



# 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<sub>2</sub> 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<sub>2</sub> 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 from the total energy production capacity of the Australian energy from the total energy production capacity of the Australian energy from the total energy production capacity of the Australian energy from the total energy production capacity of the Australian energy from the total energy production capacity of the Australian energy 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> emissions resulting from burning, it is excluded from the CO<sub>2</sub> emissions model, as they are carbon-neutral energy resources. In other words, they captured already a nearly equivalent amount of CO<sub>2</sub> 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<sub>2</sub> emissions to compare modelled with historical trends between 1990 and 2017 for most resources and between 2007 and 2017 for CO<sub>2</sub> 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<sub>2</sub> 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  $\pm$  20% to identify the most influential parameters in energy production capacity. The most influential parameter was the gross demand growth rate parameter.

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%

Table 1.	Energy	sector	develo	opment	scenarios.
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# 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<sub>2</sub> 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 results from model calibration. Energy production capacity (GWh/year) is the quantity of capacity that is currently under construction results from model calibration. Energy production capacity (GWh/year) is the quantity of capacity that is currently of 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub>-e) (ton). Production and consumption in GWh. CO<sub>2</sub> 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 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.

## 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.



**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.



**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.

Scenarios	Oil Dep	endency	Australia's Global CO <sub>2</sub> Footprint	Australia's Domestic CO <sub>2</sub> 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%

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

## 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<sub>2</sub> emission levels), Australia's global CO<sub>2</sub> 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<sub>2</sub> 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.

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# Appendix A

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

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 A2.	Parameters	used	for f	lows.

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 <sub>2</sub> -e)	ton/year	"Black coal (CO <sub>2</sub> -e)" + "Brown coal (CO <sub>2</sub> -e)" + "Gas (CO <sub>2</sub> -e)" + "Oil (CO <sub>2</sub> -e)"

Variable Name	Units	Parameter Value
(CO <sub>2</sub> -e)	ton/GWh	300 (coal), 250 (oil), 150 (gas)
(CO <sub>2</sub> -e)	ton/year	"Total net consumption" * "(CO <sub>2</sub> -e)"
Total net consumption	GWh/year	"Energy production capacity" * "Domestic consumption of total production"/100
Australia's domestic CO <sub>2</sub> % footprint	%	"Total CO <sub>2</sub> emissions of total consumption"/"Global CO <sub>2</sub> emissions" * 100
Australia's global $CO_2$ % footprint	%	"Total CO <sub>2</sub> emissions of total production"/"Global CO <sub>2</sub> emissions" * 100
Total CO <sub>2</sub> emissions of total production	ton/year	("Energy production capacity (black coal)" * "Black coal-(CO <sub>2</sub> -e)") + ("Energy production capacity (brown coal)" * "Brown coal-(CO <sub>2</sub> -e)") + ("Total net oil consumption" * "Oil-(CO <sub>2</sub> -e)") + ("Energy production capacity (gas)" * "Gas-(CO <sub>2</sub> -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")

#### Table A3. Cont.

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