FUTURE FUELS CRC

Modelling literature review to assist with the broad scale assessment of the costs and benefits of investing in future fuels – Part 1

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Regional and national implications of developing future fuels over the next 30 years

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IMPORTANT DISCLAIMER

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Summary of the Report

The implications of future changes in the energy system, such as the impact of reductions in greenhouse gas intensity, are typically explored through models. This report provides a review of the models being used to investigate the opportunities and challenges of alternative energy resources for Australia, coupled with a review of approaches being taken in other developed countries. This report complies with the second deliverable of Future Fuels CRC RP1.1-01: *Regional and national implications of developing future fuels over the next 30 years*. This report consists of two parts. Part 1 is structured as follows:

- First, we review studies on decarbonising energy systems including some which modelled the introduction of hydrogen (Section 2). This review will assist with better understanding of the literature gap, and with the development of our modelling approach.
- Then, we review a series of dynamic economic models (such as Computable General Equilibrium models) that are being used to support energy transition policy analyses (Section 3), as well as techno-economic models that are being used to simulate energy systems from production to distribution and consumption (Section 4). All the models under review can include actual or potential harnessing of future fuels supply chains.
- Finally, we propose a modelling framework and identify the modelling requirements to meet the objectives of RP1.1-01 (i.e. developing a model to investigate the regional and national implications of future fuels). This modelling framework includes two coupled components:
    - a dynamic economic model that can simulate the Australian economy (National and regional levels) under different energy scenarios, and
    - a techno-economic model of the energy system that can dynamically respond to economic scenarios and identify logistical constraints and opportunities associated with the introduction of future fuels in the Australian energy sector.

NOTE: *Part 2 of the report has been removed from the public version.*

1. Introduction

The potential implications of adoption of 'future fuels' such as low carbon intensity hydrogen as part of Australia's energy system are currently uncertain. In order to address this gap, the Future Fuels CRC has a work stream focussed on exploring the understanding of the technical, commercial and market barriers to, and opportunities for, the use of future fuels.

This review aims to provide an inventory of existing simulation models used to assess the constraints and opportunities of energy transitions in Australia and beyond. Due to the complex nature of the interactions between economic, social, technological and political dimensions, such models cannot be developed in isolation of their policy context and associated techno-economic pathways. Therefore, our report starts with a review of recent seminal reports addressing the Australian energy transition, their assumptions, methods and recommendations (Section 2). Then, we review well-known dynamic economic models (Section 3) and techno-economic models (Section 4) that have been used in the context of energy transition analyses, or have the potential to do so. Finally, we propose a scenario-based modelling framework (Section 5) that draws from lessons of the above reviews, as well as the recent report by Kosturjak, Dey, Young and Whetton: *Advancing Hydrogen: Learning from 19 plans to advance hydrogen from across the globe* (Future Fuels CRC, 2019).

The latter report emphasizes that hydrogen has a potentially important role in the decarbonisation of energy supply chains around the world aim to achieve one or more of the following objectives: reduced GHG emissions, improved air quality, higher energy security, as well as more flexible shifting of energy supply between regions and/or seasons. The report also lists various complementary mechanisms through which countries aim to use hydrogen in order to reach these objectives: long-term energy storage, industrial heat, industrial feedstock, household heating, combined heat and power generation, fuel cell-powered heavy vehicles, fuel cell-powered small passenger vehicles or energy exportation.

The energy transition pathways selected for Australia will dictate which economic scenarios need to be develop, as well as the very nature of the modelling framework we need to build.

2. Future Fuels Studies Review

The studies reviewed in this section include:

- Jacobs Australia (2016): Modelling illustrative electricity sector emissions reduction policies (iteration with CGE modelling)
- Deloitte Access Economics (2017): Decarbonising Australia’s gas distribution networks
- CSIRO (2018): National Hydrogen Roadmap
- ACIL Allen Consulting (2018): Opportunities for Australia from Hydrogen Exports
- Fisher (2019): Economics Consequences of Alternative Australian Climate Policy Approaches (using BAEGEMv16.1)
- Navigant Netherlands B.V. (2019): Gas for Climate. The optimal role for gas in a net-zero emissions energy system

This review shows that:

- Most of these studies analyse the implications of different sets of emissions policies to meet Paris commitment (with the target of 2^{o}C) (Jacobs, 2016; ACIL Allen Consulting 2018; Fisher, 2019; Navigant Netherlands B.V. 2019).
- The range of decarbonisation policies considered is broad, including one or more of the following approaches: renewable electricity (Fisher, 2019), renewable electricity and gas (Deloitte, 2017; Navigant Netherlands B.V. 2019), cap and trade (Jacobs, 2016; Fisher, 2019), and emissions intensity (Jacobs, 2016).
- Although reducing emissions from the electricity sector has generally been the focus of energy sector decarbonisation debates; it may not be possible to shift all the energy consumption currently met by hydrocarbons such as gas, petrol and diesel to electricity (or where technically possible, may not be economically viable) and thus, moving towards renewable and low-carbon gas may be required and could bring economic benefits by lowering the costs of decarbonisation (Deloitte, 2017; Navigant Netherlands B.V. 2019).
- Most studies use a modelling framework that brings together a dynamic economic model and a techno-economic model identifying the least cost ‘basket’ of energy technologies that will meet expected energy demand (Jacobs, 2016; ACIL Allen Consulting, 2018; Navigant Netherlands B.V. 2019).
- Gas system decarbonisation can be achieved through hydrogen and/or biogas (Deloitte, 2017; Navigant Netherlands B.V. 2019)
- Australia has potential significant comparative advantages in becoming a hydrogen exporter (Deloitte, 2017; CSIRO, 2018; ACIL Allen Consulting, 2018).

When analysing broad economy-wide scenarios, one of the most difficult challenges to resolve is the question of which suite of international policy assumptions to make. If many countries decide to pursue a zero-emission greenhouse gas policy then, for example, prospects for the development of a viable hydrogen production sector are likely to be very different to one where many countries decide that this is an aspirational rather than mandatory policy goal.

Table 1 summarises these studies and provides more information regarding the aim of the studies and the modelling approach.

Based on this preliminary review, we decided to split our modelling review into two sections: dynamic economic models (Section 3) and techno-economic models (Section 4). Section 5 brings all the previous elements together in order to propose an integrated modelling framework.

Table 1: Future fuels and decarbonising energy sector literature review

Author	Study	Country	Aim	Scenarios	Model
Jacobs Australia (2016)	Modelling illustrative electricity sector emissions reduction policies (iteration with CGE modelling)	Australia	To examine the effects of electricity sector emissions reduction policies	• Cap and Trade where the revenue is used to decrease income taxes • Cap and Trade where the revenue is transferred to households in lump-sum manner • Emissions Intensity where generators with intensity below (above) the baseline receive a subsidy (tax).	An integration of Jacobs' detailed electricity sector model and the Victoria University's economy-wide CGE model (VURM).
Deloitte Access Economics (2017)	Decarbonising Australia's gas distribution networks	Australia	To identify an approach to decarbonise Australia's gas network	• H2 produced by electrolysis using renewable energy electricity • H2 produced by Steam Methane Reforming (SMR) of natural gas or coal gasification combined with Carbon Capture and Storage (CCS) • Biogas from anaerobic digestion of waste or another biomass.	Commercial assessment via estimating and comparing the levelled cost of production of each decarbonisation gas technologies by 2050.
CSIRO (2018)	National Hydrogen Roadmap	Australia	To quantify economic opportunities of hydrogen technologies in Australia	• Base case: the current state of hydrogen technologies (in 2018) • Best case: which could be achieved by 2025 given the investment in hydrogen technologies.	Techno-economic model of levelled cost of hydrogen-related technologies
ACIL Allen Consulting (2018)	Opportunities for Australia from Hydrogen Exports	Australia	To quantify the Australian market opportunities for exporting hydrogen	• Low hydrogen uptake by 2040: current R&D funding with limited commercial applications of H_2 tech, and low carbon price • Medium hydrogen uptake: current R&D funding with moderate commercial applications of H_2 tech and moderate carbon price • High hydrogen uptake: Increased current R&D funding with increased commercial applications of H_2 tech and high carbon price	An energy demand market and a potential supply model are developed to estimate Australia's hydrogen export, following by an input-output model to quantify the economic impact of hydrogen export

Fisher (2019)	Economics Consequences of Alternative Australian Climate Policy Approaches (using BAEGEMv16.1)	28 countries including Australia	To simulates the consequences of the emissions reduction approaches proposed by the Coalition government and by the Labor Party	• A reference case where current mitigation policies continue to 2030 without any new international agreement. 6 policy scenarios: • Three scenarios to support LNP targets (-27% emissions relative to 2005 by 2030, -27% emissions with use of Kyoto carryover, -27% emissions with use of carryover and permit trading) • Three scenarios to support ALP targets (-45% emissions and 50% renewables, -45% emissions and 50% renewables with use of carryover, -45% emissions and 50% renewables with carryover and trading).	BAEGEMv16.1: a multi-regional, multi-sector CGE model
Navigant Netherlands B.V. (2019)	Gas for Climate. The optimal role for gas in a net-zero emissions energy system	EU	To study the role of low-carbon gas in fully decarbonising the EU energy system by 2050	• Minimal gas: most of the current demand of gas will be met by electricity by 2050 • Optimised gas: low-carbon gas (including renewable methane and hydrogen) are used in addition to renewable electricity.	An optimisation model which estimates and compares the cost saving (in terms of societal cost) of using low-carbon gas

3. Dynamic Economic Modelling Review

Among the available approaches used to investigate how an economy might react to changes in policy, technology or other external factors, computable general equilibrium (CGE) appears to be the most broadly applied. CGE models are founded in microeconomic theory that equates supply with demand. Specifically, these models describe an economy as a group of sectors including households, industries, government, foreign sector and the monetary sector. Interdependent relationships between these sectors are modelled using a set of equations that describe how changes in prices and or production costs in one sector impact on other sectors through changing demand for inputs and outputs and changing patterns of production and trade. At the start of each model run, a database that describes the current state of the economy is used to populate the equation system. The model is then run to estimate the likely state of the economy at the end of a defined period. “Shocks” can then be modelled relative to this base case by, for example, exploring the impact of a change to tax rates, an increase or decrease to productivity in a sector, or a change in world markets. Constraints on rates of change to the underlying dataset can be imposed, for example, by setting a limit for greenhouse gas emissions, immigration rates, etc.

The advantages of CGE models are (Charney, 2003): First, these models are very flexible. In other words, the designer can make decisions about how to show economic relationships and interactions including which variables will be determined endogenously by the model, and which to set as exogenous. Secondly, the models explicitly capture the ***net*** impact of “shocks” through the whole economy not just the first order impacts on demand and supply and therefore do not assume a constant relationship between inputs and outputs. Thirdly and importantly, CGE models conform to many economic theories. Fourthly, these models can be applied in investigating the impacts of policy and technology changes on either one or several sectors or regions, or a whole economy. Due to such advantages, researchers have shown an increased interest in using CGE models for economic analysis. RP1.1-01 can also benefit from these advantages and use a CGE model to estimate the demand of energy in detail under different scenarios and calculate the economic gain/losses that shifting towards future fuels and other decarbonisation scenarios can bring to the economy at national and regional levels, and by industry sector.

There are two alternative approaches to a CGE modelling paradigm. The first one is to use input-output tables (I-O model). This approach, although potentially very granular, tends to produce serious over-estimates of benefits and costs as it only models the first order impact of a shock without including second order impacts such as changes to input costs, or changes to the mix of inputs used in production, arising from increased (or decreased) demand. For example, the overall impact of the Australian resource investment boom from roughly 2009 to 2015 was much smaller than an IO model would have suggested, as the very large direct impact on employment, household income and GDP from the investment was partially offset by reductions in activity on other sectors and regions (relative to a no boom scenario) due to the higher wages employers had to pay to retain staff and the increased value of the Australian dollar relative to many of our key trading partners. The second alternative approach, rarely used in Australia, involves whole-of-system and long-term analysis of the economy using a Stocks and Flows framework to create ‘what if’ scenarios quantifying sustainability challenges and exploring potential solutions (Turner et al., 2011).

As noted above, the use of CGE models in environmental and energy studies in Australia is extensive, to the point that many of the implemented national policy design and development processes have been influenced by CGE model results. We review some of the most prominent environmental CGE models developed for the Australian economy including ORANI, GTEM, VURM and G-Cubed.

These models have common features including:

- They can be used for forecasting with a recursive dynamic approach (except G-Cubed which is a forward-looking optimisation model). In this approach, the model includes iterative adjustment paths such as physical capital accumulation which indicate the sequences of solutions for every year, and policy analysis is conducted through a comparison of the sequences of solutions with and without the policy.
- These models can be used to model different types of adjustment dynamics by choosing which sets of variables to make exogenous and endogenous in the model solution.
- Industries can produce various types of commodities.
- Sectors, commodities and regions can be (dis)aggregated to the desired level (to the extent that it is supported by available data).

Table 2 summarises these studies including the advantages that the models can bring to RP1.1-01.

Table 2: Australia's prominent CGE models

Model	Developer / Owner	Database	Scale - Regions	Sectors	Software	Advantages
ORANI-E	CoPS	input-output statistics	National – Australia	100+	GEMPACK	• Substitution can happen between energy and capital, between different sources of energy, between different techniques of generating electricity, and between different modes of transport. • Good details on electricity sector and fossil fuels: fossil fuels are disaggregated into six products and electricity industry is disaggregated into seven based on the generation technologies. • It is suitable for analysis at national level.
GTEM	ABARE	Global Trade Analysis Project (GTAP)	International: 13 countries including Australia	19 sectors in each region	GEMPACK	• The model consists of three modules of economic, population (in which population is endogenously estimated) and environment (including greenhouse gas emissions account). • Electricity sector is disaggregated into 12 sectors based on the production technologies. • It is suitable for international analysis.
VURM	CoPS	multi-regional input-output statistics	Regional: Eight states and territories of Australia which can be disaggregated into 56 sub-state regions.	58 sectors in each region	GEMPACK	• There is an energy and gas emission accounting module by each region and industry • It is rich in industry detail • Electricity sector is disaggregated into one end-use supplier and 5 production sectors based on the fuel usage with the possibility of inter-fuel substitution. Electricity can be distributed to local and inter-state users • Each region has its own economic characteristics such as region-specific industries, region-specific consumers and region-specific prices. • It models the emissions from burning fuels due to fuel usage with equations that make allowance for inter-fuel substitution in electricity generation by region. • It is suitable for inter(sub)state analysis.

G-cubed	McKibbin et al.	Regional input-output data and the US time-series to estimate substitution elasticities	International: 11 countries including Australia.	Each region has an energy sector including 5 industries and a non-energy sector including 7 industries.	McKibbin Software Group Pty Ltd (MSGOL)	• Unlike other CGE models which can be used for forecasting with a recursive dynamic approach, G-Cubed model is basically solved as an inter-temporal optimization problem. This can result in lower economic costs of environmental policies. • The model benefits of a rigid macroeconomic foundation as it has explicit financial market and can incorporate nominal wage rigidity and stickiness. • It can show the spill over effect of environmental policies on the countries not adopting such policies. • It is suitable for international analysis.

4. Techno-economic Modelling Review

Over the last two decades, energy systems and markets have been in rapid transition in many countries. They have been challenged by many developments, including:

- liberalisation and restructuring of electricity markets;
- introduction of environmental policies for energy decarbonisation;
- significant growth of large scale renewable generation (wind and solar farms), and significant reductions in the capital cost of such generation;
- emergence of distributed local energy generation (such as solar PV, wind energy, batteries and "smart" energy control systems).

Regulations and rules used to manage these energy systems have also been in a state of ongoing flux. As a result, whole-of-system dynamic economic models have been found unable to address the new complexities of the decentralised and liberalised electricity markets. As a result, hybrid techno-economic models of energy systems aim to provide a more accurate description of the interactions between economic decisions and technological choices. In a nutshell, these models represent energy demand, supply, distribution, storage and trading, based on various technological pathways and sets of regulations (Foley *et al.*, 2010). Although most of these models initially focused on electricity systems and markets, they have progressively incorporated gas systems in order to reflect their growing influence. In the context of competitive electricity markets, such as Australia's National Electricity Market (NEM), regulators increasingly rely on these models to represent the system and predict its short-term to medium-term behaviour.

Overall, energy systems models can be clustered into three main groups (Sarica *et al.*, 2012):

- Optimisation models
- Equilibrium models
- Simulation models

Optimisation models focus on least-cost expansion of the whole system, or profit maximisation of one firm competing in the market. Equilibrium models rely on competition considerations in relation to market participants when presenting the overall market dynamics. Simulation models are usually an alternative to the optimisation and equilibrium models when the problem to be represented and solved is too complex to be dealt with an optimisation or equilibrium framework.

A comprehensive review of different computer modelling tools that can be used to analyse the integration of renewable energy is presented by Connolly *et al.* (2010). 37 tools (from a single building system to a national system) are included in the final analysis. It includes two of the selected tools in this review - EMCAS and TIMES.

Table 3: Techno-economic models

Model	Organisation (link)	Country
EMCAS	Argonne National Laboratory (ANL), https://ceeesa.es.anl.gov/projects/emcas.html	USA
ESME	http://www.eti.co.uk	UK
EWG-LUT	EnergyWatchGroup, Berlin and LUT University, Lappeenranta	Germany and Finland

Genersys	CSIRO and GW Simulation	Australia
Jacobs	Jacobs (2017): Report to the Independent Review into the Future Security of the National Electricity Market	Australia
PLEXOS	Energy Exemplar Pty Ltd, Adelaide, SA, https://energyexemplar.com/	Australia
REMod-D	Fraunhofer Institute for Solar Energy System (ISE), Freiburg, https://www.ise.fraunhofer.de/en/press-media/press-releases/2015/what-will-the-energy-transformation-cost.html	Germany
TIMES	The Energy Technology Systems Analysis Program (ETSAP), https://iea-etsap.org/	International Energy Agency (IEA), France

Connolly *et al.* (2010) consider seven different tool types when reviewing these models:

- Simulation tool. A simulation tool simulates the operation of the system components. Typically, simulation tools operate at a given time interval – hour, day, year, etc.
- Scenario tool. A scenario tool is usually used to describe the evolution of an energy supply system over several years. A typical time horizon is 20-50 years.
- Equilibrium tool. An equilibrium tool aims to explain the behaviour of supply, demand and prices in the whole economy or in some sectors of the economy (general or partial equilibrium). Based on economic theory, it is assumed that an equilibrium could be achieved between producers and consumers in terms of the prices of the products and supply and demand.
- Top-down tool. A top-down tool is a macroeconomic tool that uses generic data to determine the evolution of the energy prices and energy demand services. Typically, top-down models are also equilibrium models.
- Bottom-up tool. A bottom-up tool builds the energy system to be modelled and analysed by its components – for example representing all major generating units and plants in a region of interest.
- Optimisation tool. An optimisation tool optimises the operation of a given energy system. The system model is represented as an optimisation problem with an objective function (e.g., minimising total cost) and a set of constraints. The optimisation problem is solved by software engines based on linear or non-linear programming algorithms. The power of linear programming is that it can find an optimal solution to a problem with many thousands or even hundreds of thousands of decision variables. Many optimisation tools also include simulation modules to represent some components and operations of the modelled system.
- Investment tool. Some tools optimise or simulate capacity expansion or investment in new generation plants, new transmission lines, etc. Typically, these tools are also scenario-based tools.

The type of each techno-economic model reviewed in this paper is represented in Table 4. All these models are bottom-up models, so no column for top-down models is included in this Table.

Table 4: Type of each techno-economic model reviewed

Model	Simulation	Scenario	Equilibrium	Bottom-up	Optimisation	Investment
EMCAS	Yes	Yes	-	Yes	-	Yes
ESME	-[1]	Yes	-	Yes	Yes	Yes
EWG-LUT	-	Yes	-	Yes	Yes	Yes
Genersys	Yes	Yes	-	Yes	-[2]	Yes
Jacobs	Yes	Yes		Yes	-	Yes
PLEXOS	-[3]	Yes	-	Yes	Yes	Yes
REMod-D	Yes	Yes	-	Yes	Yes	Yes
TIMES	-	Yes	Yes	Yes	Yes	Yes

Table 5: Type of analysis conducted by each tool

Model	Geographical area	Scenario timeframe	Time-step	Electricity	Gas	Renewables
EMCAS	Regional, State, National	Several decades	Hourly	Yes	-	Yes
ESME	National (UK), Regional (12)	2050	5-year; 2 seasonal & 5 diurnal time slices	Yes	Yes	Yes
EWG-LUT	Europe, 20 European regions	2050	Hourly	Yes	Yes	Yes
Genersys	Regional, State, National	Several decades	Hourly	Yes	Yes	Yes

[1] ESME has a module for Monte Carlo simulations in order to consider uncertainty of future energy prices and future cost of energy technologies.
[2] Genersys uses an optimisation dispatch heuristic.
[3] PLEXOS has a Monte Carlo simulation of forced outages and optimised maintenance.

Jacobs	Regional, State, National	2050	Hourly	Yes	Yes	Yes
PLEXOS	Region, Several states, Big interconnection (PJM)	Several decades for capacity expansion	5 min, 60 min (default)	Yes	Yes	Yes
REMod-D	Germany, 2 regions	2050	Hourly	Yes	Yes	Yes
TIMES	Regional, State, National	From one year to many decades	Hourly, daily, monthly using user-defined time slices	Yes	Yes	Yes

Close collaboration between model designers, industry stakeholders and policy makers is critical for the development of relevant and useful modelling scenarios (Chiodi *et al.*, 2015). And importantly, the value of any given modelling output, regardless of its accuracy, rests on the capacity of the modellers and key stakeholders to engage with a broader audience, to establish trusted communication channels and to adapt the messages in the most compelling way.

5. Conclusions

So far, the future fuels studies we have reviewed (Section 2) have attempted to estimate the production costs of future fuels, including hydrogen, and/or to look at hydrogen uptake in the future. However, to the best of our knowledge, none of these studies looked at scenarios including both production, transition and consumption of renewable gas and its economic contribution at national and regional levels. And several of the studies focussed on decarbonisation pathways largely ignore the role of gas in stationary energy, instead focussing on its role as fuel for electricity generation. Furthermore, the applicability of their conclusions is directly linked to the limitations of their modelling assumptions and paradigm.

To address this issue, RP1.1-01 proposes to first develop several scenarios that are plausible trajectories for the future of Australia's energy sector, and then to simulate those scenarios using a model that comprises both demand and supply side of energy sector, including gas systems. Key model requirements for such an exercise include:

1. A flexible structure, capable of modelling existing and emerging generation technologies, including the cost (and geographic availability of) carbon capture and storage (CCS).
2. Inclusion of both electricity and gas energy systems, including transmission and distribution networks. The model must allow for the substitution of energy technologies based on least-cost and performance criteria, including environmental considerations.
3. Capacity to impose specified restrictions on the greenhouse gas intensity of energy (as reflected in the basket of energy technologies: coal, natural gas, solar, wind, hydro, future fuels, nuclear and other renewables.)

4. Regional modelling to allow considerations for local climate, specific renewable (wind, solar, etc.) energy resource, availability of transmission and distribution infrastructure and the emergence of new industrial processes.
5. A multi-regional reporting structure (e.g., part of a State, a State, and the Nation as a whole as well as being able to include global energy demand trends as exogenous factors in the modelling).
6. Granular representation of demand for energy services to end-sectors (residential, industrial and commercial), including demand from transport services.
7. Inclusion of international trade to evaluate the future fuels export opportunities.
8. Substitution of energy and fuels (natural gas, hydrogen, electricity, etc.) at end-user level.
9. Modelling of various energy storage solutions (battery, pumped hydro, heat conversion, compressed air storage, or hydrogen).
10. Modelling of the impact of supply and demand on the cost of transmission and distribution networks, as well as the impact on energy prices.
11. Modelling functionality to allow expansion of electricity generation using different production technologies.
12. Inclusion of carbon accounting and estimation of emissions produced under each scenario.
13. Consideration of various types of carbon tax/cap or trading systems.

Beyond the strict modelling requirements, there is also a need for well-defined questions to answer. For example, some studies explored the consequences of Australia's decision to reduce greenhouse gas emissions by 45% in 2030. They used a standard emission-trading model to do so, without much consideration for the technological and investment shocks it would create. Henceforth, it is necessary to build carefully coherent input scenarios before jumping onto questionable modelling outputs.

Drawing on our literature review, we propose a modelling framework made of two coupled components in order to meet the above list of criteria, in the most cost-effective manner:

a) A techno-economic model which can identify the nature of the infrastructure and technology needed to produce the requisite amount of energy, combined with an assessment of the levelised cost of efficiently producing this energy. Initially this would involve use of Genersys initially developed by CSIRO and supported by GW Simulation.

b) A dynamic economic model (using a CGE approach) capable of describing the economy-wide changes that result from a change in input costs and demand that the previously modelled technological change can be expected to have across space and through time. Based on an assessment of the available models, the VURM model most closely meets the identified needs of the CRC.

These models then iterate with one another, as the levelised cost of energy from the techno-economic model may change the demand for energy, which could change the cost of production. This changed energy demand is then re-entered into the techno-economic model and the levelised cost of energy is recalculated. If this levelised cost of energy changes then CGE model is re-run with the new costs, until the two models solve at a consistent energy price level.

The techno-economic model meets requirements 1, 2, 3, 4, 5, 9, 10, 11 and 12; and the dynamic economic model meets requirements 5, 6, 7, 8, 11 and 12.

The figure below illustrates how coherent input scenarios will inform both the dynamic economic model and the techno-economic model. The dynamic economic model will try to reach an optimal response to the scenario narrative while passing on boundary conditions and technological options to the techno-economic model. In return, the latter model will provide a set of output and constraints to evaluate the viability of the scenario.

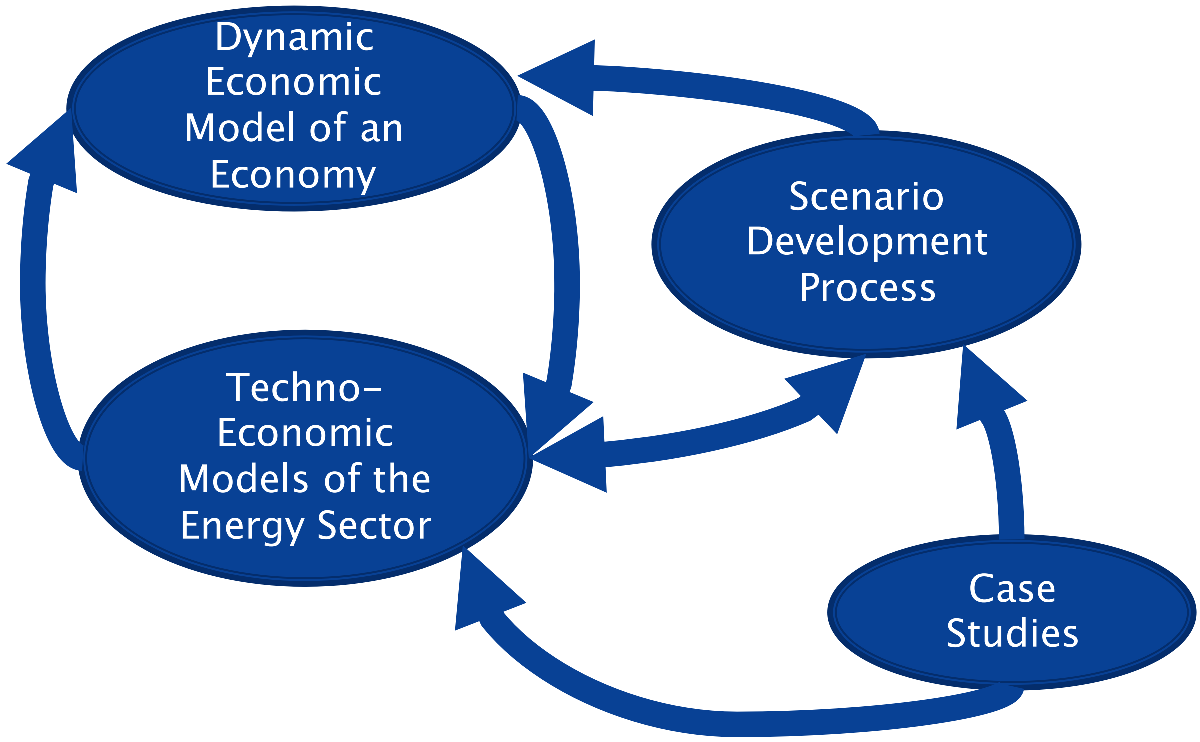

Figure 1: Scenario modelling framework

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