CO_2-e)”)+(“Total net oil consumption”*“Oil-(CO_2-e) ”)+(“Energy production capacity (gas)”*“Gas-(CO_2-e)”)+(“Oil production”*250)
Total energy production	GWh	“Total non-RE production”+“Total RE”

Total non-RE production	GWh	“Oil production”+“Energy production capacity (black coal)”+“Production Capacity (brown coal)”+“Energy Production Capacity (gas)”
Total energy consumption	GWh	(“Total non-RE”+“Total RE”)
Oil dependency	%	“Total net oil consumption”/“Total energy consumption”*100
Effect of efficiency factor on consumption	GWh	pulse (“Total energy consumption”*(1 - (“time”-2018)*“Energy efficiency factor”/100),2018,1)
Energy productivity	GWh	pulse (“Total energy consumption”-“Effect of efficiency factor on consumption”,2018,1)
(CO_2-e) reduction due to energy efficiency	ton/year	“Energy productivity”*150)
(CO_2-e) reduction due to switching to RE transportation	ton/year	pulse (“Capacity replacement”*“Transportation system oil share”*250/100,2018,1)
Domestic (CO_2-e)-reduction due to switching to RE electricity	ton/year	pulse (“Electricity generation by RE”*0.458*300+“Electricity generation by RE”*0.169*300+ “Electricity generation by RE”*0.196*150+“Electricity generation by RE”*0.02*250,2018,1)
(CO_2-e) reduction due to electrification of other sectors	ton/year	pulse (“Capacity replacement”*150,2018,1)-“(CO_2-e) reduction due to energy efficiency”
Non-RE %	%	“Electricity generation by non-RE”/“Total”*100
RE %	%	“Electricity generation by RE”/“Total”*100
Total domestic (CO_2-e) best case	ton/year	“Total domestic (CO_2-e)”-“(CO_2-e) reduction due to switching to RE transportation”-“Domestic (CO_2-e)- reduction due to switching to RE electricity”-“(CO_2-e) reduction due to electrification of other sectors”-“(CO_2-e) reduction due to energy efficiency”

Appendix B: Energy units and conversions

Table B1

Scale of numbers

Description	Equivalent	Term	Abbreviation
Thousand	10^3	Kilo	k
Million	10^6	Mega	M
Billion	10^9	Giga	G
Trillion	10^{12}	Tera	T
Quadrillion	10^{15}	Peta	*P
Quintillion	10^{18}	Exa	E

*1 PJ = 277.77 GWh

Table B2

Approximate energy content

Solid fuels	**GJ/ton**	***GWh/ton**
Black coal	29	0.0081
Brown coal (lignite)	10	0.0028
Gaseous fuels	**GJ/m^3**	**GWh/m^3**
Natural gas	0.038	0.00001
Liquid fuels	**GJ/bbl**	**GWh/bbl**
Crude oil	6.36	0.00177

*1 GWh = 3600 GJ

Appendix C. Tracing causal dependency (four items are selected for example)

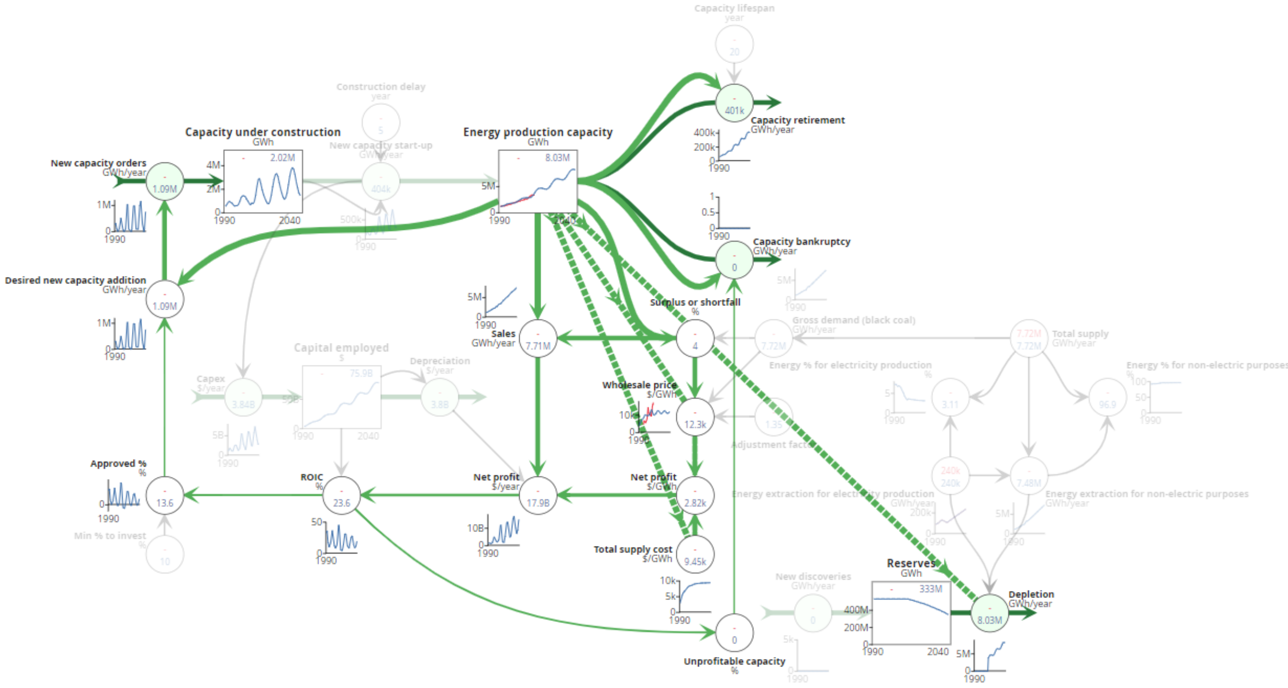

Fig. C1. Tracing causal dependency of energy production capacity. Green lines show items caused by energy production capacity item, thicker lines are direct causes of the selected parameter, dashed lines are unlinked causes.

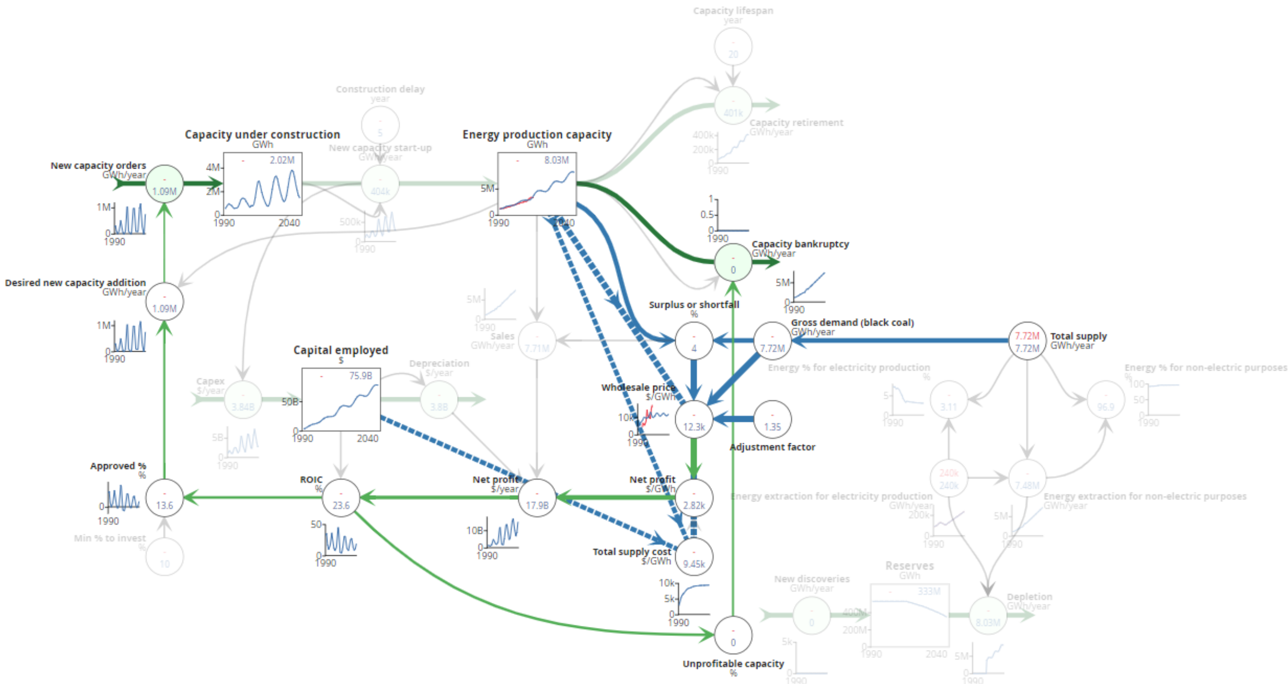

Fig. C2. Tracing causal dependency of wholesale price. Blue lines show items leading to change the selected item).

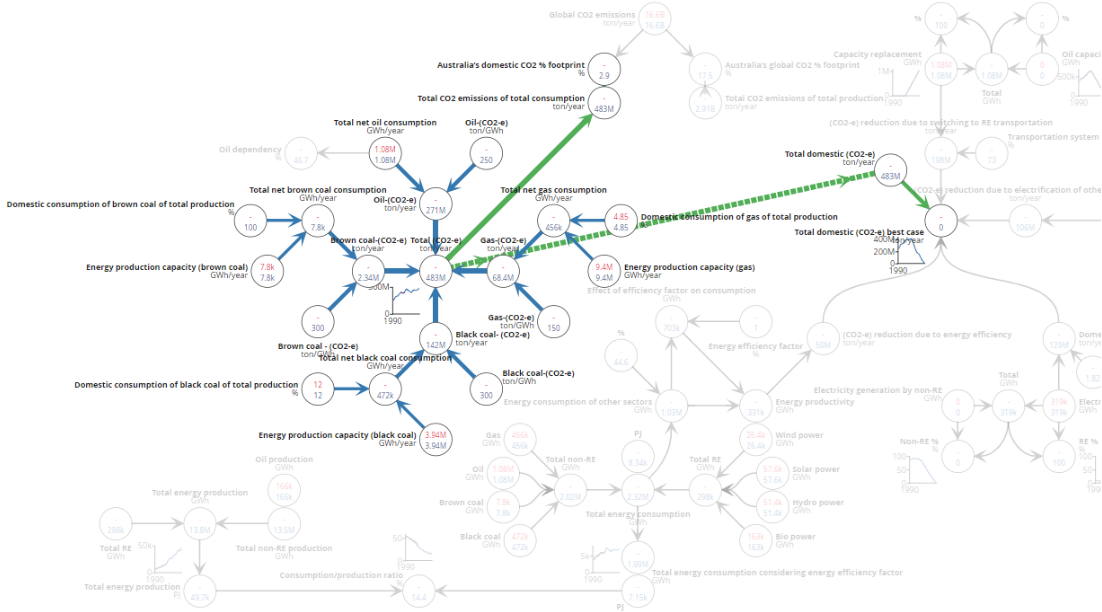

Fig. C3. Tracing causal dependency of total domestic CO_2 emissions.

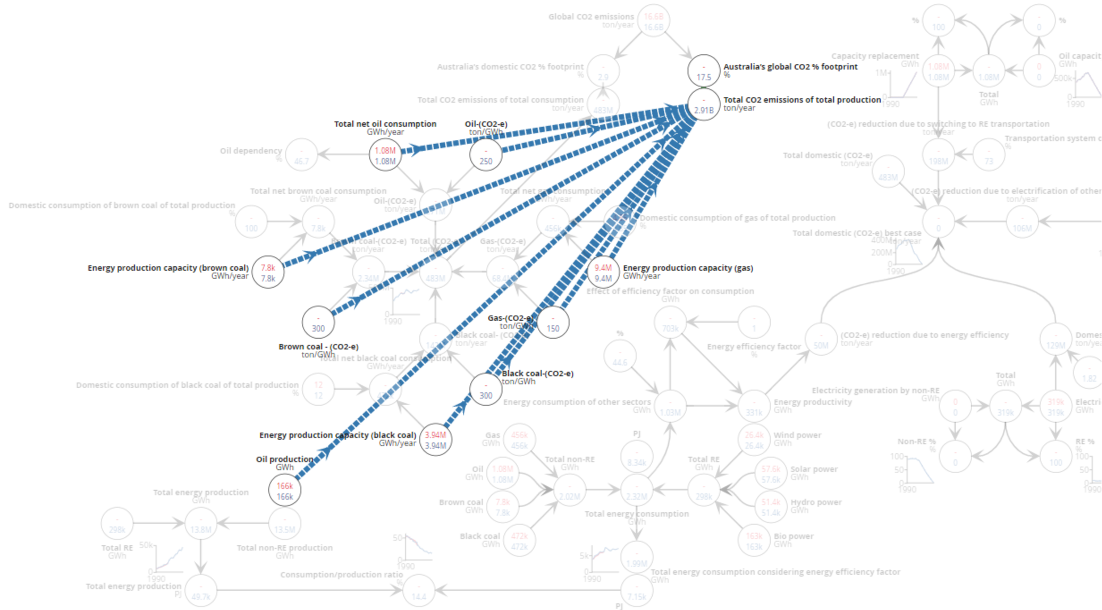

Fig. C4. Tracing causal dependency of total CO_2 emissions of total production.

Appendix D. Data used in the energy sector development simulation model

Table D1

Discrepancy coefficients

Black coal

Year	Actual values	Simulated values	Si-Sm	Ai-Am	Si-Sm-Ai-Am	(Si-Sm-Ai-Am)²	square root sum (Si-Sm-Ai-Am)²	(Ai-Am)²	square root sum (Ai-Am)²	(Si-Sm)²	square root sum (Si-Sm)²	DC
1990	1176111.1	1176111.1	-1070011.1	-975491.7	-94519.3	8933908816		9.516E+11		1.14492E+12		
1991	1221111.1	1197305.5	-1048816.6	-930491.7	-118324.9	1400078487		8.658E+11		1.10002E+12		
1992	1300027.7	1248484.7	-997637.4	-851575	-146062.4	2133422634		7.252E+11		9.95281E+11		
1993	1327222.2	1329215.1	-916907	-824380.6	-92526.4	8561135154		6.796E+11		8.40719E+11		
1994	1329611.1	1441129.8	-804992.3	-821991.7	16999.3	288978910.2		6.757E+11		6.48013E+11		
1995	1437000	1564265.3	-681856.9	-714602.8	32745.9	1072296803		5.107E+11		4.64929E+11		
1996	1453333.3	1663837.0	-582285.1	-698269.5	115984.3	13452366213		4.876E+11		3.39056E+11		
1997	1550000	1744464.0	-501658.1	-601602.8	99944.7	9988946188		3.619E+11		2.51661E+11		
1998	1661111.1	1789523.0	-456599.2	-490491.7	33892.5	1148703931		2.406E+11		2.08483E+11		
1999	1664972.2	1814509.6	-431612.6	-486630.6	55018	3026983060		2.368E+11		1.86289E+11		
2000	1771055.5	1845284.1	-400838	-380547.3	-20290.7	411714827.3		1.448E+11		1.60671E+11		
2001	1911833.3	1874679.6	-371442.5	-239769.5	-131673	17337784372		5.749E+10		1.3797E+11		
2002	2022861.1	1927473.1	-318649	-128741.7	-189907.3	36064800230		1.657E+10		1.01537E+11		
2003	2024258.2	2033339.6	-212782.5	-127344.5	-85437.9	7299639629		1.622E+10		45276397146		
2004	2093112.8	2196312.9	-49809.2	-58490	8680.8	75356437.2		3.421E+09		2480959821		
2005	2237432.2	2376463.5	130341.3	85829.4	44511.9	1981314139		7.367E+09		16988875901		
2006	2261473.3	2543402	297279.8	109870.5	187409.3	35122246683		1.207E+10		88375303088		
2007	2397756.6	2694370.5	448248.3	246153.8	202094.5	40842191554		6.059E+10		2.00927E+11		
2008	2403080.7	2795179.2	549057	251477.9	297579.1	88553351907		6.324E+10		3.01464E+11		
2009	2502483.5	2858215.3	612093.1	350880.6	261212.4	68231948817		1.231E+11		3.74658E+11		
2010	2710923.9	2877540.6	631418.3	559321.1	72097.2	5198017275		3.128E+11		3.98689E+11		

2011	2567887.4	2867113		620990.8	416284.5	204706.2	41904652661		1.733E+11		3.8563E+11		
2012	2745910.6	2891031.7		644909.5	594307.8	50601.7	2560535681		3.532E+11		4.15908E+11		
2013	3028206.9	2900315		654192.8	876604	-222411.2	49466775101		7.684E+11		4.27968E+11		
2014	3279672.9	2946210.5		700088.3	1128070	-427981.7	1.83168E+11		1.273E+12		4.90124E+11		
2015	3413308.3	3102167.4		856045.2	1261705	-405660.2	1.6456E+11		1.592E+12		7.32813E+11		
2016	3376910	3397484.9		1151362.7	1225307.2	-73944.4	5467779663		1.501E+12		1.32564E+12		
2017	3376211.8	3795992.6		1549870.3	1224609	325261.3	1.05795E+11		1.5E+12		2.4021E+12		
Mean	2151602.8	2246122.2	**Sum**	1.30385E-08	4.19095E-09		9.3585E+11	967393	1.371E+13	37031831	1.41886E+13	3766773	0.13

Brown coal

Year	Actual values	Simulated values		Si-Sm	Ai-Am	Si-Sm-Ai-Am	(Si-Sm-Ai-Am)^2	square root sum (Si-Sm-Ai-Am)^2	(Ai-Am)^2	square root sum(Ai-Am)^2	(Si-Sm)^2	square root sum (Si-Sm)^2	DC
1990	125194.4	125194.4		-72977	-51505.9	-21471.1	461008670		2.653E+09		5325656179		
1991	134472.2	126934.7		-71236.8	-42228.2	-29008.6	841499712.6		1.783E+09		5074683886		
1992	138138.8	131995.7		-66175.7	-38561.5	-27614.2	762545850.6		1.487E+09		4379233041		
1993	129666.6	141632		-56539.4	-47033.7	-9505.7	90358642.8		2.212E+09		3196712504		
1994	131722.2	154476.5		-43695	-44978.2	1283.1	1646527.9		2.023E+09		1909255649		
1995	136666.6	164521.8		-33649.7	-40033.7	6384	40756126.9		1.603E+09		1132302884		
1996	142888.8	170511		-27660.4	-33811.5	6151	37835522.3		1.143E+09		765102288.7		
1997	155305.5	173357.7		-24813.7	-21394.8	-3418.9	11688945.9		457740508		615723733.6		
1998	176805.5	173787.6		-24383.8	105.1	-24488.9	599710855.3		11052		594572903.8		
1999	185833.3	173613.7		-24557.7	9132.9	-33690.6	1135063237		83410025		603085080.6		
2000	186194.4	179511.6		-18659.8	9494	-28153.8	792640355.5		90136395		348190015.1		
2001	185000	192438.6		-5732.8	8299.5	-14032.4	196909703.2		68883010		32865831.2		
2002	185972.2	209322.9		11151.3	9271.7	1879.5	3532778.3		85966255		124352998.8		
2003	203297.9	225290.8		27119.3	26597.5	521.8	272277.6		707429609		735459209.5		
2004	201844.6	236222.1		38050.6	25144.2	12906.3	166574185.8		632234260		1447850531		
2005	204809.2	244197.1		46025.6	28108.8	17916.8	321012336.8		790105702		2118359177		
2006	206848.3	247816.2		49644.6	30147.8	19496.7	380124399.3		908895207		2464593074		

2007	202276.2	248088.5		49916.9	25575.8	24341.1	592490685		654123537		2491703941		
2008	203456.3	245814.5		47643	26755.8	20887.1	436272880		715877592		2269858805		
2009	208848.8	241628.2		43456.6	32148.4	11308.2	127876739.8		1.034E+09		1888484665		
2010	210937.4	236030.3		37858.8	34236.9	3621.8	13117447.9		1.172E+09		1433288789		
2011	204694.7	229415.6		31244	27994.3	3249.7	10561043.3		783681892		976193461.1		
2012	206846.6	223626.5		25455	30146.1	-4691.1	22007201.8		908792707		647957305.9		
2013	179102.3	218385.1		20213.6	2401.9	17811.6	317254272.6		5769454.7		408589705.7		
2014	173697.5	215737.9		17566.4	-3002.8	20569.2	423095970.7		9017354.8		308578610.1		
2015	188442.9	211568.6		13397.1	11742.5	1654.6	2737860.7		137886516		179483820.1		
2016	176369.1	206284.3		8112.8	-331.2	8444.1	71303034.6		109740.5		65818194.8		
2017	162278.3	201397.8		3226.2	-14422	17648.3	311464862.2		207996711		10408857.1		
Mean	176700.4	198171.5	**Sum**	4.36557E-10	-9.31323E-10		8171362126	90395	2.236E+10	149525.8	41548365142	203834.1	0.25

Gas

Year	Actual values	Simulated values	Si-Sm	Ai-Am	Si-Sm-Ai-Am	(Si-Sm-Ai-Am)²	square root sum (Si-Sm-Ai-Am)²	(Ai-Am)²	square root sum(Ai-Am)²	(Si-Sm)²	square root sum (Si-Sm)²	DC
1990	221472.2	221472.2	-264208.3	-257717	-6491.3	42137085.5		6.642E+10		69806051587		
1991	233444.4	237065.2	-248615.2	-245744.8	-2870.4	8239614		6.039E+10		61809563990		
1992	258916.6	257754.6	-227925.9	-220272.6	-7653.3	58573982.6		4.852E+10		51950245290		
1993	271694.4	280333.2	-205347.3	-207494.8	2147.5	4611800.2		4.305E+10		42167517772		
1994	295805.5	307667.4	-178013.1	-183383.7	5370.5	28842889.3		3.363E+10		31688682541		
1995	326361.1	333736.8	-151943.7	-152828.1	884.4	782237		2.336E+10		23086890605		
1996	334472.2	358634.2	-127046.3	-144717	17670.6	312253158.9		2.094E+10		16140776046		
1997	340472.2	386550.5	-99129.9	-138717	39587	1567135142		1.924E+10		9826753450		
1998	354305.5	408593.4	-77087.1	-124883.7	47796.5	2284510657		1.56E+10		5942429542		
1999	370166.6	417519.9	-68160.5	-109022.6	40862	1669703128		1.189E+10		4645867300		
2000	365694.4	416214.7	-69465.7	-113494.8	44029	1938556403		1.288E+10		4825494578		
2001	381888.8	411505.4	-74175	-97300.3	23125.2	534778695.8		9.467E+09		5501945126		
2002	385805.5	403152	-82528.5	-93383.7	10855.1	117834527.1		8.721E+09		6810961407		

2003	398779.4	402566.6		-83113.9	-80409.8	-2704.1	7312424.3		6.466E+09		6907928655		
2004	399628.2	412795		-72885.5	-79561	6675.5	44562365.2		6.33E+09		5312298368		
2005	447535	437096.8		-48583.7	-31654.1	-16929.5	286609087.6		1.002E+09		2360376232		
2006	464213.9	465406.7		-20273.8	-14975.3	-5298.4	28073930.3		224260519		411027539.7		
2007	492373.2	509416.3		23735.7	13184.01964	10551.7	111339279		173818374		563386425.3		
2008	512544.4	559150.9		73470.4	33355.1	40115.2	1609236304		1.113E+09		5397903689		
2009	537675.8	605831.2		120150.6	58486.5	61664.1	3802464789		3.421E+09		14436190352		
2010	572810.7	637592.6		151912	93621.4	58290.5	3397789945		8.765E+09		23077269249		
2011	630644.5	651771.5		166090.9	151455.2	14635.7	214204316.9		2.294E+10		27586217033		
2012	598627.8	658159.6		172479	119438.6	53040.4	2813286062		1.427E+10		29749018818		
2013	684464.3	682952.3		197271.7	205275	-8003.2	64052733.7		4.214E+10		38916156945		
2014	704033.5	699410.7		213730.2	224844.3	-11114	123522898.9		5.055E+10		45680608665		
2015	738707.5	744388.1		258707.6	259518.2	-810.6	657142.3		6.735E+10		66929625662		
2016	940636.9	809175		323494.4	461447.6	-137953.1	19031085100		2.129E+11		1.04649E+11		
2017	1154123.6	883141.8		397461.2	674934.3896	-277473.1	76991336959		4.555E+11		1.57975E+11		
Mean	479189.2	485680.5	**Sum**	-6.98492E-10	-2.44472E-09		1.17093E+11	342189	1.267E+12	1125751.3	8.64155E+11	929599	0.16

Wind power

Year	**Actual values**	**Simulated values**		**Si-Sm**	**Ai-Am**	**Si-Sm-Ai-Am**	**(Si-Sm-Ai-Am)²**	**square root sum (Si-Sm-Ai-Am)²**	**(Ai-Am)²**	**square root sum(Ai-Am)²**	**(Si-Sm)²**	**square root sum (Si-Sm)²**	**DC**
2005	885	885		-5617	-5630.9	13.8	191.1		31707077		31551559.4		
2006	1713	1599.6		-4902.4	-4802.9	-99.5	9914.9		23067885		24034285.4		
2007	2611	2021.2		-4480.8	-3904.9	-575.9	331698.4		15248273		20077895.5		
2008	3093	2462.5		-4039.5	-3422.9	-616.6	380247.9		11716270		16317934		
2009	3823.8	3290.4		-3211.6	-2692.1	-519.5	269914.1		7247422.7		10314608		
2010	5051.7	4371		-2131	-1464.2	-666.8	444673.7		2143892.7		4541341.7		
2011	6084.9	5586.8		-915.1	-431	-484.1	234431.5		185764.2		837563.7		
2012	6969.8	7081.5		579.4	453.9	125.5	15757.6		206047.2		335766.5		
2013	7959.6	8704.2		2202.1	1443.6	758.4	575317		2084258.8		4849653.1		

2014	10251.9	10094.6		3592.5	3736	-143.4	20579.9		13957944		12906603.1		
2015	11466.5	11012.8		4510.7	4950.5	-439.8	193435.6		24508413		20347172.7		
2016	12199.4	12605.2		6103.1	5683.5	419.6	176065.9		32303243		37249006.4		
2017	12596.9	14811.6		8309.5	6081	2228.5	4966289.4		36979549		69049427.9		
Mean	6515.9	6502	**Sum**				7618517.5	2760	201356041	14189.9	252412817.8	15887.5	0.09

Solar power

Year	Actual values	Simulated values		Si-Sm	Ai-Am	Si-Sm-Ai-Am	(Si-Sm-Ai-Am)^2	square root sum (Si-Sm-Ai-Am)^2	(Ai-Am)^2	square root sum(Ai-Am)^2	(Si-Sm)^2	square root sum (Si-Sm)^2	DC
2010	424.8	424.8		-2913	-3724.8	811.8	659110.4		13874608		8485611.8		
2011	1530.5	907.8		-2429.9	-2619.1	189.1	35783		6860017.4		5904896.8		
2012	2558.6	1142.7		-2195	-1591	-604	364825		2531483.1		4818339.6		
2013	3826.2	1666.9		-1670.8	-323.4	-1347.3	1815395.1		104628.6		2791671.2		
2014	4415.9	2826.4		-511.4	266.2	-777.6	604810.4		70912.2		261532.1		
2015	5531.3	4757.4		1419.6	1381.6	37.9	1441.2		1909013.4		2015359.6		
2016	6838.2	6722.9		3385.1	2688.5	696.5	485160.1		7228556.5		11459117.9		
2017	8071.6	8253.3		4915.5	3921.9	993.5	987145.4		15382025		24162576.8		
Mean	4149.6	3337.8	**Sum**				4953671.7	2225	47961245	6925.4	59899106.1	7739.4	0.15

Hydro power

Year	Actual values	Simulated values		Si-Sm	Ai-Am	Si-Sm-Ai-Am	(Si-Sm-Ai-Am)^2	square root sum (Si-Sm-Ai-Am)^2	(Ai-Am)^2	square root sum(Ai-Am)^2	(Si-Sm)^2	square root sum (Si-Sm)^2	DC
1990	14880	14880		-1080.2	-843.6	-236.6	56019		711683		1167040.4		
1991	16103	15582.4		-377.8	379.3	-757.2	573478		143934.4		142805.7		
1992	15768	15942.9		-17.3	44.3	-61.7	3807.9		1970.1		300		
1993	16953	16297.5		337.2	1229.3	-892.1	795923.3		1511392.1		113731.8		
1994	16649	16420.5		460.2	925.3	-465.1	216362.3		856340.9		211820.1		

1995	16239	16675.3		715	515.3	199.6	39869.4		265623.6		511311.2		
1996	15731	16831.5		871.2	7.3	863.8	746246.6		54.5		759063.6		
1997	16852	16821.3		861	1128.3	-267.3	71457.5		1273257		741443.9		
1998	15733	16702.5		742.2	9.3	732.8	537137.8		88.1		550985.2		
1999	16563	16532.4		572.1	839.3	-267.1	71393.9		704570.3		327401.8		
2000	16720	16311.1		350.8	996.3	-645.5	416722.9		992786.8		123092.9		
2001	16933	16076.5		116.2	1209.3	-1093.1	1195043.5		1462616.7		13503.9		
2002	16054	15993.2		32.9	330.3	-297.3	88445.2		109155.5		1088.3		
2003	16490	16205.1		244.8	766.3	-521.5	271995.2		587348.8		59954		
2004	16331.1	16266.4		306.1	607.4	-301.2	90780.3		369040.3		93751.7		
2005	15612.2	16322.6		362.3	-111.4	473.7	224471.9		12412.8		131313.1		
2006	16029.2	16283.2		322.9	305.5	17.3	300.5		93383.3		104279.4		
2007	14517	16148.8		188.5	-1206.6	1395.2	1946607.1		1455915.2		35568.2		
2008	12056.9	15787		-173.2	-3666.7	3493.4	12204163.7		13444785		30021.5		
2009	11869.4	13862.6		-2097.6	-3854.2	1756.5	3085614.1		14854959		4400015.8		
2010	13548.7	12969.6		-2990.6	-2174.9	-815.7	665444.9		4730247		8944054.4		
2011	16806.7	12748		-3212.2	1083	-4295.3	18449996.3		1173077.2		10318607.9		
2012	14083.3	12769.4		-3190.8	-1640.3	-1550.5	2404126.1		2690627.1		10181444.3		
2013	18269.6	14365.96		-1594.3	2545.9	-4140.3	17142223.5		6482049.3		2541887.9		
2014	18421	15901.5		-58.7	2697.3	-2756.1	7596222.9		7275896.1		3450.1		
2015	13445	18416.8		2456.5	-2278.6	4735.1	22421834.7		5192077.7		6034671.6		
2016	15318.1	18840		2879.7	-405.4	3285.1	10792141.9		164376		8292709.2		
2017	16284.8	18932.9		2972.6	561.2	2411.3	5814782		315028.2		8836705.9		
Mean	15723.6	15960.2	**Sum**	-3.09228E-11	4.72937E-11	-7.82165E-11	107922614	10388	66874696	8177.6	64672025	8041.8	0.64

Bio power

Year	Actual values	Simulated values		Si-Sm	Ai-Am	Si-Sm-Ai-Am	(Si-Sm-Ai-Am)^2	square root sum (Si-Sm-Ai-Am)^2	(Ai-Am)^2	square root sum(Ai-Am)^2	(Si-Sm)^2	square root sum (Si-Sm)^2	DC
1990	49833.3	49833.3		-9896.05	-4331.3	-5564.7	30965912.6		18760608		97931888.1		

1991	49527.7	48172.2		-11557.1	-4636.9	-6920.2	47890040.6		21500858		133568059		
1992	45861.1	49058.1		-10671.2	-8303.5	-2367.6	5605848.7		68949304		113875344.9		
1993	50777.7	52079.9		-7649.3	-3386.9	-4262.4	18168752.3		11471104		58513071.4		
1994	53444.4	54270.9		-5458.4	-720.2	-4738.2	22450658.4		518748.2		29794724		
1995	55638.8	57000.4		-2728.9	1474.2	-4203.1	17666241		2173289.9		7446974.6		
1996	58499.9	60403.1		673.7	4335.3	-3661.5	13406741.2		18794984		454001.7		
1997	60944.4	64059.8		4330.4	6779.7	-2449.2	5999031.9		45965121		18752936.4		
1998	61555.5	67730.3		8000.9	7390.8	610.1	372245.5		54624933		64015801		
1999	60749.9	70937.8		11208.4	6585.3	4623.1	21373247.5		43366416		125629109.2		
2000	59416.6	72516.6		12787.3	5251.9	7535.3	56781163.6		27583380		163515448.4		
2001	57749.9	72728.4		12999	3585.3	9413.7	88618783.9		12854507		168975905.4		
2002	51861.1	70172.6		10443.2	-2303.5	12746.8	162481579.9		5306443		109061564.1		
2003	55666.6	63742.3		4012.9	1501.9	2510.9	6305066.9		2255968.6		16103988		
2004	56749.9	62396.5		2667.1	2585.3	81.8	6702.9		6683870.3		7113900		
2005	57972.2	60835.9		1106.6	3807.5	-2700.9	7295019.5		14497347		1224583.1		
2006	57777.7	59450.1		-279.1	3613.1	-3892.2	15149909.2		13054479		77947.1		
2007	58194.4	59458.1		-271.1	4029.7	-4300.9	18498025.3		16238951		73535.8		
2008	58194.4	60899.4		1170	4029.7	-2859.7	8177974.9		16238951		1368999		
2009	42972.2	63459.5		3730.2	-11192.4	14922.6	222686352.7		125271201		13914521.5		
2010	50249.9	58956.9		-772.4	-3914.6	3142.2	9873763.7		15324733		596643.8		
2011	46666.6	60127.9		398.5	-7498	7896.6	62356294.8		56220331		158864.7		
2012	46777.7	57606		-2123	-7386.9	5263.5	27704773.1		54566318		4508697.6		
2013	51777.7	56670.1		-3059.2	-2386.9	-672.3	452016.6		5697300.1		9358849		
2014	50833.3	55710.4		-4018.9	-3331.3	-687.6	472823.1		11097905		16152145.2		
2015	54138.8	54851.4		-4877.9	-25.7	-4852.1	23543467.5		665.2		23794424.5		
2016	55027.7	54028.9		-5700.3	863.1	-6563.4	43079294.1		744938.5		32494373.6		
2017	57749.9	55264.3		-4465	3585.3	-8050.3	64808283.7		12854507		19936591.3		
Mean	54164.6	59729.3	**Sum**				1002190016	31657.3	682617163	26126.9	1238412893	35191	0.51

CO_2 E.

Year	Actual values	Simulated values		Si-Sm	Ai-Am	Si-Sm-Ai-Am	(Si-Sm-Ai-Am)^2	square root sum (Si-Sm-Ai-Am)^2	(Ai-Am)^2	square root sum(Ai-Am)^2	(Si-Sm)^2	square root sum (Si-Sm)^2	DC
2007	396800000	398743461		-2539892.7	-4581818.1	2041925.4	4.16946E+12		2.099E+13		6.45106E+12		
2008	407100000	403567881		2284527.8	5718181.8	-3433653.9	1.179E+13		3.27E+13		5.21907E+12		
2009	402100000	403223522		1940169.1	718181.8	1221987.2	1.49325E+12		5.158E+11		3.76426E+12		
2010	397600000	397854678		-3428675.3	-3781818.1	353142.7	1.2471E+11		1.43E+13		1.17558E+13		
2011	403500000	402741503		1458149.5	2118181.8	-660032.2	4.35643E+11		4.487E+12		2.1262E+12		
2012	396200000	396818943		-4464410.6	-5181818.1	717407.4	5.14674E+11		2.685E+13		1.9931E+13		
2013	392300000	392557799		-8725554.1	-9081818.1	356264.1	1.26924E+11		8.248E+13		7.61353E+13		
2014	399400000	398265210		-3018142.8	-1981818.1	-1036324.6	1.07397E+12		3.928E+12		9.10919E+12		
2015	407100000	408504406		7221053.1	5718181.8	1502871.3	2.25862E+12		3.27E+13		5.21436E+13		
2016	407100000	405618781		4335427.7	5718181.8	-1382754	1.91201E+12		3.27E+13		1.87959E+13		
2017	406000000	406220702		4937348.2	4618181.8	319166.4	1.01867E+11		2.133E+13		2.43774E+13		
Mean	401381818	401283353	**Sum**				2.40011E+13	4899092	2.73E+14	16521996	2.29809E+14	15159445	0.15

T. C.

Year	Actual values	Simulated values		Si-Sm	Ai-Am	Si-Sm-Ai-Am	(Si-Sm-Ai-Am)^2	square root sum (Si-Sm-Ai-Am)^2	(Ai-Am)^2	square root sum(Ai-Am)^2	(Si-Sm)^2	square root sum (Si-Sm)^2	DC
1990	1096083.3	1099038.2		-393477.5	-338989.1	-54488.4	2968990862		1.149E+11		1.54825E+11		
1991	1097194.4	1084097.5		-408418.2	-337877.9	-70540.2	4975929703		1.142E+11		1.66805E+11		
1992	1106305.5	1093614.3		-398901.4	-328766.8	-70134.5	4918862044		1.081E+11		1.59122E+11		
1993	1133833.3	1156090.9		-336424.8	-301239.1	-35185.7	1238038715		9.074E+10		1.13182E+11		
1994	1161638.8	1227324.6		-265191.2	-273433.5	8242.3	67935960.1		7.477E+10		70326377562		
1995	1212583.3	1286452.7		-206063	-222489.1	16426	269815127.3		4.95E+10		42461975020		
1996	1251527.7	1358823.9		-133691.8	-183544.6	49852.8	2485304671		3.369E+10		17873501842		
1997	1280833.3	1387466.8		-105049	-154239.1	49190	2419663471		2.379E+10		11035294893		
1998	1327111.1	1406333.4		-86182.3	-107961.3	21778.9	474324455.2		1.166E+10		7427391529		

1999	1356861.1	1425444.8	-67070.9	-78211.3	11140.3	124106875.9		6.117E+09		4498516388		
2000	1380833.3	1441230.2	-51285.6	-54239.1	2953.4	8723030.4		2.942E+09		2630213700		
2001	1392166.6	1427364.5	-65151.2	-42905.7	-22245.5	494863370		1.841E+09		4244689482		
2002	1415833.3	1448550.6	-43965.1	-19239.1	-24726	611376831.2		370142460		1932931977		
2003	1427416.6	1466087.9	-26427.8	-7655.7	-18772.1	352391872.9		58610612		698431803.6		
2004	1468000	1536070.5	43554.7	32927.5	10627.1	112935845.6		1.084E+09		1897012853		
2005	1499777.7	1570496	77980.2	64705.3	13274.9	176223054.2		4.187E+09		6080920386		
2006	1540750	1610825.7	118309.9	105677.5	12632.3	159575867.2		1.117E+10		13997236557		
2007	1590000	1664579.1	172063.3	154927.5	17135.7	293633886.5		2.4E+10		29605790219		
2008	1593972.2	1711906.6	219390.8	158899.8	60491	3659168864		2.525E+10		48132352762		
2009	1625250	1699968	207452.2	190177.5	17274.6	298414435		3.617E+10		43036439903		
2010	1619777.7	1678471.7	185955.9	184705.3	1250.6	1564045.9		3.412E+10		34579623308		
2011	1641555.5	1719576.6	227060.8	206483.1	20577.7	423442204.5		4.264E+10		51556627135		
2012	1637694.4	1686419.2	193903.4	202622	-8718.6	76014385.1		4.106E+10		37598528657		
2013	1647416.6	1677905	185389.2	212344.2	-26954.9	726570793.5		4.509E+10		34369179969		
2014	1640250	1715049.4	222533.6	205177.5	17356	301231994.3		4.21E+10		49521211792		
2015	1640944.4	1756566.7	264050.9	205872	58178.8	3384781701		4.238E+10		69722877775		
2016	1689250	1732294.2	239778.3	254177.5	-14399.1	207336667.2		6.461E+10		57493677944		
2017	1707166.6	1722392.4	229876.6	272094.2	-42217.6	1782328322		7.404E+10		52843257089		
Mean	1435072.4	1492515.8				33013549055	181696	1.121E+12	1058543.9	1.2875E+12	1134679	0.08

T. P.

Year	Actual values	Simulated values	Si-Sm	Ai-Am	Si-Sm-Ai-Am	(Si-Sm-Ai-Am)^2	square root sum (Si-Sm-Ai-Am)^2	(Ai-Am)^2	square root sum(Ai-Am)^2	(Si-Sm)^2	square root sum (Si-Sm)^2	DC
1990	1944833.3	1916324.4	-1381168.2	-1258644.6	-122523.5	15012015036		1.584E+12		1.90763E+12		
1991	2009861.1	1953476.8	-1344015.8	-1193616.9	-150398.9	22619831777		1.425E+12		1.80638E+12		
1992	2107638.8	2025014	-1272478.6	-1095839.1	-176639.4	31201510907		1.201E+12		1.6192E+12		
1993	2140416.6	2135113.6	-1162378.9	-1063061.3	-99317.6	9863990715		1.13E+12		1.35112E+12		
1994	2153388.8	2271465.3	-1026027.3	-1050089.1	24061.8	578971891.3		1.103E+12		1.05273E+12		
1995	2319972.2	2456755.4	-840737.1	-883505.8	42768.6	1829155004		7.806E+11		7.06839E+11		

1996	2344000	2581133.7	-716358.8	-859478	143119.1	20483084280		7.387E+11		5.1317E+11		
1997	2471916.6	2704364.7	-593127.8	-731561.3	138433.5	19163837597		5.352E+11		3.51801E+11		
1998	2652666.6	2805392.6	-492100	-550811.3	58711.3	3447022327		3.034E+11		2.42162E+11		
1999	2614972.2	2779835.9	-517656.7	-588505.8	70849	5019589920		3.463E+11		2.67968E+11		
2000	2814194.4	2914894.1	-382598.5	-389283.5	6685	44689619.2		1.515E+11		1.46382E+11		
2001	2980361.1	2965234.4	-332258.2	-223116.9	-109141.3	11911826081		4.978E+10		1.10396E+11		
2002	3070972.2	2997142.3	-300350.2	-132505.8	-167844.4	28171757436		1.756E+10		90210270543		
2003	3080706.3	3083599.8	-213892.7	-122771.6	-91121.1	8303057868		1.507E+10		45750124846		
2004	3093402.4	3210494.8	-86997.7	-110075.6	23077.8	532586475		1.212E+10		7568612935		
2005	3263093	3396574.8	99082.2	59614.9	39467.2	1557663256		3.554E+09		9817288767		
2006	3284916.7	3571904.5	274411.9	81438.7	192973.2	37238658889		6.632E+09		75301906120		
2007	3493025.3	3815923.3	518430.7	289547.3	228883.3	52387600599		8.384E+10		2.6877E+11		
2008	3494311	3945182.5	647689.9	290833	356856.8	1.27347E+11		8.458E+10		4.19502E+11		
2009	3630748.7	4071865.2	774372.5	427270.7	347101.8	1.2048E+11		1.826E+11		5.99653E+11		
2010	3879162.4	4104306.4	806813.8	675684.3	131129.4	17194927797		4.565E+11		6.50949E+11		
2011	3775683	4090307	792814.3	572205.8	220608.5	48668134393		3.274E+11		6.28555E+11		
2012	3907110.4	4097789.9	800297.3	703632.4	96664.8	9344094393		4.951E+11		6.40476E+11		
2013	4228122.7	4100771.5	803278.9	1024644.6	-221365.7	49002800643		1.05E+12		6.45257E+11		
2014	4488032.9	4152868.6	855376	1284554.9	-429178.9	1.84195E+11		1.65E+12		7.31668E+11		
2015	4657801.8	4343388.6	1045896	1454323.8	-408427.8	1.66813E+11		2.115E+12		1.0939E+12		
2016	4807977	4694689.4	1397196.7	1604498.9	-207302.2	42974205033		2.574E+12		1.95216E+12		
2017	4988095.1	5143979.2	1846486.5	1784617.1	61869.4	3827825211		3.185E+12		3.40951E+12		
Mean	3203478	3297492.6				1.03921E+12	1019418	2.161E+13	4648373.2	2.13448E+13	4620046	0.11

Table D2

Some of parameters' results that have not been discussed in the text body

Black coal

Year	**Actual values (GWh)**	**Simulated values (GWh)**	**Simulated values (ton)**	**Capital employed (AU$)**	**Capex (AU$/year)**	**Total supply cost (AU$/GWh)**
1990	1176111.11	1176111.11	144467646.5	3000000000	760000000	2550.779407
1991	1221111.11	1197305.555	147071066.8	3610000000	1054922222	3015.10336
1992	1300027.77	1248484.721	153357661.4	4484422222	1359969548	3591.891952
1993	1327222.22	1329215.174	163274189.2	5620170659	1694566593	4228.187254
1994	1329611.11	1441129.847	177021231.6	7033728719	1854323486	4880.704356
1995	1437000	1564265.3	192146579.1	8536365769	1688957384	5457.108694
1996	1453333.33	1663837.023	204377474.9	9798504865	1556279557	5889.101354
1997	1550000	1744464.072	214281301.1	10864859179	1256680264	6228.193145
1998	1661111.11	1789523.002	219816116.2	11578296483	1087396124	6470.046192
1999	1664972.22	1814509.602	222885346	12086777783	1154250266	6661.181496
2000	1771055.55	1845284.15	226665538.6	12636689160	1155767378	6848.099336
2001	1911833.33	1874679.666	230276337.8	13160622080	1392010657	7020.197807
2002	2022861.11	1927473.12	236761223.5	13894601633	1921282222	7208.713567
2003	2024258.27	2033339.698	249765348	15121153774	2514082489	7436.609725
2004	2093112.81	2196312.975	269784175.8	16879178574	2754679520	7685.233736
2005	2237432.28	2376463.592	291912982.7	18789899165	2714735553	7906.664015
2006	2261473.39	2543402.049	312418873.5	20565139759	2642316523	8085.681839
2007	2397756.66	2694370.528	330963091.5	22179199294	2237509134	8231.681226
2008	2403080.77	2795179.279	343345937.7	23307748464	1926552792	8338.552249
2009	2502483.53	2858215.346	351088975.1	24068913833	1541242234	8420.958857
2010	2710923.97	2877540.603	353462793.7	24406710375	1267769805	8481.795304
2011	2567887.41	2867113.026	352181921.9	24454144662	1589106874	8529.187527
2012	2745910.69	2891031.783	355119983.1	24820544303	1461430871	8585.358504
2013	3028206.94	2900315.022	356260290.2	25040947958	1813657404	8633.871758
2014	3279672.95	2946210.577	361897872.1	25602557965	2881040321	8689.995945
2015	3413308.3	3102167.45	381054839.7	27203470387	4279046173	8769.181814
2016	3376910.07	3397484.991	417330179.4	30122343041	5399627748	8866.070969
2017	3376211.87	3795992.609	466280875.7	34015853636	5544527848	8960.990481
2018		4189827.489	514657596	37859588802	4622729770	9036.073419
2019		4466939.248	548696628	40589339132	3698183816	9086.61096
2020		4632874.793	569079326	42258055992	2958547053	9121.346439
2021		4712657.059	578879383.2	43103700245	2366837642	9146.368961
2022		4726165.01	580538632.9	43315352876	1893470114	9165.010697

2023		4689169.403	575994276.3	43043055346	1514776091	9179.249382
2024		4614161.048	566780622.5	42405678669	1431044709	9190.33346
2025		4534089.281	556945004.4	41716439444	1921314789	9200.621528
2026		4509628.479	553940361	41551932261	2927168926	9214.047777
2027		4592270.1	564091647.2	42401504574	4187833134	9233.234033
2028		4803481.135	590035761.6	44469262479	5353523929	9257.71565
2029		5126835.913	629755056.2	47599323284	6162329043	9284.346933
2030		5519160.332	677946239.1	51381686163	6338354888	9309.692611
2031		5910397.567	726003877.5	55150956743	5845223358	9331.175461
2032		6230164.358	765282441.7	58238632264	4867044537	9347.848454
2033		6430976.618	789949222.2	60193745187	3893635629	9359.96953
2034		6519284.169	800796483.1	61077693557	3114908504	9368.773009
2035		6521205.066	801032436.6	61138717383	2491926803	9375.37108
2036		6457452.897	793201436.8	60573708317	2170039968	9380.433629
2037		6363005.512	781599989.2	59715062869	2427850337	9384.725937
2038		6300418.43	773912102.9	59157160063	3258627273	9389.401787
2039		6328410.906	777350559.6	59457929333	4495054803	9395.396446
2040		6485154.024	796604105.6	60980087670	5822798688	9403.028432
2041		6773822.5	832062707.3	63753881974	6864570559	9411.802859
2042		7157717.75	879218492.8	67430758434	7315116491	9420.706542
2043		7569844.125	929842049.5	71374337003	7059157455	9428.772354
2044		7934421.124	974624877.1	74864777608	6203973145	9435.442918
2045		8190749.873	1006111027	77325511872	5018317340	9440.590065
2046		8309456.31	1020692336	78477553619	4014653872	9444.366839
2047		8316578.639	1021567208	78568329810	3211723098	9447.193759
2048		8238825.822	1012016438	77851636418	2789185240	9449.360637
2049		8120482.977	997479790.9	76748239837	2997206674	9451.191518
2050		8029954.268	986359693.9	75908034519	3840238812	9453.109194

Mean (AU$/GWh)						8249.417281
Mean (AU$/ton)						67.15850609

Brown coal

Year	Actual values (GWh)	Simulated values (GWh)	Simulated values (ton)	Capital employed (AU$)	Capex (AU$/year)	Total supply cost (AU$/GWh)
1990	125194.44	125194.44	44712300	200000000	24000000	1597.515033
1991	134472.22	126934.718	45333827.86	214000000	34223332.8	1685.905979
1992	138138.88	131995.7597	47141342.75	237523332.8	48708253.24	1799.476993
1993	129666.66	141632.0561	50582877.19	274355419.4	59778150.54	1937.099742
1994	131722.22	154476.5035	55170179.82	320415799	53307440.02	2074.204113
1995	136666.66	164521.825	58757794.64	357702449	42645952.01	2174.194512

1996	142888.88	170511.0511	60896803.96	382463278.6	34116761.61	2243.041
1997	155305.55	173357.7524	61913483	397456876.3	27293409.29	2292.697447
1998	176805.55	173787.6679	62067024.24	404877441.8	25546375.23	2329.724811
1999	185833.33	173613.7429	62004908.18	410179944.9	43735882.27	2362.600668
2000	186194.44	179511.6832	64111315.42	433406829.9	65707684.95	2414.365585
2001	185000	192438.6607	68728093.1	477444173.4	79518520.41	2481.020039
2002	185972.22	209322.9011	74758178.97	533090485.1	79302386.03	2546.737516
2003	203297.97	225290.8847	80461030.26	585738346.9	66587472.55	2599.92031
2004	201844.69	236222.1647	84365058.81	623038902.1	59358339.5	2637.512458
2005	204809.24	244197.1696	87213274.86	651245296.5	47486671.6	2666.883066
2006	206848.31	247816.2017	88505786.31	666169703.3	37989337.28	2688.160414
2007	202276.26	248088.504	88603037.14	670850555.4	30391469.82	2704.077555
2008	203456.31	245814.5687	87790917.41	667699497.4	24313175.86	2716.273087
2009	208848.86	241628.2323	86295797.23	658627698.4	19450540.69	2725.7895
2010	210937.42	236030.3342	84296547.93	645146854.2	15560432.55	2733.321784
2011	204694.74	229415.6283	81934152.98	628449944	17045076.35	2739.351057
2012	206846.61	223626.539	79866621.09	614072523.2	17819770.3	2745.97338
2013	179102.39	218385.1355	77994691.26	601188667.3	24816181.51	2752.882727
2014	173697.53	215737.9393	77049264.02	595945415.5	19852945.21	2762.357968
2015	188442.93	211568.6907	75560246.68	586001089.9	15882356.17	2769.791163
2016	176369.15	206284.3749	73672991.03	572583391.6	16282960.33	2775.699284
2017	162278.33	201397.8096	71927789.14	560237182.3	13026368.27	2781.744168
2018		195670.0419	69882157.81	545251691.5	10421094.61	2786.587493
2019		189360.238	67628656.42	528410201.5	8336875.69	2790.502416
2020		182671.1846	65239708.8	510326567.1	6669500.552	2793.689482
2021		175760.7923	62771711.52	491479739.3	5335600.442	2796.299067
2022		168751.2861	60268316.47	472241352.8	4268480.353	2798.445948
2023		161736.5486	57763053.07	452897765.5	3414784.283	2800.219056
2024		154787.9826	55281422.36	433667661.5	4408707.704	2801.688182
2025		148518.1527	53042197.39	416392986.1	7607210.685	2803.650453
2026		143627.982	51295707.84	403180547.5	12139966.07	2807.116984
2027		140493.2382	50176156.51	395161486.2	16697970.83	2812.672633
2028		139034.5666	49655202.35	392101382.7	19880256.47	2820.171935
2029		138709.5904	49539139.43	392376570.1	20648326.24	2828.763093
2030		138656.8863	49520316.54	393406067.8	18684381.44	2837.263105
2031		137952.1691	49268631.84	392420145.9	14947505.16	2844.610189
2032		136037.0624	48584665.14	387746643.7	11958004.12	2850.301505
2033		133221.2107	47579003.81	380317315.7	9566403.3	2854.78051
2034		129748.9512	46338911.15	370867853.2	7653122.64	2858.349526
2035		125812.5445	44933051.62	359977583.2	6122498.112	2861.221705

2036		121562.75	43415267.86	348101202.1	4897998.489	2863.551557
2037		117117.2787	41827599.53	335594140.5	3918398.791	2865.453708
2038		112567.5477	40202695.6	322732832.3	3134719.033	2867.014863
2039		107984.0766	38565741.66	309730909.7	2507775.227	2868.301692
2040		103420.7979	36935999.24	296752139.4	2006220.181	2869.366177
2041		98918.49805	35328035.02	283920752.6	1604976.145	2870.249329
2042		94507.56519	33752701.85	271329691.1	1283980.916	2870.983826
2043		90210.18057	32217921.63	259047187.5	1027184.733	2871.595931
2044		86042.06645	30729309.45	247122012.9	821747.7862	2872.106901
2045		82013.87906	29290671.09	235587660	657398.229	2872.534048
2046		78132.31785	27904399.23	224465675.2	550930.7569	2872.891544
2047		74409.34554	26574766.27	213793322.2	574799.5223	2873.20525
2048		70880.47811	25314456.47	203678455.6	590307.991	2873.547993
2049		67533.22353	24119008.4	194084840.9	472246.3928	2873.916433
2050		64313.97782	22969277.79	184852845.2	377797.1142	2874.225036
Mean (AU$/GWh)						2664.649163
Mean (AU$/ton)						21.69290883

Natural gas

Year	Actual values (GWh)	Simulated values (GWh)	Simulated values (GJ)	Capital employed (AU$)	Capex (AU$/year)	Total supply cost (AU$/GWh)
1990	221472.22	221472.22	790972214.3	1000000000	240000000	4515.238977
1991	233444.44	237065.2757	846661698.8	1190000000	292883332	5019.714493
1992	258916.66	257754.6043	920552158.3	1423383332	319197461.4	5522.242118
1993	271694.44	280333.2587	1001190210	1671411627	372157383	5962.230934
1994	295805.55	307667.4161	1098812200	1959998428	373075333.7	6370.510252
1995	326361.11	333736.8601	1191917358	2235073841	374257779.8	6697.114127
1996	334472.22	358634.2149	1280836482	2497577928	412632738.6	6964.137343
1997	340472.22	386550.5862	1380537808	2785331771	372333207.7	7205.607416
1998	354305.55	408593.4133	1459262190	3018398390	264206041.5	7387.290865
1999	370166.66	417519.9695	1491142748	3131684512	176137361	7500.681981
2000	365694.44	416214.7889	1486481389	3151237647	144912794.4	7571.18135
2001	381888.88	411505.4711	1469662397	3138588559	109996400.3	7627.088289
2002	385805.55	403152.0198	1439828642	3091655532	176149801.9	7668.709023
2003	398779.46	402566.619	1437737925	3113222557	273210887.5	7733.434443
2004	399628.24	412795.0533	1474268048	3230772317	404474083.2	7826.577113
2005	447535.09	437096.8655	1561060234	3473707784	451482592.4	7947.226481
2006	464213.93	465406.7547	1662166981	3751504987	605519230.1	8060.701633
2007	492373.28	509416.3314	1819344041	4169448968	676849331.7	8184.757164
2008	512544.4	559150.9961	1996967843	4637825851	671740389.1	8294.406848

2009	537675.83	605831.2673	2163683098	5077674948	558476183.8	8381.335236
2010	572810.74	637592.6133	2277116476	5382267384	414527187.9	8441.546016
2011	630644.53	651771.559	2327755568	5527681203	350789638.6	8481.010143
2012	598627.88	658159.6076	2350570027	5602086781	519306534.6	8511.745049
2013	684464.34	682952.3533	2439115547	5841288977	455454515.1	8552.996338
2014	704033.57	699410.7929	2497895689	6004679043	719531299	8585.339409
2015	738707.51	744388.1753	2658529198	6423976390	918056186.6	8629.874309
2016	940636.9	809175.0095	2889910748	7020833757	1029830140	8676.533104
2017	1154123.65	883141.8301	3154077965	7699622209	1703715339	8718.443569
2018		1028286.443	3672451582	9018356437	2759238221	8770.276511
2019		1283454.145	4583764805	11326676837	3403231192	8825.151158
2020		1644320.717	5872573991	14163574187	3393740538	8866.540933
2021		2064643.757	7373727703	16849136015	2648405827	8893.102879
2022		2473641.159	8834432710	18655085041	1765603884	8908.123817
2023		2797563.273	9991297403	19487934674	1177069256	8916.370437
2024		2987804.324	10670729730	19690607196	784712837.5	8921.325962
2025		3058493.585	10923191375	19490789674	523141891.7	8924.46685
2026		3073911.531	10978255467	19039392082	872469888.9	8926.525317
2027		3129537.906	11176921095	18959892367	1849213858	8929.880031
2028		3318253.206	11850904307	19861111606	2975631114	8936.362546
2029		3662845.217	13081590062	21843687140	3823323029	8944.978488
2030		4124139.428	14729069387	24574825812	4070661825	8953.494438
2031		4615649.799	16484463569	27416746346	3479606712	8960.368879
2032		0	0	0	0	0
2033		0	0	0	0	0
2034		0	0	0	0	0
2035		0	0	0	0	0
2036		0	0	0	0	0
2037		0	0	0	0	0
2038		0	0	0	0	0
2039		0	0	0	0	0
2040		0	0	0	0	0
2041		0	0	0	0	0
2042		0	0	0	0	0
2043		0	0	0	0	0
2044		0	0	0	0	0
2045		0	0	0	0	0
2046		0	0	0	0	0
2047		0	0	0	0	0
2048		0	0	0	0	0

2049	0	0	0	0	0
2050	0	0	0	0	0

Mean (AU$/GWh)	7993.205768
Mean (AU$/GJ)	2.238097615

Wind power

Year	Actual values (GWh)	Simulated values (GWh)	Capital employed (AU$)	Capex (AU$/year)	Total supply cost (AU$/GWh)
2005	885	885	100000000	45000000	112994.3503
2006	1713	1599.6	140000000	29137500	87521.88047
2007	2611	2021.241	162137500	31328390.93	80216.8074
2008	3093	2462.531209	185359015.9	55584669.78	75271.74286
2009	3823.8	3290.441124	231675734.9	72732695.87	70408.7161
2010	5051.7	4371.035076	292824644	83441924.46	66992.05999
2011	6084.9	5586.892414	361625336.3	103086863.9	64727.4566
2012	6969.828	7081.531116	446630933.4	114360024.1	63069.82573
2013	7959.6	8704.270274	538659410.8	104313247.6	61884.49967
2014	10251.937	10094.65359	616039688	79319644.76	61026.33265
2015	11466.501	11012.86153	664557348.3	121975609.6	60343.74869
2016	12199.498	12605.27389	753305090.5	162636785.1	59761.10452
2017	12596.985	14811.67602	878276621.1	154351177.4	59296.23493
2018		16791.7286	988713967.5	80384431.46	58881.01164
2019		17459.79998	1019662701	63289234.67	58400.59459
2020		17816.22856	1031968800	130574231.8	57922.96594
2021		19279.81662	1110944592	247939854.3	57622.15555
2022		22640.95486	1303337217	345538257.4	82565.4704
2023		27494.28762	1583708613	375622445.8	82601.36924
2024		32654.89021	1880145628	259330244.1	82576.23487
2025		35670.86534	2045468591	129665122.1	82342.83628
2026		36405.11609	2072860284	64832561.04	81938.70824
2027		36029.45413	2034049830	32416280.52	81455.19421
2028		35128.54731	1964763619	148079356.3	80930.68231
2029		36191.39469	2014604795	386614991.1	80665.29867
2030		41187.32209	2300489546	573046039.5	80854.31219
2031		49090.59653	2758511108	534658331.1	81192.25073
2032		56037.94485	3155243884	267329165.5	81305.48894
2033		56349.20154	3264810855	133664582.8	82938.90182
2034		56322.97652	3235234895	66832291.39	82440.76565
2035		55183.92898	3140305442	33416145.69	81906.15909
2036		53533.50759	3016706316	159403680.4	81351.74028

2037		54048.89529	3025274680	448589087	80972.92348
2038		59363.42426	3322600033	692045634	80970.4915
2039		68522.98119	3848515665	655649659.3	81163.86793
2040		76709.55626	4311739542	327824829.7	81208.6362
2041		77350.16131	4423977394	163912414.8	82194.1586
2042		76988.02844	4366690939	81956207.42	81719.09033
2043		75274.44409	4230312600	40978103.71	81198.52329
2044		72946.43473	4059775073	125952689.3	80654.1946
2045		72127.78883	3982739009	421585396.4	80217.81652
2046		76269.10055	4205187455	756108575.4	80136.18785
2047		85820.14611	4751036658	821522630.1	80360.38882
2048		96079.38411	5335007455	472355322.8	80527.078
2049		100045.0861	5540612405	236177661.4	80381.15486
2050		98223.12887	5499759446	118088830.7	80992.50919

Mean (AU$/GWh) 76437.04178
Mean (AU$/MWh) 76.43704178

Solar power

Year	Actual values (GWh)	Simulated values (GWh)	Capital employed (AU$)	Capex (AU$/year)	Total supply cost (AU$/GWh)
2010	424.8	424.8	50000000	11000000	117702.4482
2011	1530.5	607.808	58500000	6668200	96247.49921
2012	2558.6	704.73568	62243200	36685057.29	88321.34056
2013	3826.2	1343.547294	95816097.29	83923669.77	71315.76066
2014	4415.957	2815.690308	174948962.2	130856247.8	62133.59535
2015	5531.334	5082.267201	297057761.9	128121134.5	58449.85125
2016	6838.261	7208.451686	410326008.3	93472193.72	56922.9047
2017	8071.656	8619.60805	483281901.6	51840605.42	56067.7352
2018		9217.38019	510958412	28045387.44	55434.23418
2019		9358.601118	513455878.8	164141100.1	54864.597
2020		11968.64071	651924185	391600049.6	54469.35878
2021		18609.89599	1010928025	586918606.7	54322.06747
2022		28536.74754	1547300231	639121558.2	79221.32388
2023		39015.6696	2109056777	660596430.2	79056.65977
2024		49465.88701	2664200369	430151619.6	78859.34691
2025		55308.19006	2961141970	215075809.8	78538.94182
2026		57006.33173	3028160681	107537904.9	78119.72529
2027		56681.31309	2984290552	63191771.13	77650.34257
2028		55563.00186	2898267795	322780157.2	77161.82888
2029		59209.21192	3076134563	755128328.3	76953.64814

2030		70570.44941	3677456163	1052098647	77110.42573
2031		86876.69774	4545682002	929808493.9	77323.37462
2032		100307.2388	5248206396	464904247	77321.31258
2033		99074.22103	5450700323	232452123.5	80016.33286
2034		99337.65444	5410617430	116226061.7	79466.93362
2035		97477.34938	5256312620	86233604.85	78923.42584
2036		95146.13913	5079730594	421889955.3	78388.72014
2037		99011.02003	5247634020	966426401.3	78000.50457
2038		112621.9683	5951678720	1310751605	77846.51661
2039		131948.937	6964846389	1082555477	77784.40698
2040		146353.8064	7699159547	541277738.6	77606.48656
2041		144302.3732	7855479308	270638869.3	79437.63076
2042		143450.985	7733344212	135319434.6	78909.31414
2043		140173.2989	7481996436	67659717.32	78376.7593
2044		135796.5436	7175556332	413304487.5	77840.49313
2045		137879.3089	7230083003	1087247906	77437.76646
2046		152132.2803	7955826758	1577166925	77295.45459
2047		174722.7514	9135202346	1380787877	77283.98862
2048		192839.0755	10059230105	690393938.3	77163.85777
2049		190806.3823	10246662538	345196969.2	78701.88572
2050		189450.4355	10079526380	172598484.6	78204.02854
Mean (AU$/GWh)					75420.80071
Mean (AU$/MWh)					75.42080071

Hydro power

Year	Actual values (GWh)	Simulated values (GWh)	Capital employed (AU$)	Capex (AU$/year)	Total supply cost (AU$/GWh)
1990	14880	14880	1000000000	75000000	67204.30108
1991	16103	15582.4	1025000000	50420082.74	65779.34079
1992	15768	15943.01977	1024170083	50510068.73	64239.40367
1993	16953	16297.62696	1023471647	33673379.15	62798.81421
1994	16649	16420.65281	1005971444	43741827.46	61262.57317
1995	16239	16675.46412	999414699.4	36725015.77	59933.24638
1996	15731	16831.62171	986168980.2	24483343.85	58590.25334
1997	16852	16821.43386	961343875	16322229.23	57149.93638
1998	15733	16702.63491	929598910.5	12297860.11	55655.8241
1999	16563	16532.55368	895416825.1	8198573.409	54160.82975
2000	16720	16311.21692	858844557.2	6870707.935	52653.61632
2001	16933	16076.60202	822773037.3	17874100.47	51178.2923

2002	16054	15993.39132	799508485.9	39877453.95	49989.92835
2003	16490	16205.22288	799410515.6	28906349.77	49330.424
2004	16331.1	16266.53642	788346339.6	28612434.98	48464.30238
2005	15612.2	16322.70482	777541457.6	21526541.88	47635.57671
2006	16029.2	16283.27128	760190926.6	14351027.92	46685.39346
2007	14517	16148.9529	736532408.2	9567351.948	45608.67896
2008	12056.9	15788.2878	709273139.7	6378234.632	44924.00623
2009	11869.4	13869.62204	680187717.4	4252156.421	49041.54672
2010	13548.7	12973.04608	650430487.9	2834770.947	50137.06757
2011	16806.7	12751.3821	620743734.5	20616553.2	48680.50611
2012	14083.3	12771.24184	610323100.9	138712770.7	47788.86099
2013	18269.6	14365.32061	718519716.6	136534747.4	50017.65962
2014	18421	15898.4775	819128478.2	212391518.7	51522.44788
2015	13445	18412.39486	990563573	223326834.5	53798.73614
2016	15318.18	18841.56924	1164362229	148884556.3	61797.51876
2017	16284.88692	18935.09818	1255028674	99256370.87	66280.54748
2018		19021.7996	1291533611	66170913.92	67897.55112
2019		19081.99743	1293127844	44113942.61	67766.90169
2020		19288.54339	1272585395	29409295.07	65976.23103
2021		19294.89645	1238365420	19606196.72	64180.98293
2022		19170.41448	1196053346	13070797.81	62390.58352
2023		18961.28349	1149321476	8713865.207	60614.11805
2024		18698.24269	1100569268	26766415.37	58859.50277
2025		18681.16338	1072307220	66238844.36	57400.45188
2026		19190.7247	1084930703	112684790.1	56534.11842
2027		20309.37408	1143368958	145110874.7	56297.59704
2028		21837.99826	1231311385	146678026.1	56383.89427
2029		23356.94531	1316423842	115264941.9	56361.13046
2030		24426.67229	1365867591	76843294.6	55917.05555
2031		24962.71611	1374417506	51228863.06	55058.81253
2032		25146.51329	1356925494	34152575.38	53960.7809
2033		25098.9507	1323231795	22768383.58	52720.60217
2034		24900.55013	1279838589	17268968.82	51398.00454
2035		24632.79205	1233115628	37378259.42	50059.92117
2036		24638.513	1208838106	78094156.46	49062.94897
2037		25186.99816	1226490357	124163827.6	48695.37646
2038		26338.7759	1289329667	154976266.4	48951.76875
2039		27878.3506	1379839450	154852310.6	49495.01748
2040		29385.48106	1465699788	122404077.3	49878.3663
2041		30429.8258	1514818876	81602718.21	49780.72782

2042		30909.26553	1520680650	54401812.14	49198.21369
2043		31016.43772	1499048430	36267874.76	48330.77363
2044		30879.68062	1460363883	24178583.17	47292.06565
2045		30584.46812	1411524272	27995756.65	46151.66976
2046		30346.05551	1368943815	57757015.41	45111.09573
2047		30509.22794	1358253640	104076917.9	44519.43663
2048		31286.73562	1394417876	148345172.7	44568.97942
2049		32638.93655	1473042155	170077998.5	45131.43842
2050		34253.86446	1569468046	157712406	45818.71477
Mean (AU$/GWh)					53837.28633
Mean (AU$/MWh)					53.83728633

Bio power

Year	Actual values (GWh)	Simulated values (GWh)	Capital employed (AU$)	Capex (AU$/year)	Total supply cost (AU$/GWh)
1990	49833.32	49833.32	4000000000	0	80267.58
1991	49527.77	48172.20933	3800000000	161958290	78883.65621
1992	45861.1	49058.13502	3771958290	302713227.8	76887.51903
1993	50777.77	52079.99044	3886073603	255250402.4	74617.4024
1994	53444.43	54270.92002	3947020326	295007092.1	72728.08944
1995	55638.88	57000.46	4044676401	344677216.3	70958.66246
1996	58499.99	60403.17108	4187119798	368557052.8	69319.5361
1997	60944.43	64059.84054	4346320861	377380210.9	67847.82515
1998	61555.54	67730.36192	4506385028	355233535.8	66534.19383
1999	60749.99	70937.81451	4636299313	256326229.3	65357.23358
2000	59416.66	72516.70115	4660810576	170884152.9	64272.23664
2001	57749.99	72728.46474	4598654201	113922768.6	63230.4589
2002	51861.1	70173.19153	4482644259	75948512.39	63879.72616
2003	55666.66	63743.73745	4334460559	50632341.59	67998.21805
2004	56749.99	62397.90531	4168369872	33754894.4	66803.04173
2005	57972.21	60837.2812	3993706273	41698770.55	65645.70596
2006	57777.77	59450.89137	3835719730	129268093.4	64519.12901
2007	58194.43	59457.93489	3773201837	222442806.6	63460.02167
2008	58194.43	60898.20075	3806984552	298326573.7	62513.90853
2009	42972.21	63457.90032	3914961898	305796597.6	61693.84549
2010	50249.99	58958.8118	4025010400	203864398.4	68268.17362
2011	46666.65	60129.89343	4027624279	135909598.9	66982.06248
2012	46777.77	57607.22249	3962152664	90606399.3	68778.74844
2013	51777.77	56670.70516	3854651430	60404266.2	68018.41303
2014	50833.32	55710.97806	3722323125	64859497.91	66814.89456

2015	54138.88	54851.78388		3601066466	65363289.58	65650.8542
2016	55027.77	54028.98016		3486376433	197333260.6	64527.89637
2017	57749.99	55263.91047		3509390872	335282164.6	63502.39861
2018		58579.96727		3669203493	473152221.2	62635.80647
2019		63906.56664		3958895539	559117257.2	61948.18072
2020		70378.1517		4320068019	477718999.5	61383.65266
2021		75381.73638		4581783618	318479333	60781.08356
2022		77654.4436		4671173770	212319555.3	60153.33513
2023		76638.51051		4649934637	141546370.2	60673.60399
2024		75842.67118		4558984275	94364246.82	60111.0721
2025		74766.33978		4425399308	62909497.88	59189.72791
2026		73241.96689		4267038841	41939665.25	58259.47913
2027		71445.79361		4095626564	27959776.84	57324.95025
2028		69494.41757		3918805013	18639851.22	56390.21305
2029		67464.70392		3741504613	64904725.46	55458.6976
2030		66214.4147		3619334108	165883782.6	54660.81856
2031		66559.32573		3604251185	283237697.4	54150.95699
2032		68698.18458		3707276323	363610234.2	53964.69129
2033		72002.2487		3885522741	365430949.8	53963.90823
2034		75224.18835		4056677554	284368922.1	53927.83416
2035		77091.6219		4138212599	189579281.4	53679.14822
2036		77438.5055		4120881250	126386187.6	53214.8861
2037		76801.62487		4041223375	84257458.41	52618.98276
2038		75537.8393		3923419665	56171638.94	51939.79205
2039		73884.09038		3783420321	38954494.82	51207.51032
2040		72020.58729		3633203799	83881597.01	50446.73941
2041		70910.38716		3535425206	179077495.2	49857.64918
2042		71301.74597		3537731441	288018378.6	49616.33678
2043		73356.07308		3648863248	361363476.4	49741.80179
2044		76470.30875		3827783562	361498713	50055.81414
2045		79482.81712		3997893097	284993312.4	50298.83491
2046		81217.90238		4082991754	189995541.6	50272.06607
2047		81433.6473		4068837708	126663694.4	49965.0678
2048		80667.86461		3992059517	84442462.95	49487.6062
2049		79278.0506		3876899004	56294975.3	48902.55215
2050		77501.52546		3739349029	61775252.67	48248.7152
Mean (AU$/GWh)						60565.45814
Mean (AU$/MWh)						60.56545814