Energy- and multi-sector modelling of climate change mitigation in New Zealand: current practice and future needs

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Abstract

As New Zealand charts its course toward a low-emissions economy, the quality of energy-sector and multi-sector modelling is becoming increasingly important. This paper outlines why models are useful for answering complex questions, provides a stocktake of energy-sector and multi-sector models used for climate change mitigation modelling in New Zealand, and makes suggestions for improving future modelling work. While New Zealand is fortunate to have a range of different modelling tools, these have historically been used in a sporadic and ad hoc way, and underlying datasets are deficient in some areas. As the foundation for a more strategic development of New Zealand's modelling capability, this paper profiles some of the energy-sector and multi-sector models and datasets currently applied in New Zealand. New Zealand's modelling capability could be strengthened by collecting and sharing data more effectively; building understanding of underlying relationships informed by primary research; creating more collaborative and transparent processes for applying common datasets; increasing international collaboration; and conducting more integrated modelling across environmental issues. These improvements will require strategic policies and processes for refining model development; providing increased, predictable and sustained funding for modelling activities, underlying data collection and primary research; and strengthening networks across modellers inside and outside of government. Many of the suggested improvements could be realised by creating an integrated framework for climate change mitigation modelling in New Zealand. This framework would bring together a suite of models and a network of researchers to assess climate change mitigation policies regularly. Core elements of the framework would include a central repository of data, input assumptions and scenarios, and a "dashboard" that synthesises results from different models to allow decision-makers to understand and apply the insights from the models more easily.

JEL codes

C31, D58, Q4, Q54

Keywords

Applied general equilibrium; Electricity; Greenhouse gases; Policy analysis; Transportation.

Summary haiku

NZ models need
collaboration, data
and development

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Figures and Tables

Table 1: Key abbreviations used in this paper

Abbreviation	**Meaning**
AIMMS	Advanced Interactive Multidimensional Modelling System
AOGCM	Atmosphere ocean general circulation models
APERC	Asia Pacific Energy Research Centre
BVCM	Biomass Value Chain Model
CEPII	Centre d'Etudes Prospectives et d'Informations Internationales
CGE	Computable general equilibrium
CliMAT-DGE	Climate Mitigation, Adaptation and Trade in Dynamic General Equilibrium
CO_2-e	Carbon dioxide emissions
CoPS	Centre of Policy Studies
CRAGE	Competitive Risk Averse Generation Expansion
CRL	Consulting, Research and Laboratories
DIA	Dependent inflow adjustment
DOASA	Dynamic Outer Approximation Sampling Algorithm
EDGS	Electricity Demand and Supply Generation
EECA	Energy Efficiency and Conservation Authority
EITE	Energy-intensive trade-exposed
EMBER	Electricity Market Benchmarking ExpeRiment
EMI-DOASA	Electricity Market Information Dynamic Outer Approximation Sampling Algorithm
ENZ	Energy and emissions in New Zealand
EPOC	Electric Power Optimisation Centre
ESSAM	Energy Substitution, Social Accounting Matrix
ETI	Energy Technologies Institute
ETS	Emissions trading scheme
EV	Electric vehicle
GAMS	Generic Algebraic Modelling System
GDP	Gross domestic product
GDX	GAMS Data Exchange
GEM	Generation Expansion Model
GEMstone	Generation Expansion Model in a STOchastic and Noisy Environment
GHG	Greenhouse gas
GIS	Geographic information system
GTAP	Global Trade Analysis Project
GTM	Global Timber Model
GUI	Graphical user interface
GWAP	Generation weighted average spot price
GYE	Global Yields Emulator
Hydro	Hydrological
ICE	Internal combustion engine
IMPACT	International Model for Policy Analysis of Agricultural Commodities and Trade
IO	Input–output
IPPU	Industrial processes and product use
LRMC	Long-run marginal cost

LTEM	Lincoln Trade and Environment Model
LURNZ	Land Use in Rural New Zealand
MAC	Marginal abatement cost
MAGICC	Model for the Assessment of Greenhouse Gas Induced Climate Change
MBIE	Ministry of Business, Innovation and Employment
MED	Ministry of Economic Development
MfE	Ministry for the Environment
MILP	Mixed-integer linear programming
MIT-EPPA	Massachusetts Institute of Technology Emissions Prediction and Policy Analysis
MNZG	Monash–New Zealand–Green
MOT	Ministry of Transport
MPI	Ministry for Primary Industries
NZ-FARM	New Zealand Forest and Agriculture Regional Model
NZIAMS	New Zealand Integrated Modelling System
NZIER	New Zealand Institute of Economic Research
OECD	Organization for Economic Co-operation and Development
PE	Partial equilibrium
PRM	Project Rank Model
PSI	Paul Scherrer Institute
SADEM	Supply and Demand Energy Model
SAM	Social accounting matrix
SDDP	Stochastic Dynamic Dual Programming
SOL	Stochastic Optimization Limited
SOO	Statement of Opportunities
SPD	Scheduling, Pricing and Dispatch
Stats NZ	Statistics New Zealand
STELLA	Systems Thinking, Experimental Learning Laboratory with Animation
TWAP	Time Weighted Average Price
UNFCCC	United Nations Framework Convention on Climate Change
VFM	Vehicle Fleet Model
ViEW	Vivid Economy Wide
vSPD	Vectorised Scheduling, Pricing and Dispatch

1 Introduction

As New Zealand joins with other countries to achieve net zero greenhouse gas (GHG) emissions by later this century, it will come under increasing pressure from changing economic opportunities and global consumer preferences, the emergence of potentially disruptive new technologies, natural resource constraints, and evolving social and political drivers. New Zealand faces the challenge of developing its economy in ways that will not only be resilient to those future pressures, but also sustain the well-being of both urban and rural communities as well as our natural environment.

High-quality modelling tools and data are essential for making robust decisions on New Zealand's transition to a low-emission economy under uncertainty. New Zealand has a suite of "stand-alone" energy-sector and multi-sector models, with infrequent coordination among models. These have been developed over time by government, research organisations and private sector entities in different contexts and to address a range of environmental and economic issues and regulatory/reporting needs. However, when it comes to applying these tools to assess the impacts of alternative energy and GHG mitigation policies as well as economic, social and environmental drivers of change, we have a history of using many of these tools in a sporadic and ad hoc way. We have limited capacity to model low-emission innovations extending beyond historical norms, complex interactions between sectors (especially the energy and land sectors), and the implications for New Zealand of changes to overseas markets and policies. During the past decade, modelling undertaken to help inform major climate change policy decisions (e.g. New Zealand's successive international emission-reduction targets and the design of the New Zealand Emissions Trading Scheme, ETS) has often produced conflicting results whose differences and limitations complicate assessment by policy-makers, stakeholders and the general public, and affect confidence in the decision-making process.

Motu Economic and Public Policy Research convened a workshop in Wellington, New Zealand, on 1 May 2018 that brought together some of New Zealand's expert energy-sector and economy-wide modelling practitioners from government, research institutions and the private sector. The intent of the workshop was to explore the merit of the modelling community taking a more strategic approach to climate change mitigation modelling. The workshop involved:

- sharing information on recent empirical research and modelling efforts relevant to assessment of energy-sector and multi-sector climate change mitigation options;
- identifying further research and modelling needs for evidence-based decision-making on these issues by government and business; and
- proposing priorities for future work.

Drawing from the workshop outcomes as well as inputs from expert modellers across New Zealand, this report profiles current energy-sector and multi-sector models and datasets in New

Zealand, and provides recommendations to the modelling community, research institutes, and the public and private sectors for strengthening New Zealand's capability to conduct climate change mitigation modelling across the economy. A companion report profiles land-use models and datasets relevant to assessing a broad range of environmental issues.

The structure of the report is as follows. Section 2 provides background information on why it is important to model the impacts of climate change mitigation policies on the energy sector and the broader economy. Section 3 provides a stocktake of some of the energy-sector and multi-sector models in New Zealand and key datasets. Section 4 discusses where the modelling community should focus its future efforts and how to improve the process of modelling in New Zealand. Finally, section 5 concludes with key insights.

2 Why are models used to understand multi-sector change?

A model is a simplified representation of reality that focuses on the key factors and (cause-and-effect) relationships of a phenomenon. Models describe how these factors are related, and the strengths of the different relationships. Constructing a model requires scientists to specify their assumptions explicitly, identify the phenomena they are concerned with, explain their methodology and use data to calibrate the model. By capturing the key agents, elements, processes and decisions, models enable complex systems and situations to be understood and complex problems to be solved.

People may think like a modeller when making a decision in a complex situation. They select certain key details, make assumptions about details they have ignored, and apply intuition and judgement to inform their decisions. Scientists make these models more explicit.

Among scientists, the formal and frequent use of models is well established. However, to those outside the scientific community models can seem like black boxes. The wide variety of available models generally causes confusion.

Energy- and multi-sector models provide a structured way to think about energy use and GHG emissions and how they may be expected to change in relation to key drivers. Energy-sector models are focused on the impact of changes in policies, technologies or other factors on energy-related sectors such as electricity, industrial heat and transport. Multi-sector models address the impacts of change in policies, technologies or other factors within and between different sectors, and can offer insights into the outcomes of complex multi-sector interactions. Such models can be used to help inform decision-making by the government and private sectors on policies and practices affecting energy production and use and GHG emissions in the context of geographic and natural resource variability, economic uncertainty, technological change and interactions between different sectors in the economy.

Energy- and multi-sector models aim to deepen understanding of how people and systems react to policy change. Some energy- and multi-sector models consider outcomes in aggregate – for example, how much of different types of energy (e.g. electricity, industrial heat and liquid fossil fuels) are used in a given area. Other energy- and multi-sector models may include the specific configurations of different sectors, and how they change over time.

Different types of energy- and multi-sector models can be required to answer different types of questions, to model different situations and to work at different levels of detail. Such models typically apply different assumptions, use different data and methodologies, and face different limitations. As the economic, environmental and other impacts from changes in energy- and emissions-related technologies, policies and practices may be too complex for any one model to capture fully, using multiple models in combination can provide a more complete and robust understanding. In addition, cross-model comparisons can be used to help validate the different models. Furthermore, models that represent a particular aspect of an economy in detail can be used to inform models with a broader representation. For example, an electricity-sector model may be used to inform the scope for electricity from new forms of generation, capturing the physical and cost/price dynamics of the interaction between demand, transmission and hydrology that are material drivers for our system. The outputs can be an input to an economy-wide model. Hence, when used appropriately, the variety of available models should be seen as a strength rather than as a weakness.

As well as contributing to policy development, models can be used to inform the direction of research, provide tools to answer research questions, and express results in a repeatable and robust way that helps promote, but does not guarantee, better understanding of changes in energy use and emissions. Through peer review processes, the quality of a model and the robustness of its conclusions can be tested within the scientific community before model results are made available to the wider society. This helps ensure that modelling upholds the standards of rigour that are expected by the scientific community.

3 Stocktake: energy- and multi-sector modelling in New Zealand

New Zealand has a range of different energy-sector and multi-sector models that are relevant to assessing climate change mitigation options and implications. This section profiles models that have been used, or are planned to be used, for climate change mitigation modelling in New Zealand.

It contains three parts:

- An overview of multi-sector models in New Zealand, split into:
    - computable general equilibrium (CGE) models; and
    - other multi-sector models.
- An overview of energy models in New Zealand, split into:
    - electricity-focused models; and
    - other energy-focused models.
- An overview of datasets used by the modelling community.

Table 2 provides a list of the key energy- and multi-sector models used in New Zealand, classifies them according to their design and focus, and identifies their associated organisation(s). The models not profiled in the paper are indicated in the table with an asterisk.

Table 2: A list of energy- and multi-sector models in New Zealand

Multi-sector models	
Name	**Organisation**
Climate Mitigation, Adaptation and Trade in Dynamic General Equilibrium (CliMAT-DGE)	Owned by Manaaki Whenua – Landcare Research; collaborating organisations included AgResearch, New Zealand Agricultural Greenhouse Gas Research Centre, New Zealand Institute of Economic Research (NZIER) and Lincoln University
Energy and Emissions in New Zealand (ENZ)	Concept Consulting
Energy Substitution, Social Accounting Matrix (ESSAM)	Infometrics
Monash–New Zealand–Green (MNZG)	NZIER
TIMES-NZ	Owned by the BusinessNZ Energy Council and will be hosted and maintained by the University of Auckland Energy Centre. It is still under development at the Paul Scherrer Institute (PSI) in Switzerland
Vivid Economy Wide (ViEW)	Vivid Economics
Energy-sector models	
Name	**Organisation**
Biomass Supply Model*	Scion
Biomass Value Chain Model (BVCM)	Scion
Competitive Risk Averse Generation Expansion (CRAGE)	Electric Power Optimisation Centre (EPOC)
Concept Fuel Flexibility Models	Concept Consultng
Electricity Market Information Dynamic Outer Approximation Sampling Algorithm (EMI-DOASA)*	Electricity Authority (public version) Stochastic Optimization Limited (proprietary version)

Dynamic Outer Approximation Sampling Algorithm (DOASA)	Stochastic Optimization Limited (SOL)
Electricity Indicator Model*	Ministry of Business, Innovation and Employment (MBIE)
EMarket	Energy Link Limited Energy Efficiency and Conservation Authority (EECA) has licensed this model for a number of electricity-system projects
Generation Expansion Model in a STOchastic and Noisy Environment (GEMstone)	EPOC
Generation Expansion Model (GEM)	Electricity Authority, MBIE
Hydro-Sim	Concept Consulting
HydrovSPD	EPOC
Oil and Gas Simulation Model*	MBIE
OptGen*	Power System Modelling
Process Heat Emissions Reduction	University of Waikato Energy Research Group, MBIE and EECA
Project Rank Model (PRM)*	MBIE
Stochastic Dynamic Dual Programming (SDDP)*	Power System Modelling
Supply and Demand Energy Model (SADEM)	MBIE
UniSyd	Unitec, Stanford University, Asia Pacific Energy Research Centre (APERC), Iceland University, Reykjavik University, Massachusetts Institute of Technology, Kanagawa University and Aoyama University
UniTrac	Unitec and Kanagawa University
Vectorised Scheduling, Pricing and Dispatch (vSPD)	Electricity Authority
Vehicle Fleet Model (VFM)*	Ministry of Transport (MOT)
Woodscape*	Scion

* Models are not profiled in this report.

Source: Ministry of Business, Innovation and Employment (2016)

3.1 Profiles of multi-sector models

Model descriptions presented below are based on responses that energy -and multi-sector modellers from around New Zealand gave to a questionnaire. Some participants responded question by question and others responded with a brief description of the model they use.

3.1.1 Computable general equilibrium (CGE) models

CGE models represent economies as a series of interconnected sectors, include a detailed representation of energy production and use, and link production to GHG emissions (Ledvina & Winchester, 2018). They are simulation tools that combine general equilibrium theory with realistic economic data to solve numerically for the levels of supply, demand and price that support equilibrium across all markets (Sue Wing, 2004). CGE models are useful for evaluating how policies targeting a small number of sectors will impact other sectors and the overall economy. They are also useful for looking at how policies influencing all industries affect the economy.

Climate Mitigation, Adaptation and Trade in Dynamic General Equilibrium (CliMAT-DGE)

Who owns/operates the model?

CliMAT-DGE model is operated by Manaaki Whenua – Landcare Research and was developed by a research consortium led by Manaaki Whenua – Landcare Research. Collaborating organisations included AgResearch, the New Zealand Agricultural Greenhouse Gas Research Centre, NZIER and Lincoln University. Development funding was provided by the Ministry for Primary Industries (MPI) through the Sustainable Land Management and Climate Change Fund.

What is the scope and extent of the model?

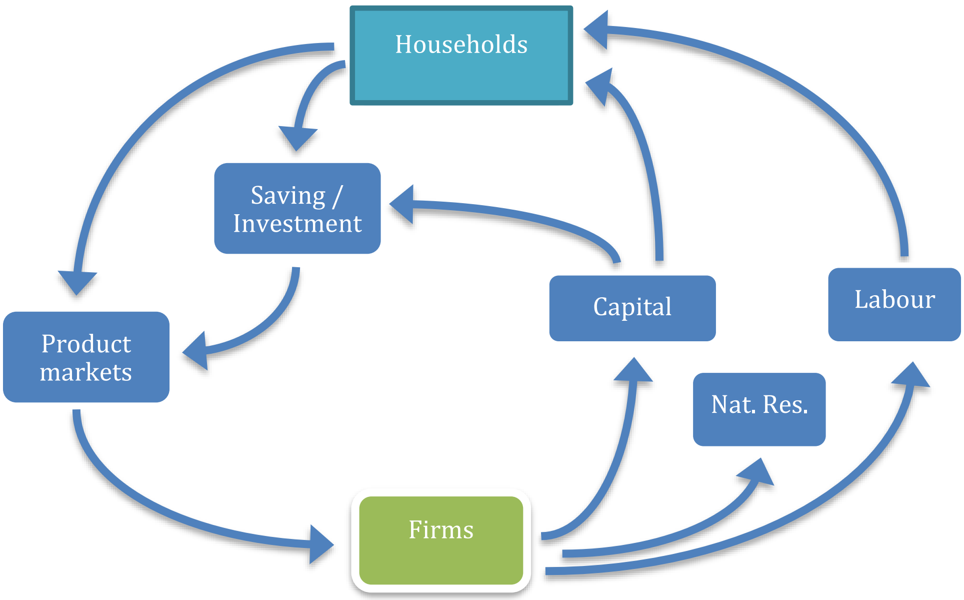
CliMAT-DGE analyses the responses of the New Zealand economy to changes in domestic and foreign environmental policy and/or trade patterns. It can be used to analyse questions such as:

- What effect will a particular policy scenario have on reducing GHG emissions?
- How will regions, industries or sectors be affected by GHG emission-reduction policy?
- How will the policy impact regional trade and/or commodity prices?
- What impacts will climatic changes have on primary production?

The CliMAT-DGE model framework is loosely based on the dynamic version of the Massachusetts Institute of Technology Emissions Prediction and Policy Analysis (MIT-EPPA) model, with adaptations for the New Zealand context.

Figure 1 provides a simple depiction of how income flow in the economy is represented in CliMAT-DGE. The consumer sector (households) supplies factor inputs such as capital and labour to the producer sectors (firms). The producer sector, in turn, produces goods and services that are demanded by consumers. There is a reverse flow of payments, where households receive income for the factors they supply and then use that income to purchase the goods and services they consume. The government sector is not included in this figure as it is modelled as a passive entity that simply collects taxes from producers and transfers the full value of these proceeds to the households. Trade flows for goods between regions/countries are also accounted for.

Figure 1: The flow of regional income in CliMAT-DGE



How does the model work?

CliMAT-DGE is a top-down dynamic multi-sectoral and multi-regional CGE model that describes the global economy and generation of GHG emissions from energy and non-energy sectors through 2100.

The model represents all transactions for a particular year that take place within the economy, in a regional, national or worldwide context. Because the model has been calibrated for multiple years, it is suitable for dynamic analysis incorporating long-term issues such as climate change and GHG emission-reduction policies.

CliMAT-DGE currently uses 20 aggregated economic sectors, including detailed energy and primary production sectors. The energy sectors include major GHG emitters, as well as carbon-free electricity, which is a significant part of New Zealand's energy share. The primary production sectors are aggregated to focus on land and food sectors, including dairy, sheep and beef, forestry, and grains.

Model outputs are produced at the regional and sector level, and are listed in annual values (2007 base year). They include:

- GDP – consumption, investment and trade flows (exports and imports);
- production – output value;
- output price – relative change from 2007;
- GHGs – emissions by gas (carbon dioxide, methane, nitrous oxide, etc.); and
- input use – capital, labour and land.

What datasets are used?

The model primarily uses the GTAP version 8 dataset, which accounts for 129 regions of the globe and 57 economic sectors. CliMAT-DGE is calibrated to represent observed data from 2007.

The CliMAT-DGE dynamic baseline requires information and data on projected changes in regional population, GDP, technology and consumption growth. For this purpose, the model incorporates realistic projections of key macroeconomic (e.g. labour productivity) and other variables (e.g. energy efficiency), and has been developed from a number of sources. The economic baseline is primarily constructed on a growth scenario developed by the Centre d'Etudes Prospectives et d'Informations Internationales (CEPII), *The world economy in 2050: a tentative picture* (Fouré et al., 2010). In turn, that scenario built on economic forecasts of the International Monetary Fund, labour force projections of the International Labour Organisation and demographic projections of the United Nations. Energy supply and efficiency projections are based primarily on several 2009–12 editions of the *World energy outlook* (International Energy Agency, 2013). The baseline scenario is also currently defined as involving neither climate policies nor climate impacts for all regions of the globe, although this could be changed if desired. More details on the baseline projections are provided in appendix 4 of Lennox et al. (2013).

What are the strengths and limitations of the model?

Strengths:

- CliMAT-DGE represents a global dynamic economic model with a strong focus on New Zealand as a distinct region. Other global CGE models tend to aggregate New Zealand together with Australia (e.g. Babiker et al. ,2008) or Oceania (e.g. Golub et al., 2013), making it difficult to determine the effects of international climate policies on New Zealand.
- It uses global databases updated by other institutions, e.g. GTAP.
- It disaggregates different agricultural sectors in the model (agriculture is not a single lumped sector).
- The model is coded in Generic Algebraic Modelling System (GAMS) which is a proprietary language and modelling system.
- It can be linked with other models to improve the specificity of different sectors (see the section below on linkages with other models).

Limitations:

- Due to the reliance on exogenous elasticity values and a single base-year observation, comprehensive sensitivity analysis on key elasticities should be performed.
- It is widely recognised that backstop technologies having zero or even negative emissions are necessary to achieve ambitious emission-reductions targets (Vuuren et al.,

2011). CliMAT-DGE does include backstop technologies, but we found that the model became much more difficult to solve at a large scale if backstops were included. This has been partially resolved and the remaining numerical difficulties may be overcome through further research, as a larger set of backstop technologies may be necessary to widen the scope of future analyses.

- Current computation limitations in the model typically mean that it solves efficiently with configurations of up to eight regions, 20 sectors and time horizons of less than 100 years.
- The model is coded in GAMS, which is a proprietary language and modelling system. This comes at a cost to the user.

What linkages are there to other modelling work?

CliMAT-DGE has been linked to two other modelling systems. These are outlined below.

New Zealand Integrated Assessment Modelling System (NZIAMS)

CliMAT-DGE can be linked to NZIAMS. This system links biophysical and economic models with a strong focus on agriculture and forestry, as these sectors make up a large share of the New Zealand economy. The CliMAT-DGE model is the core model in NZIAMS. The component models of NZIAMS are described below.

The Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC) has been used to translate global emissions into global atmospheric GHG concentrations and mean temperatures. MAGICC models the global atmosphere and ocean system (Wigley, 2008) to emulate the responses of global climate variables in complex atmosphere ocean general circulation models (AOGCMs).

The Global Yields Emulator (GYE) model emulates the responses of complex crop models using a statistical pattern-scaling methodology. GYE estimates regional yield changes for wheat, maize, soya and rice, and relies on the mean climatic variables produced by MAGICC. The yield changes are fed into either the top-down or bottom-up components of CliMAT-DGE.

NZIAMS links the three models through feedback loops and thereby accounts for the impacts of the climatic and biophysical changes. NZIAMS also includes a downscaled partial equilibrium (PE) sub-model that provides further detail to the agriculture and forestry sectors and can be linked to NZIAMS.

Global Timber Model (GTM) and the New Zealand Forest and Agriculture Regional Model (NZ-FARM)

GTM is an economic model capable of examining global forestry land use, management and trade responses to policies. In responding to a policy, the model captures afforestation, forest management and avoided deforestation behaviour. The regional GHG prices estimated with CliMAT-DGE may be fed into GTM. The timber model can then estimate the change in regional forest stock and carbon sequestration as a result of the proposed GHG emission-reduction policy.

National-level NZ-FARM is a recursive dynamic PE non-linear mathematical programming model of the New Zealand forest and agriculture sectors. It is designed for detailed modelling of land use at the regional scale to enable the consistent comparison of policy scenarios against a baseline by assessing relative changes in economic and environmental outputs. For policy analysis, users can feed the GHG prices estimated with CliMAT-DGE into NZ-FARM. The model then estimates the change in land use, farm production and GHG emissions.

What questions have been looked at in the past?

Some examples of past analysis include:

- impact of the Paris Agreement on New Zealand agriculture (range of different analyses);
- comparison of different domestic climate policy scenarios (and inclusion of agriculture in domestic climate policy) for New Zealand (range of different analyses); and
- leakage resulting from carbon taxes on industrial and energy GHG emissions in Organization for Economic Co-operation and Development (OECD) countries and China.

What areas are there for future development?

The underpinning GTAP data need to be updated in CliMAT-DGE as new GTAP databases are now available. Other developments have been identified but are dependent on future use and directions of stakeholder needs.

Bibliography of recent work

For a full list of publications, see Table 7.

Energy Substitution, Social Accounting Matrix (ESSAM)

The ESSAM model is a multi-industry general equilibrium model of the New Zealand economy. It has been applied in one form or another to economic questions in New Zealand since 1986.

Who owns/operates the model?

ESSAM is a proprietary model of Infometrics Consulting Ltd. It is not publicly available.

What is the scope and extent of the model?

The ESSAM model takes into account the main inter-dependencies in the economy, such as flows of goods from one industry to another, and the passing on of higher costs in one industry into prices and hence the costs of other industries. ESSAM includes New Zealand exports and imports, but it does not represent the rest of the world.

Some of the model’s features include: 55 industry groups; substitution between inputs into production – labour, capital, materials, energy; four energy types: –coal, oil, gas and electricity, between which substitution is also allowed; substitution between goods and services consumed by households; and social accounting matrix (SAM) for tracking financial flows between households, government, business and the rest of the world.

The model's output is extremely comprehensive, covering the standard collection of macroeconomic and industry variables, including GDP, private consumption, exports and imports, employment, etc.; demand for goods and services by industry, government, households and the rest of the world; industry data on output, employment, exports, etc.; import–domestic shares; fiscal effects; and energy and emissions.

How does the model work?

The model is a large set of non-linear equations solved by a numerical algorithm that is very much like the Davidon–Fletcher–Powell method. It is written in GAUSS software. Its parameter values are sourced from New Zealand and overseas studies.

The usual procedure for analysing scenarios is to produce a "business as usual" projection against which other scenarios are compared. The power of the model is in analysing the differences between scenarios rather than in understanding the absolute levels of those scenarios.

What datasets are used?

The core of the model is an IO (or inter-industry) table and accompanying industry data published every five years or so by Stats NZ. The model also draws heavily on other national accounts information, including data on trade, employment, capital formation, inter-sectoral financial flows and household expenditure. In addition, it incorporates data on energy use by industry and households (from MBIE), together with associated GHG emission coefficients. Non-energy emissions from agriculture and industrial processes are also included.

What are the strengths and limitations of the model?

Strength:

- The strength of the model is in analysing issues and polices that are large enough to affect the allocative efficiency of the economy and thus to have macroeconomic (as well as microeconomic) impacts. Examples include shocks to the terms of trade, carbon prices and climate change.

Limitations:

- A weakness of the model is its lack of spatial detail – the model deals with the national economy, not regional economies.
- Another weakness is that its industry detail can at times be insufficient for a particular application. Although the published IO tables are more detailed than the industries in the model, data on key industries is limited by confidentiality provisions.

- The model distinguishes only five types of household, classified by income. Thus, it is limited in its ability to study distributional questions in detail.

What linkages are there to other modelling work?

ESSAM has previously been used to complement research with other models such as Land Use in Rural New Zealand (LURNZ); New Zealand Forest and Agriculture Regional Model (NZ-FARM); Lincoln Trade and Environment Model (LTEM); energy models operated by MBIE and its predecessor, the Ministry of Economic Development (MED), and other general equilibrium models run by NZIER.

What questions have been looked at in the past?

The model has previously been used to analyse the economy-wide and industry-specific effects of a varied range of issues. For example:

- analysis of the New Zealand ETS and other options to reduce GHG emissions;
- changes in import tariffs;
- faster technological progress and public good science funding;
- funding regimes for investment in road infrastructure; and
- release of genetically modified organisms.

What areas are there for future development?

Ongoing updating of data is the main priority for future development. If resources permit, likely improvements include:

- econometrically estimated industrial production functions specific to New Zealand;
- incorporation of water use and discharge data; and
- additional disaggregation of the household sector and accompanying routines for more detailed tax and benefit modelling.

Bibliography of recent work

For a full list of publications, see Table 7.

Monash–New Zealand–Green (MNZG)

MNZG is a dynamic CGE model of the New Zealand economy that incorporates GHG emissions. It is designed to explore the economic implications and trade-offs associated with climate change policy in New Zealand.

Who owns/operates the model?

The underlying dynamic CGE model at the core of MNZG was funded and developed by the New Zealand Institute of Economic Research (NZIER), in conjunction with experts from the Centre of Policy Studies (CoPS) at Victoria University, Melbourne. It is proprietary software and operated by NZIER staff and research associates. NZIER developed MNZG by including GHG emissions in its dynamic CGE model as part of a 2018 research contract with the Ministry for the Environment (MfE) to explore the macroeconomic impacts of setting 2050 emissions targets.

What is the scope and extent of the model?

MNZG covers the entire New Zealand economy, spanning 111 industries that produce 210 commodities. It is based on the 2013 input–output (IO) tables produced by Statistics New Zealand (Stats NZ), but has a more detailed split of electricity-generation industry than the raw IO table.

The model produces macroeconomic outputs such as gross domestic production (GDP), exports and imports, real gross national disposable income, real wages, employment, GHG emissions, etc. It also delivers industry-level results for these variables. In modelling emission-reduction policies, the model generates implied emissions prices for a given emissions target, or can swap these variables to determine the emission reductions associated with a given emissions price. All GHGs are expressed in carbon dioxide emissions (CO_2-e), and the model does not produce separate results for carbon dioxide, methane, etc. It has a top-down regional module that apportions changes in the national economy across 15 regions, largely based on the relative contribution of industries to regional economies. MNZG includes New Zealand exports and imports but it does not represent the rest of the world.

How does the model work?

The model data are linked together through a set of equations that capture how the economy evolves over time in response to a shock. These equations, which are based on the economic theory of general equilibrium, ensure that supply and demand for goods, services and factors of production in the economy are balanced, and determine how firms and households react in response to changes in the relative prices of factors of production and intermediate inputs. The first step is to project an economic and emissions baseline across the period of interest. This shows how the New Zealand economy, and its 111 industries, will develop over time in the absence of policy change. The modeller then designs scenarios to explore the potential changes in policy. These scenarios involve “shocking” certain parameters in the model to proxy changes in policy, preferences, technological change, etc. By comparing the scenario results with the baseline results, the user can identify how the economy – and its emissions profile – adjusts in response to policy or other changes. It is possible to see these adjustments at a very detailed industry and commodity level, and also at a regional level.

MNZG incorporates several dynamic features:

- labour market adjustment to allow both wages and employment to vary (in a static modelling approach, one of these must be held constant);
- a capital-accumulation mechanism to allow investment to respond to changes in rates of return by industry; and
- changes in the current account and capital account over time, which can be used to explore the effects of overseas borrowing and debt repayment.

A technical description of the model is provided in Dixon and Rimmer (2002).

What datasets are used?

MNZG is based on a wide range of datasets. The core database is shaped around Stats NZ's IO table, which captures the various interlinkages between suppliers and users of goods and services and each industry's use of factors of production, including energy. The level of emissions in each industry is driven by its energy use, and is based on data from Ministry for the Environment (2017) along with data on fuel use by broad industry from the Ministry of Business, Innovation and Employment (MBIE). The model aligns emissions by broad industry with those from Stats NZ's Environmental-economic accounts. The economy is projected forward using Treasury estimates of New Zealand's long-run growth from its Long-term Fiscal Model. The model then apportions this growth across its 111 industries, and generates emissions at the industry level. Energy-efficiency improvements, based on observed historical trends or specific insights from relevant government officials, are also built into these projections. In the scenarios, firms and households respond to changes in relative prices through behavioural parameters that are determined by price elasticities. These elasticities are sourced from CoPS.

What are the strengths and limitations of the model?

Strengths:

- The key strength of a CGE model is that it explicitly builds in various constraints around resource availability in the economy, so that any expansion of one part of the economy leads to fewer resources being available elsewhere in the economy (unless the shock is a productivity gain).
- The model incorporates a very high level of industry and commodity detail, so that the distributional impacts of shocks to the economy (i.e. winners and losers) can be estimated. It can also explore the regional distribution of economic impacts.
- The CGE model is based on a strong theoretical framework that incorporates utility-maximising households and cost-minimising firms.

- MNZG's dynamic model features allows the exploration of the impacts of shocks over time, so it captures intertemporal adjustments. This is in contrast to static models, which look at "before" and "after" the shock, but not the transition between these two states.
- Recently, the model has included a new "nest" that allocates primary sector land, including forestry, across the primary industries depending on relative land prices. This ensures there are trade-offs between an expansion in forestry and land available for other primary sector uses, such as dairy, sheep and beef, and horticulture.

Limitations:[1]

- Since they represent the inner workings of an entire economy, rather than one sector, CGE models depend on many data sources, parameters, equations and assumptions.
- The economic theory underpinning CGE models is usually neoclassical in nature. In this setting, consumers maximise utility, firms minimise costs, resources can move between sectors, and firms do not generate super-normal profits. These assumptions can legitimately be questioned.
- CGE models cannot predict if or when disruptive technological changes, such as a methane vaccine, may occur. The modeller has to design scenarios that introduce such changes into the model. Similarly, if a new industry develops in the future, this CGE model will not capture it unless modellers tell it to.
- This model cannot predict how global consumer preferences might adjust in response to concerns over climate change.
- This CGE model does not incorporate endogenous technical change. In other words, innovation is not directly linked to the carbon price, and has to be imposed by the modeller as part of the scenario design.
- In the past, forestry net emissions have been imposed exogenously on the model, rather than planting and harvesting behaviour being determined by the carbon price. Modellers have assumed that additional forestry planting does not materially reduce the amount of productive land available for other uses.
- This CGE model does not incorporate the physical impacts of climate change on the New Zealand economy, such as rising sea levels, changes to crop yields, increased incidence of severe drought, etc. Nor does it consider potential co-benefits of climate change mitigation policies, such as water-quality improvements.

What linkages are there to other modelling work?

In their work on emissions targets, the MNZG designers have drawn on the assumptions in Vivid Economics, Concept Consulting & Motu Economic and Public Policy Research (2018) to inform

1 This draws on New Zealand Institute of Economic Research (2018).

this scenario design. The aim is to link MNZG to the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) framework to explore the physical impacts of climate change.

What questions have been looked at in the past?

Modellers have used the pre-existing dynamic CGE model for a variety of projects for private and public sector clients, including analysis of:

- the introduction of new pests and diseases into the New Zealand economy (e.g. myrtle rust);
- the economic contributions of various industries;
- the value of irrigation to the New Zealand economy;
- the costs/benefits of infrastructure developments such as convention centres; and
- the impacts of land-use policy changes.

MNZG is a newly developed model and to date has been used only on the research by NZIER into the economic impacts of 2050 emissions targets.

What areas are there for future development?

Key development areas include:

- incorporating endogenous technical change;
- bringing afforestation inside the model, rather than imposing it exogenously;
- analysing different GHGs separately, rather than combining them into CO_2-e; and
- incorporating the physical impacts of climate on crop yields and primary sector productivity.

Bibliography of recent work

As mentioned above, MNZG has not yet been used for any other projects. The pre-existing dynamic CGE model has been used extensively for consulting work, but many of those reports are client confidential.

Vivid Economy Wide (ViEW)

The ViEW model developed by Vivid Economics is a CGE model that has been used for policy analysis in New Zealand but did not feature at the workshop. The version of the ViEW model used for New Zealand represents 30 sectors, sectoral GHG emissions (by gas), and sectoral exports and imports. A key feature of the ViEW model is that land-use change responds to the carbon price, with higher carbon prices resulting in more land allocated to forestry and ultimately the sequestration of carbon, as well decreasing land available for agriculture. More details about the ViEW model are available in appendix C of Vivid Economics and Ernst & Young (2018).

3.1.2 Other multi-sector models

Energy Emissions in New Zealand (ENZ)

Information on the ENZ model has been partially taken from Vivid Economics, Concept Consulting, and Motu Economic and Public Policy Research (2018).

All the models involved are proprietary models that have been developed by Concept Consulting. The clients of ENZ include public sector agencies (e.g. MfE, Parliamentary Commissioner for the Environment, Productivity Commission, EECA, MBIE, Electricity Authority, Commerce Commission, Gas Industry Company), in support of various functions such as policy development and market design; and market participants (generators, retailers, network companies, gas companies, etc.), in support of business strategy, mergers and acquisitions, and the like.

Who owns/operates the model?

The ENZ model was developed by Concept Consulting.

What is the scope and extent of the model?

ENZ is a series of inter-dependent modules or sub-models. The sub-models seek to identify the least-cost means of meeting demand for a service (e.g. transport, process heat, electricity), given the underlying market drivers (e.g. population growth, emissions prices, fossil fuel prices, technological costs) and accounting for exogenously imposed policy actions (e.g. support for transport-mode shifting to public transport/cycling, or the forced closure of a fossil-fuel power station).

Some sub-models are highly dynamic and model the key drivers of outcomes in significant detail. For example, the electricity-sector modelling accounts for the intermittency in renewable generation (particularly in hydro and wind), and the transport-sector modelling addresses the differences in outcomes between light and heavy fleet road transport. Conversely, some sub-models are relatively simple, reflecting the relatively small share of emissions and/or significant inherent degrees of uncertainty. For example, modelling of waste-sector emissions is based on marginal abatement cost (MAC) curves interacting with the emissions price. Figure 2 shows the scale of the ENZ model, what sectors are involved, and what factors feed into each part of the model. Importantly, it models the physical and financial characteristics of the different sectors, some of which are shown in Table 3.

Table 3: Important physical and financial characteristics of the sectors modelled in ENZ

Sector	**Important characteristics**
Electricity	• The variability of demand • The variability of different types of renewable generation (hydro, wind, solar) across different timescales – and the diminishing returns from higher proportions of each type of renewables • The different financial structures of different types of renewable generation – capital (noting that existing stations have sunk capital), operating, fuel, CO_2 • The increase in gas and (to a lesser extent) coal price for delivery of progressively lower-capacity factor
Transport	• The ability to model mode shifting (e.g. increased uptake of public transport, cycling, etc.) and the impact on the demand for transport services • The ability to model the changing capital stock • The different financial characteristics of the fuel options • The effect of different electricity consumer price structures on electric vehicle (EV) vs internal combustion engine (ICE) outcomes • The distinction between five key land transport models (light private, light commercial, heavy, bus and motorcycle), including different drivers of demand and economics of alternative options
Industrial process heat	• The variation in circumstance faced by different users of process heat, including current fuel contracts, network costs, age of existing boiler, profile of demand, etc. • Significant variation in the marginal abatement cost for different options
Key energy-intensive trade-exposed (EITE) sectors	• The extent to which New Zealand producers sit on the global cost/supply curve, and how this moves with changes in international and domestic CO_2 prices (noting that this is something that is currently subject to material uncertainty, and worthy of further research)
Gas sector	• The ability to model the implications of different scenarios of future gas demand on New Zealand gas reserves (and vice versa – linked by price), given scenarios about future exploration
Economy generally	• The ability to model in an internally consistent fashion the interlinkages between the sectors • The ability to "open up" the model to see exactly what is happening with regards projections of sectoral demand for different parts of the economy, what is meeting that demand, and the cost and emissions implications (split by different gases). This contrasts with models that are much more "black box" representations

How does the model work?

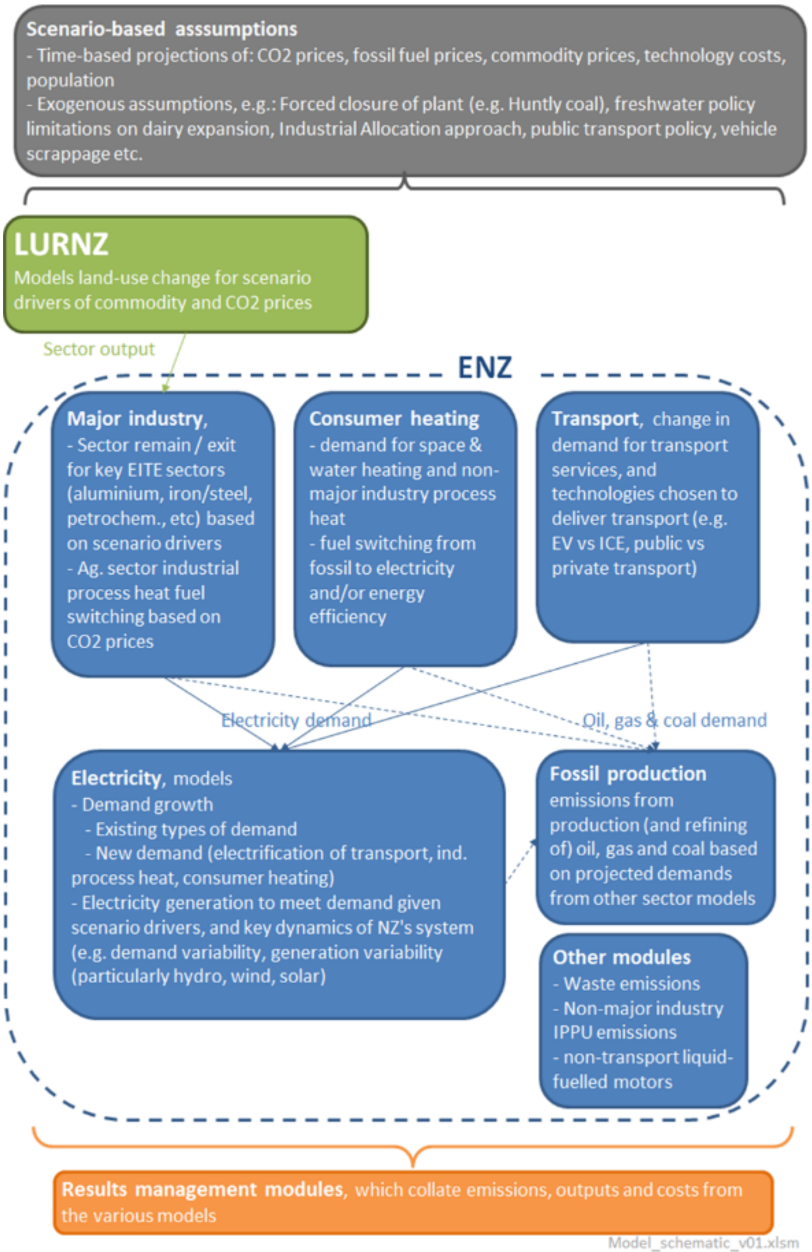
ENZ comprises a number of sub-modules that are all interlinked. It seeks to capture key dynamics, combining the physical with the financial, informed from multiple sub-models. The physical patterns and limitations include understanding the heterogeneity of situations, physical constraints and what matters. The financial aspect means cost structures really matter, distinguishing between public and private benefit, and that dynamic is often more important than static.

Fundamentally, the modules:

- project the demand for energy services – heating (space, water, process heat, etc.), lighting , transport, etc. – in an internally consistent manner;
- determine the most cost-effective means of meeting that demand using a mix of existing capital and new capital, given the fundamental external drivers (e.g. fossil-fuel prices, technology costs, CO_2 prices, etc.);
- model the relative international competitiveness of key energy-intensive trade-exposed (EITE) sectors (aluminium, steel, methanol, urea, etc.); and
- are completely internally consistent across the different parts of the New Zealand economy with respect to:
    - common macro drivers – population, fuel prices, CO_2 prices (international and domestic, etc.; and
    - the inter-connectedness of various sectors, particularly the demand for electricity and fossil fuels.

Many aspects of ENZ have been informed by specific individual models. Examples of this include: more detailed models of the operation of the electricity market to develop key relationships with respect to renewables variability; fuel market flexibility models; and detailed financial models of power stations (existing or proposed), industrial process heat plants, or consumer space and water heating.

Figure 2: Schematic representation of the ENZ model



Source: Vivid Economics, Concept Consulting, and Motu Economic and Public Policy Research (2018)

What datasets are used?

Table 4: The key datasets used by ENZ

Sector	Datasets
Electricity	Some projections are from within the electricity model, whereas others are driven by outputs from other ENZ models: • electric vehicle (EV) demand from the transport model; • electrification of industrial process heat, from the major industry model; and • electrification of fossil-fuel-based space and water heating from the consumer heating model.
Transport	The demand projections are based off the MOT historical transport statistics and the observed relationships between factors such as population and GDP, and observed outcomes such as vehicle kilometres travelled and freight travel.
Industrial process heat	The model projects future growth in demand for the heating "service", driven by factors such as population and assumed rates of energy-efficiency improvement, then uses a MAC curve approach to model the fuel-switching outcomes from consumers. The MAC curves are based on stand-alone analyses and seek to capture the factors in the fuel-choice decisions of households and businesses. There is significant uncertainty as to the levels for these.
Key EITE sectors	One of the most important factors is the extent to which a domestic New Zealand emissions price diverges from an international emissions price, and the extent to which EITE New Zealand producers receive "protection" from potential price imbalances. This is modelled through the operation of the industrial allocation mechanism.

Source: Vivid Economics, Concept Consulting, and Motu Economic and Public Policy Research (2018)

What are the strengths and limitations of the model?

Strengths:

- The model takes account of the interlinkages of the New Zealand economy.
- It allows for non-linearities in drivers of the outcomes.
- It allows for "drilling down" on projected outcomes to understand what drives results – for instance, the relationships between future vehicle ownership, rates of electric vehicle (EV) uptake, mode shifting that drives projected land transport emissions, or competition between land use for forestry and agriculture.

Limitations:

- Significant simplifications had to be made for some sectors (e.g. waste).
- There are inherent uncertainties over certain factors that will significantly drive outcomes (e.g. the future rate of technology cost reduction, future world oil prices, future world CO_2 prices). The effects of these are addressed by running scenarios with varying values for such inherently uncertain drivers.
- There are material data gaps in some sectors.

TIMES-NZ

The TIMES-NZ model is owned by the BusinessNZ Energy Council and will be hosted and maintained by the University of Auckland Energy Centre. It is still under development at the Paul Scherrer Institute (PSI) in Switzerland.

TIMES-NZ is an energy-system model, including all sectors of the economy and their various end-use energy demands. The model includes the energy inputs and outputs of the energy sector, and the energy inputs to all sectors of the economy, be they for heating, cooling, lighting, electric appliances, transport demands, etc. Given a range of energy resources and energy-transformation technologies, it will calculate the least-cost pathway to meet those energy-service demands for each sector. In other words, it's a PE model; it includes the energy inputs and outputs of the energy sector, and the energy demands across all sectors.

The TIMES-NZ model generator combines two different, but complementary, systematic approaches to modelling energy: a technical engineering approach and an economic approach. TIMES-NZ is a technology-rich, bottom-up model generator, which uses linear programming to produce a least-cost energy system, optimised according to a number of user constraints, over medium- to long-term time horizons. In a nutshell, TIMES-NZ is used for the exploration of possible energy futures based on contrasted scenarios.

National-level applications of the TIMES-NZ model tend to focus on energy planning and policy issues, taking into account renewable energy deployments, environmental effects and national obligations for emission reductions. National TIMES-NZ models are currently used in countries such as Sweden, Ireland, USA, UK, Portugal, China and Norway.

Other applications of the model include estimating CO_2 marginal abatement costs, integrating agriculture within an energy-systems model to assess GHG reduction, studying the impact of land-use change from biofuels on GHG emissions, incorporating travel behaviour and travel time into energy-systems models, and market penetration analysis of specific technologies, such as hydrogen vehicles. The New Zealand-specific model will be used first and foremost for the BusinessNZ BEC2060 energy scenarios, and to provide insights to those in academia and research, but will also be accessible on commercial terms to those who wish to use it.

3.2 Profiles of energy-sector models

3.2.1 Electricity-focused models

Competitive Risk Averse Generation Expansion (CRAGE)

CRAGE is a Walrasian PE model of the New Zealand electricity system based on the University of Auckland PhD thesis of Corey Kok (ongoing). The CRAGE code is owned and run by EPOC. The GAMS source is not public.

The model represents the five major electricity generators, electricity retailers, and industrial loads as risk-averse investors who compete as price takers. The transmission operator is modelled as a risk-neutral price taker. The output of CRAGE is a set of capacity choices for each technology for each generating firm, and operating decisions in varying load blocks in a number of different scenarios that model wind, solar and hydro inflow uncertainty.

Risk aversion in CRAGE is modelled using coherent risk measures. These have nice properties for optimisation and equilibrium. The simplest example of a coherent risk measure is mathematical expectation, which is risk neutral. In this case, CRAGE reproduces a system optimal capacity plan (as computed by GEMstone). For risk-averse risk measures, the solution for CRAGE matches a risk-averse system solution only under special circumstances.

CRAGE was developed by researchers at EPOC at the University of Auckland in collaboration with Professor Michael Ferris from the University of Wisconsin–Madison. It is coded in GAMS and solves using PATH.

The mathematics underlying CRAGE are described in more depth in the papers by Kok et al. (2018) and Ferris and Philpott (2018).

Bibliography of recent work

For a full list of publications, see Table 7.

Dynamic Outer Approximation Sampling Algorithm (DOASA)

DOASA is a model that solves a hydrological–thermal scheduling problem in a New Zealand setting.[2] The DOASA model can be used to formulate a policy of releasing water from reservoirs for electricity generation, while satisfying demand over a fixed time horizon and minimising the expected fuel cost of thermal generation and shortage cost.

The inputs for DOASA can be modified easily, which allows for running the model under different scenarios. For instance, a scenario where hydrological (hydro) lake levels start off higher/lower than average; a scenario where resource consents for minimum/maximum river flows are enforced/relaxed; a scenario with varying levels of carbon tax; a scenario where all new plant build is renewable. DOASA is generally run over a 52-week period (a longer time horizon is less computationally tractable).

[2] https://www.emi.ea.govt.nz/Wholesale/Tools/Doasa

Who owns/operates the model?

The DOASA code is owned and developed by Stochastic Optimization Limited (SOL). SOL have constructed a DOASA version for the Electricity Authority that they own and are able to distribute freely. The The Electricity Authority do not own, nor have access to, the source code.

What is the scope and extent of the model?

- DOASA is limited to modelling the New Zealand electricity system.
- DOASA is currently limited to a three-node representation of the transmission network (North Island, Haywards and South Island).
- Weekly demand in DOASA is currently limited to three load blocks (peak, shoulder and off-peak). Work by SOL suggests that this is not really much of an issue (i.e. having more load blocks doesn't change outcomes very much).
- Historical hydro inflows date back to 1932

How does the model work?

DOASA is an implementation of the Stochastic Dynamic Dual Programming (SDDP) algorithm. At a high level, the process for running DOASA is:

- preparing the data;
- using the model to generate a hydro release policy;
- running a simulation for selected inflow sequence(s) using the policy created; and
- inspecting the results – expected generation, water values, shortages, reservoir level and system cost for each week of the study period.

What datasets are used?

The DOASA model uses a hydro modelling dataset for New Zealand that includes information on infrastructure and hydro constraints, flows, storage and spill. Examples of the data inputs are: the hydro stations and how they're linked by arcs, hydro inflows for 27 locations in the system, data for lakes (reservoirs) that can store water for future use, outages for planned maintenance, costs of different types of fuel by week, data for all thermal stations (including fuel, heat rate, etc.), and capacity of transmission links between regions.

What are the strengths and limitations of the model?

Strength:

- There are proven convergence properties of the underlying SDDP algorithm, therefore there should be confidence in the veracity of results gained.

Limitations:

- The model is suitable only for New Zealand hydro settings.
- The sampling of hydro inflows (used to create an optimal release policy) assumes stage-wise independence (which doesn't reflect reality). This limitation is overcome somewhat by the use of the dependent inflow adjustment (DIA; also called inflow spreading).
- DOASA is currently limited to three modelled regions and three weekly demand load blocks.
- The user requires a licence for the Gurobi solver.
- The New Zealand electricity system is approximated with the assumption set and calibrating the model outputs.

What questions have been looked at in the past?

DOASA was recently used by the Electricity Authority to identify the winter energy margin that minimised the expected sum of generation costs and energy shortage costs across different inflow sequences.

What areas are there for future development?

A version of DOASA will soon be available on the Electricity Market Information (EMI) website for public use. It will have a web-based interface, will solve on the Electricity Authority's infrastructure, and will offer the ability to edit input data and download outputs (much like vSPD-online; see below).

Bibliography of recent work

For a full list of publications, see Table 7.

EMarket Model

Who owns/operates the model?

EMarket is a proprietary model developed and maintained by Energy Link Limited. EECA has licensed this model for a number of electricity system projects.

What is the scope and extent of the model?

The model simulates the New Zealand electricity market at high resolution, with nodal-level dispatch, time steps as short as half-hourly, and using 86 years of inflow data.

How does the model work?

The model calculates water values for each major reservoir system across the range of historical inflow sequences, based on the offer profiles of other plant and user-defined demand. The model then simulates system dispatch across the modelled period using the range of inflow sequences and offer profiles.

What datasets are used?

Key datasets are historical inflows, grid configuration and capacity, demand estimates and profiles, and generator capacity and offer curves. For forward-looking models, both demand and generation are defined by the user. EECA have used a static grid for their purposes, but have the ability to detect where grid expansion may be required

What are the strengths and limitations of the model?

Strengths:

- The input data are flexible and transparent.
- The model enabled EECA to change a large number of variables – including solar uptake, demand quantity and shape, different generation build patterns and offer price approaches – relatively easily, with support from Energy Link for some of the data inputs.
- The model is hydro-centric (critical for the New Zealand electricity system), can be run at high resolution, and produces very comprehensive outputs, enabling users to understand what is happening in detail.
- The model has been developed and set up by experts in the New Zealand electricity industry, and the outputs have been validated by these experts and their clients, which adds considerably to the credibility of modelling outputs.

Limitations:

- The model needs to be set up carefully, and the run time is quite long for high resolution (approximately 40 minutes for one calendar year at three-hourly resolution for 86 inflow years).
- As with any modelling project, model users must have careful process and discipline around input control, output analysis and data management.
- Licensing and staff time for modelling both represent a significant investment for EECA, and may be out of reach of voluntary or academic organisations.

What linkages are there to other modelling work?

This modelling work does not have any formal linkages to other modelling work, but indirect linkages are expected with many of EECA's other projects and cross-agency projects in which EECA participates.

What questions have been looked at in the past?

- What is the financial and emissions impact of the demand avoided by EECA's energy-efficiency programmes?
- What is the cost and feasibility of achieving high levels of renewable generation (approaching 100 percent) in the New Zealand electricity system?

- What is the cost and feasibility of supplying 100 percent of New Zealand's energy demand using renewable electricity (currently in progress)?
- What is the financial and emissions impact of a flatter electricity-demand profile?

What areas are there for future development?

Future development of the model will be determined by Energy Link. EECA currently has no plans beyond completion of current modelling projects (primarily the 100 percent renewable issue).

Bibliography of recent work

EECA has not published any of the results from work to date.

Generation Expansion Model (GEM)

GEM[3] is a long-term planning model used to model capacity expansion in the New Zealand electricity sector. The model determines which plant to construct and in which year each new plant is to be commissioned, all the while satisfying a number of technical, physical and economic constraints. The model can also be configured to co-optimise the expansion of the transmission network along with the generation fleet.

The model is typically run for a series of scenarios describing possible future outcomes for factors such as demand for electricity (energy and peak), hydro- and thermal-fuel availability, fuel prices, plant costs, and policies such as carbon pricing, renewables targets and transmission pricing. Under each scenario, a build plan and a supporting set of prices is generated. The time horizon over which the model is operated is typically 20–40 years.

Who owns/operates the model?

GEM is an open-source model developed and maintained by the Market Analytics team at the Electricity Authority.[4] The current codebase is downloadable from GitHub.[5]

What is the scope and extent of the model?

GEM requires the GAMS software to solve the algorithm.[6] It is limited to modelling the New Zealand electricity sector. GEM, as a long-term model, is usually run over a long time period (e.g. 20–40 years). The time steps can be either monthly or quarterly. GEM can be run in either two-region (North Island/South Island) or 18-region network mode. The 18-region configuration is typically used when GEM is being applied to co-optimise transmission investment. It can be run with a variable number of load (demand) blocks that make up the load duration curve – in other words, demand is represented with a load duration curve commensurate with the time step (monthly or quarterly) used to solve the model rather than chronologically.

[3] https://www.emi.ea.govt.nz/Wholesale/Tools/GEM
[4] The code on the GitHub repository is licensed under the GNU General Public License, version 3 (GPLv3).
[5] https://github.com/ElectricityAuthority/gem
[6] https://www.gams.com

How does the model work?

GEM is coded using GAMS. To use GEM, the first step is to prepare the input files. This includes datasets, parameters and variables. The scenario file also needs to be prepared, and can be configured by alternate text or by using a user interface. The reporting files then need to be edited and the output inspected.

What datasets are used?

The three input files for GEM are the so-called standard input data, regional and network electricity data, and energy-demand data. The standard input data include more than 100 various global parameters and sets. The regional and network data include various parameters and sets relating to the transmission network and to regional mappings. The energy-demand data include a single input parameter for electricity load by region, year, time period and load block.

What are the strengths and limitations of the model?

Strengths:

- GEM minimises the capital cost of building new plants while simultaneously taking account of operating costs such as fuel, and variable and fixed operation and maintenance costs.
- GEM output includes a schedule for new plant build, future installed capacity by fuel/technology type and future CO_2-e.

Limitations:

- The list of locations for, and types of, new plants can be relatively speculative, especially the further in to the future you go.
- There is no capacity for reservoir optimisation (the proposed remedy for this is to iterate GEM with a model such as DOASA; see below).
- There is limited representation of intermittent and non-grid connected generation, although this is really just a data issue rather than a model formulation issue.
- Modelling is from the perspective of a central planner (i.e. it doesn’t account for departures from the assumptions underlying a perfect competition framework).

What linkages are there to other modelling work?

A version of GEM is used by MBIE in their energy modelling. MBIE iterate between using GEM and their Supply and Demand Energy Model (SADEM):

> The GEM optimisation model produces a projection of new generation plant built over the next 30 years and the expected gas demand from existing and new thermal generators. A separate pricing model then determines the wholesale price indicator based on the LRMC (long run marginal cost) of each new plant built. These models operate independently of SADEM however data is exchanged between all the models in a dynamic loop. (Ministry of Business, Innovation and Employment, 2016)

What questions have been looked at in the past?

GEM has been used in the past for the Electricity Commission/Electricity Authority's Statement of Opportunities (SOO) report, and subsequently for MBIE's Electricity Demand and Supply Generation (EDGS) modelling. Questions asked in these reports include:

- What will the trajectory of CO_2-e look like over time under different scenarios?
- When and where should new generation plants be built?
- When will certain thermal-generation plants be retired under different scenarios?
- What will the proportion of installed capacity by technology/fuel type be over time under different scenarios?
- What are the long-run marginal costs (LRMCs) and subsequently the required wholesale prices for investors in generation plant to break even?

Transpower has also used GEM to assess grid-upgrade proposals.

What areas are there for future development?

The code behind GEM is currently being refactored. The biggest change will be that all of the "non-solving" modules (e.g. data preparation and results presentation) will be written in the R programming language (gemR). Solving the optimisation problem will still occur using the GAMS software.

Follow the progress of gemR development at https://github.com/ElectricityAuthority/gemR.

Generation Expansion Model in a STOchastic and Noisy Environment (GEMstone)

GEMstone is a suite of stochastic programming capacity expansion models of the New Zealand electricity system, developed by the Electricity Power Optimisation Centre (EPOC). These are loosely based on the GEM mixed-integer programming model.

GEM is a deterministic multi-stage optimisation model with binary investment decisions. The technologies in the New Zealand electricity system are represented with a high degree of fidelity. The model's forecasts of optimal investments diverge somewhat from what is observed. There are at least two reasons for this. First, investments are made over long time horizons, and so uncertainty and risk play a role in determining which investments are chosen. GEMstone is an attempt to represent the effect of this uncertainty on system optimal decisions. The other reason is a divergence between firm optimisation and system optimisation when markets for risk are imperfectly competitive or incomplete. This is addressed by the CRAGE model (see above).

GEMstone has several versions. GEMstone2 is a two-stage stochastic convex programming problem with continuous variables solved using GAMS/Conopt. The first stage in GEMstone2 involves a capacity investment decision by a social planner that is made to minimise the system investment cost plus the annual expected operating cost of the system to meet demand in various scenarios. Current scenarios consist of 13 inflow scenarios (corresponding to years 2005–17), two independent wind scenarios and two reliability scenarios. A presentation on GEMstone2 can be downloaded from www.epoc.org.nz/publications.

GEMstoneT is a multi-stage stochastic integer programming problem. This is a more sophisticated version than the two-stage model, and uses the Dantzig–Wolfe decomposition methodology of Singh et al. (2009) to solve a multi-stage stochastic integer programming problem. A version of GEMstoneT to deal with wind-capacity expansion was developed by et al. (2017). Here, "STOchastic" describes the uncertainty over long time scales, and "Noisy" the intermittency of wind that requires investments in ramping plant. GEMstoneT has also been applied (under a different name) in Latin America by Flores-Quiroz et al. (2016). The GEMstone code is owned and run by EPOC. The source is not public.

Bibliography of recent work

For a full list of publications, see Table 7.

Hydro-Sim

Hydro-Sim is a hydro-thermal optimisation tool that schedules the within-day and within-year hydro storage releases and half-hourly station dispatch for each of the main hydro systems in New Zealand.

Hydro-Sim has been used in the past to analyse the potential impact on hydro generation and production costs of altering water-allocation rules. For example, it was used in 2017 for MfE to test a number of altered water-allocation scenarios, and the results were reviewed by all five of the major hydro generators. Feedback indicated that generators considered Hydro-Sim to provide a good representation of the generation system.

Hydro-Sim can be used to test the extent to which New Zealand's hydro system can provide additional flex to help accommodate higher percentages of renewables (particularly wind and solar). Key issues that Hydro-Sim can help inform include the extent to which additional seasonal flex can be provided, and whether altered reservoir operating regimes (e.g. increasing storage capacity by lowering the minimum operating level in Lake Pukaki) may enhance seasonal flexibility and reduce the need for non-hydro resources to address dry-year risks.

Hydro-Sim can also be used to test the extent to which possible changes in freshwater allocation may reduce the flexibility of the hydro schemes (noting that this would be the outcome from a number of the possible changes to freshwater allocation), and thereby increase the need for flexible energy from other sources.

The Hydro-Sim toolset has also been configured to allow examination of the extent to which diversity of renewable electricity sources – both diversity of type (wind, solar, hydro) and diversity of location – will impact on the generation weighted average spot price (GWAP)/time weighted average price (TWAP) price suppression that is associated with increased proportions of uncontrolled renewables on the system.

It is also possible to examine the extent to which utility solar (as distinct from rooftop solar) can implement measures that will substantially reduce this price-suppression effect, including measures such as single-axis tracking, winter-maximising orientation and overbuilding arrays in relation to summer output.[7]

Hydro Vectorised Scheduling, Pricing and Dispatch (HydrovSPD)

HydrovSPD is a multi-stage deterministic version of SPD, the New Zealand electricity market dispatch software used by Transpower every five minutes to dispatch the New Zealand wholesale electricity market. HydrovSPD is coded in GAMS, and is based on vSPD (Vectorised SPD), the GAMS/CPLEX copy of SPD that is distributed by the New Zealand Electricity Authority (see above). vSPD is essentially identical to SPD but is publicly available. With historical energy and spinning reserve offers (that are publicly available), vSPD perfectly replicates historical spot market prices. Thus, a simulation in vSPD is effectively an experiment in the real market.

HydrovSPD computes a dispatch in each half-hour of a day using vSPD, assuming that electricity demand and all energy and reserve offers for the 48 periods in the day are known. With historical offers, HydrovSPD will replicate market outcomes. With appropriate conversion factors for electricity turbines, HydrovSPD will also replicate the water releases from hydroelectric systems (subject to block-dispatch variations).

If, on the other hand, the user inputs hypothetical energy and reserve offers, then HydrovSPD will give a hypothetical dispatch and prices for every period of the day. However, the water releases computed from this hypothetical dispatch might not be feasible for the constraints imposed by flow down a river chain. Thus, HydrovSPD imposes hydrology constraints on all the dispatch variables. Users can also impose a constraint on end-of-day

[7] Overbuilding arrays in relation to inverter capacity (and thus effectively "spilling" solar during summer months) can be economic where the arrays themselves are low cost and the greatest value of output is in winter generation (where panel output matches inverter capacity).

reservoir levels (for example, to make them match historical levels), or provide a water price surface at the end of the day to incentivise best economic use of the water.

HydrovSPD is a central part of the Electricity Market Benchmarking ExpeRiment (EMBER) project in EPOC (see Philpott & Guan, 2018). This project aims to create perfectly competitive counterfactual water-release polices that can be tested against historical outcomes.

HydrovSPD is coded in GAMS/CPLEX. It was developed by Ziming Guan at EPOC, based on the work in Nick Porter's 2014 Master's thesis. It is not currently publicly available.

Bibliography of recent work

For a full list of publications, see Table 7.

Vectorised Scheduling, Pricing and Dispatch (vSPD)

The vSPD model is an audited mathematical replica of Scheduling, Pricing and Dispatch (SPD) – the model used by the system operator to schedule, price and dispatch electricity in New Zealand every 30 minutes.[8]

Who owns/operates the model?

The Electricity Authority created vSPD using the GAMS software in 2008. The model is maintained by the Electricity Authority and is available for download at https://github.com/ElectricityAuthority/vSPD. An online version of vSPD, called vSPD-online (https://www.emi.ea.govt.nz/vSPD-online), is available for use from within a web browser and without the need to learn the modelling software. Different scenarios can be tested – for instance, high/low demand; high/low South Island generation offers (i.e. supply curves, etc.). Licence information for vSPD-online and other tools available on the EMI website can be found at https://www.emi.ea.govt.nz/Content/Legal-Information/EMI%20tools%20license.pdf.

What is the scope and extent of the model?

The model can be applied to all dispatch, schedule and pricing cases in the New Zealand electricity market system. It can be run for every day from July 2009, as final pricing GAMS Data Exchange (GDX) files are published every day. Users require a licence for the GAMS software.

How does the model work?

Data from SPD case files are converted to GDX input files. vSPD is then run using these GDX input files. vSPD can be run using the command line, an Excel interface, a GAMS interface or the vSPD online version.

[8] https://www.emi.ea.govt.nz/Wholesale/Tools/vSPD

What datasets are used?

Input GDX files for final pricing cases are available daily from ftp://emiftp.ea.govt.nz /Datasets/Wholesale/Final_pricing/GDX or from www.emi.ea.govt.nz/Datasets/Wholesale /Final_pricing/GDX. Input GDX files for other cases are not available but can be created

What are the strengths and limitations of the model?

Strengths:

- It is a mathematical replica of SPD, which is used for dispatch, scheduling and pricing in the New Zealand electricity market.
- It is open source and therefore can be used for academic or industrial study/research.

Limitations:

- The model applies only to the New Zealand electricity market system.
- The user requires a GAMS licence to run vSPD. The online version is publicly available but limited to one-week runs at a time.

What linkages are there to other modelling work?

vSPD is a replica of the SPD model run by the system operator to model the New Zealand power system.[9]

What questions have been looked at in the past?

vSPD has been used to:

- evaluate the impact of changes in the New Zealand electricity market system (SPD and market design);
- study the impacts of an electricity market scenario, such as a major outage, unusual market behaviour, etc.; and
- generate a net pivotal index.

Bibliography of recent work

For a full list of publications, see Table 7.

3.2.2 Other energy-focused models

Biomass Value Chain Model (BVCM)

BVCM is a geographically high-resolution and dynamic mixed-integer linear programming (MILP) optimisation model that determines the most effective (in terms of cost and emissions) biomass value chains to achieve specific future liquid biofuel demand targets. The model determines how to progress from current energy systems to future ones, and considers the future energy mix throughout the transition towards a lower carbon economy based on biofuels.

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[9] https://www.transpower.co.nz/system-operator/electricity-market/scheduling-and-dispatch

Among the questions answered by the model are:

- what crops to grow, where to grow them and when to grow them;
- what crop-to-energy conversion technologies to use, where to build them and when to build them;
- how to transport resources through space; and
- how to store resources through time.

The model is coded in the Advanced Interactive Multidimensional Modelling System (AIMMS) and uses CPLEX as a solver.

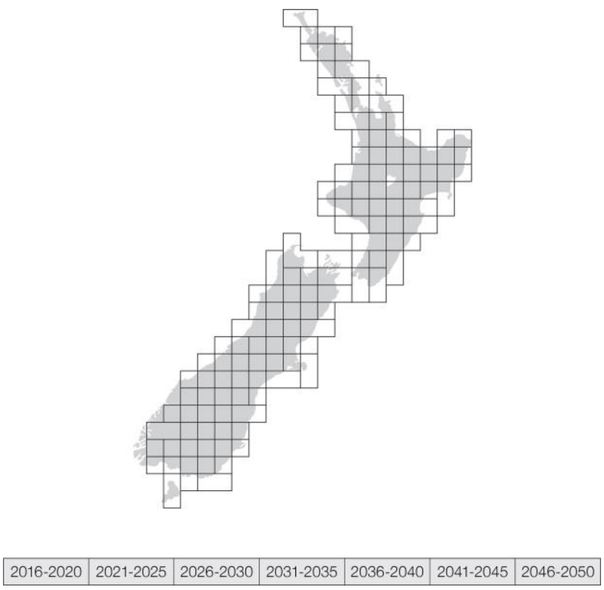
Who owns/operates the model?

BVCM was developed by the Energy Technologies Institute (ETI) in the UK, and was successfully used to assess and understand the prominent role bioenergy could play in meeting the UK's GHG emission-reduction targets. Scion licensed BVCM and modified it to make it suitable for New Zealand requirements, and then populated it with New Zealand-specific data.

What is the scope and extent of the model?

In the specific case of Scion's Biofuels Roadmap, the objective of using BVCM was to identify the optimal value chains linking land-based resources (i.e. feedstocks) to existing conversion technologies, and using existing transport infrastructure, to meet future liquid biofuel demands at the lowest cost.

Figure 3: How BVCM divides up New Zealand

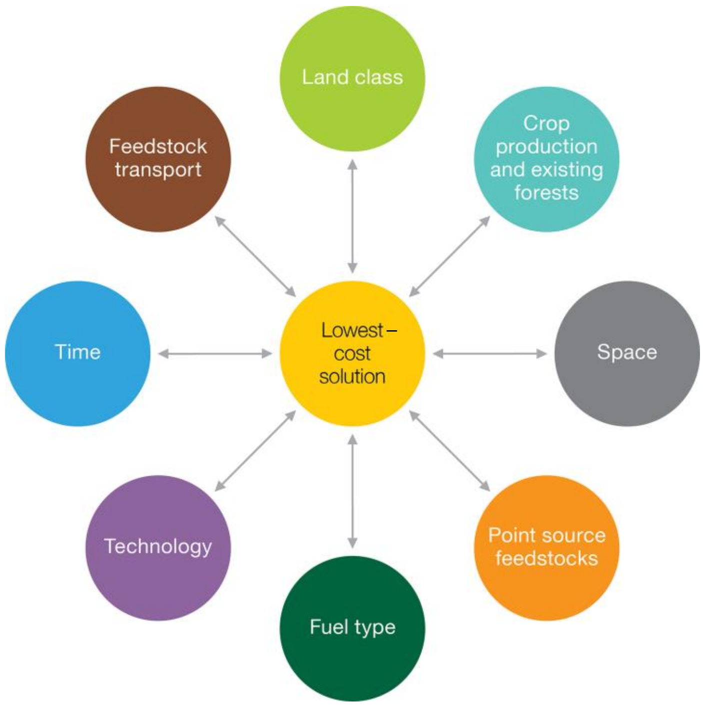


To identify such optimal value chains, the model divides New Zealand into 132 cells measuring 50km × 50km, each containing information on area of various land-quality classes, their land values, crop growth rates and costs, and feedstock availability. This is shown in Figure 3. The time horizon considered was 35 years, divided in five-year intervals. Future biofuel demand forecasts were divided into four fuel families according to their ability to substitute for fossil petrol, diesel, and aviation and marine fuels (e.g. bioethanol as a replacement for petrol, or biodiesel as a replacement for fossil diesel). The model also contains data on a range of crops, feedstocks, transport modes and conversion technologies. It includes options such as chipping or pelletisation, which produce intermediate products that can then be sent to another technology for further conversion to fuel. Co-products can be generated and sold, or disposed of at a cost.

How does the model work?

Once a specific "future" or scenario is defined, the model chooses from among the many potential biofuel pathways, identifying (using MILP optimisation) the lowest-cost solution across the whole value chain and time frame modelled. It then provides the technical, economic and environmental impacts associated with the end-to-end elements of a particular course of action. Optimisation can also be on the basis of maximising net present revenue, minimising GHG emissions or a combination of both. Figure 4 shows the factors used in the model to make the lowest-cost solution.

Figure 4: The factors used to make the lowest-cost solution



What datasets are used?

Datasets used by BVCM are defined by the user to fit the requirements of each analysis. Land use, feedstock and transport data are stored in standard text file formats. Conversion technology data are developed in an Excel workbook. Table 5 shows the datasets used for the Biofuels Roadmap project.

Table 5: Data used by BVCM

Dataset	**Source**
50km grid	Scion
Land available for growing forest or arable feedstocks	Derived data, Scion (New Zealand Land Cover Database version 4 with exclusions, aggregated into five land classes based on land-use capability and slope)
Existing plantation area by five-year age classes	Derived data, Scion (New Zealand Land Cover Database analysis, scaled by National Exotic Forest Description)
Land opportunity cost/land value	Derived data, Scion (based on a real estate database)
Existing forestry production schedule and residue availability	Derived data, Scion (based on MPI wood-availability forecasts)
Existing forestry log opportunity cost	Derived data, Scion (based on delivered price at nearest port/mill and transport cost)
Arable crop productivity, production and harvest costs, and GHG emissions by land class and cell	Derived data (Scion)
Transport/handling costs and GHG emissions by transport mode (road, rail and shipping)	Scion
Delivered price for alternative uses of logs	Scion
Point-source feedstock locations (sawmill waste, tallow, municipal solid waste, waste wood)	Scion
Port locations	Scion
Transport routes (road, rail and shipping)	Scion
Conversion technology data, including inputs required (e.g. gas, chemicals), scale, utilisation rate, capital cost, fixed and variable operating costs, fuel yield, co-product(s) yield, operating life, build rate, GHG emissions	Scion and ETI

What are the strengths and limitations of the model?

Strengths:

- BVCM is perhaps the only model in New Zealand that considers an entire value chain, including land-based resources, infrastructure, technologies, and the markets for products and by-products.
- It provides a detailed treatment of value chains, such as the consideration of the optimal location and size of individual plants as well as transport infrastructure.
- It is a fully dynamic model, explicitly showing the transition path of the optimal value chains.
- The model is large scale and yet geographically explicit, including tortuosity factors for the transport component and land-quality classes for the different cells.
- The model tracks GHG accounting across the value chain, which is critical for policy analysis on international commitments.
- It treats the forest resource at the national scale in detail, including the productivities by log grades, across space and time.
- It has a graphical user interface (GUI) that facilitates the creation of scenarios and the interpretation of results through graphs and maps.
- The generation and use of maps to show results across space and time is very useful to interpret results of when forests are harvested, where and what products are transported, and where plants are built.
- The model has a user community and development momentum beyond New Zealand.

Limitations:

- The distribution of the final biofuels produced is not modelled. This assumption is made for computational efficiency and because the cost of transporting the final biofuel to where it will be used is much less than the cost of shipping an equivalent mass of the original biomass.
- The interaction between supply and demand and its impact on costs/prices is not considered – in other words, the impact of large-scale biofuel production on other parts of the economy is not considered.
- Constant input costs and co-product prices are based on 2016 values. This is more of an assumption rather than a limitation, as the model allows for costs and prices to vary through time.
- Non-feedstock inputs (e.g. natural gas or electricity) are assumed to be available in unlimited quantities at the same cost throughout the country and there is no limit on the amounts of co-products that can be sold.

- The land opportunity cost assumes that the land is free to be used for the highest value application possible, with the exception of existing forestry land, which is assumed to be replanted.
- The model assumes that all conversion technologies are commercially ready, with cost reduction over time proportional to their readiness level.
- A single discount rate of 7 percent is applied for all parts of the value chain. This value is suggested by the Treasury for the development of new technologies.
- Imports or exports of biofuels or imports of feedstocks were not considered in the Biofuels Roadmap modelling. This is more of an assumption rather than a limitation, as the model allows for the inclusion of imports and exports.
- The level of detail (or aggregation) used in the Biofuels Roadmap project is designed for national-level modelling. For specific biofuel investment analyses, more detail will be required.

What linkages are there to other modelling work?

BVCM has only recently been used for Scion's Biofuels Roadmap project. Hence, it has not been used alongside other economic or engineering models. However, it has the capacity to be used with engineering models such as Woodscape or published international information for the generation of operating and capital expenses profiles as well as technological efficiencies. It could also be linked to land-use optimisation models such as LURNZ or NZ-FARM. This model has been linked with ESSAM (Scion, 2009). There is the possibility to link the model's outputs to other wide-economic models to obtain indirect impact such as the generation of capital and employment.

What questions have been looked at in the past?

The question investigated in Scion's Biofuels Roadmap project was:

- What are the considerations concerning technologies and investment requirements as well as the practical requirements of establishing an entirely new way to sustainably provide a large proportion of the country's liquid transport fuels?

The original UK model was used to answer variants of the above question:

- What is the most effective way of delivering a particular bioenergy outcome in the UK, taking into account the available biomass resources, the geography of the UK, time, technology options and logistics networks?

What areas are there for future development?

Key priorities for future development include:

- updating the operating and capital expenses of the various technologies;
- updating technology conversion rates;
- including additional technologies and feedstocks;
- improving the productivity dataset for feedstocks other than forestry;
- using the stochastic component of BVCM;
- using the model to include other products, such as heat and solid biofuels;
- including other negative emission technologies such as carbon capture and storage;
- including potential feedstocks from other land uses, such as dairy and sheep and beef; and
- using the model to assess the impacts on ecosystem services.

Bibliography of recent work

For a full list of publications, see Table 7.

Concept Fuel-flexibility models

Concept Consulting has a range of fuel-flexibility models to estimate the capabilities and costs of meeting the demand for energy flexibility over a range of time frames: within day/week (diurnal), within year (seasonal), and year to year (dry-/wet-year firming). The models include detailed economic representations of the following flexibility sources:

- coal-fired generation – with fuel flexibility from imports and the Huntly coal stockpile;
- gas-fired generation – with fuel flexibility from gas production swing, underground storage, gas importation, or demand response by Methanex;
- use of hydrogen generated from renewables and stored in reservoirs or as ammonia;
- use of batteries (within EVs or as stand-alone storage technologies);
- use of biomass (such as diverting pulp logs from export as a fuel source from time to time); and
- longer-cycle demand response – especially by large industrial electricity users such as the Tiwai smelter.

These models have been developed and used in a variety of engagements, ranging from longer-term evaluations of the implications of new technologies, through to supporting major investment decisions by generators or fuel suppliers. Many of them have detailed representations of the storage dynamic that is at the heart of meeting the requirement for flexible energy on varying timescales. For example, optimisation tools to develop “gas inject/extract value curves” or “hydrogen production value curves” that are analogous to the water value curves used to optimise hydro storage and release decisions.

These models have been used in multiple engagements for Concept's clients, often to support major capital investment or merger/acquisition decisions.

Process Heat Emissions Reduction

Who owns/operates the model?

The modelling approach and models have been developed by the Energy Research Group at the University of Waikato. The intention is that they become available to the public and are updated as required.

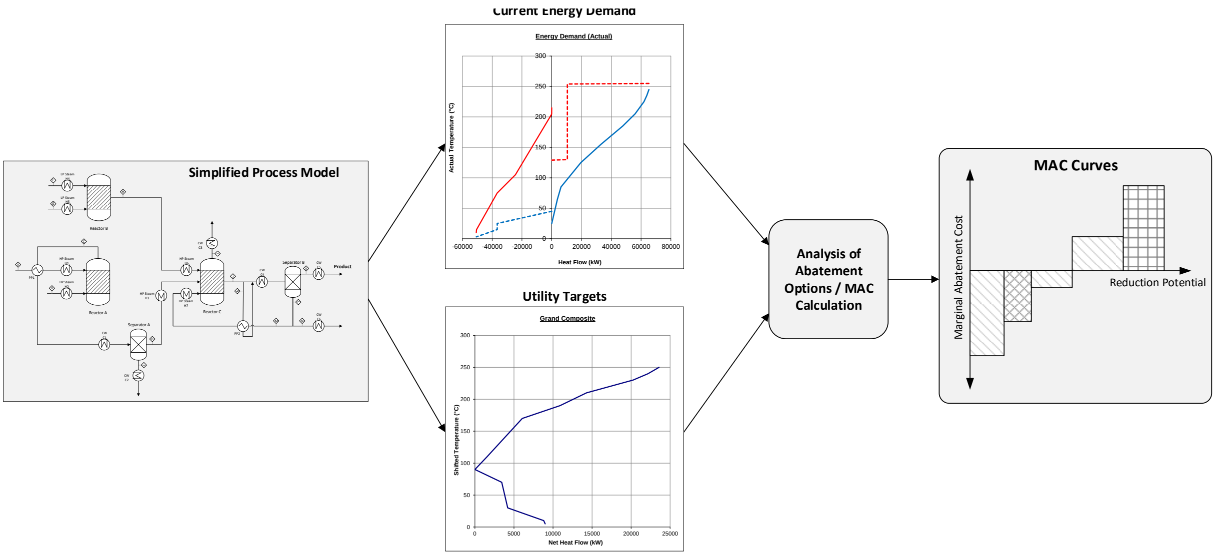
What is the scope and extent of the model?

A process integration approach/framework (based on pinch analysis) has been developed for estimating sector, regional and national GHG emission-reduction potentials from the industrial process heat sector and developing MAC curves. The basis of the framework uses process integration techniques to develop process temperature profiles for heating and cooling demand, allows benchmarking and energy targeting to be carried out, and provides a standard against which emission-reduction measures can be assessed.

How does the model work?

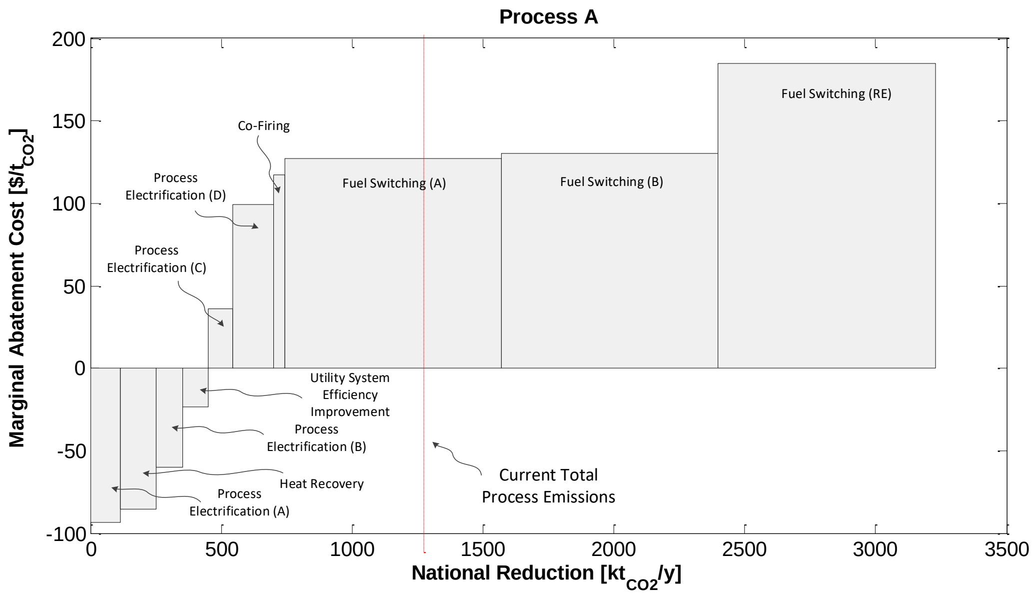
An overview of the framework of the methodology is shown in Figure 5. Priority sectors and processes have been identified using available energy demand data and are then investigated individually. A "typical" plant is modelled as a representative basis for the sector and to replicate the current processes, unit operations and practices, level of heat recovery, etc. This requires some expertise and knowledge of the process. Where appropriate, multiple models for a single process have been developed to reflect different technologies used by plants.

Figure 5: Overview of methodology framework for an individual process



The model is a simplified mass and energy balance of the typical plant, with enough detail to extract process and utility stream data. The utility system can be approximated using assumptions of typical boiler efficiency etc. ,or can be modelled separately if more detail is required. A simple pinch analysis can then be performed using the stream data and utility targets, and can be compared against existing utility use. The model can then be used to examine individual abatement options, the reduction in process heat demand/emissions, changes in the operating costs, and indicative capital costs. For each individual measure, the emission reduction can be quantified and extrapolated to estimate the total reductions for that measure at a regional or national level. The MAC is then calculated based on capital, operation costs and emission-reduction potential. A MAC curve can then be produced, as in Figure 6.

Figure 6: Example of sector-weighted marginal abatement cost curve



What datasets are used?

The available data for process heat demand are not very reliable and there are large discrepancies between datasets for various reasons, such as classification and definitional issues or commercial sensitivities. Two main datasets were used as a basis to estimate process heat energy demand, and these were harmonised by comparing energy use and emissions with production and expert input. These were the EECA Energy End-Use Database (2014) and Modified EECA Heat Plant Database (2016).

The Modified EECA Heat Plant Database is based on the 2014 Heat Plant in New Zealand database, updated by Consulting, Research and Laboratories (CRL) Energy Ltd on behalf of EECA. This 2014 dataset has been subsequently modified and updated independently by the Energy Research Group at the University of Waikato and Scion. Additional modifications included updating heat plant information, estimating actual energy used by sector, providing geographic information system (GIS) information on individual sites, and including direct heat use (i.e. not from heat plants) into the dataset to estimate total process heat use in New Zealand.

What are the strengths and limitations of the model?

Strengths:

- The tool to calculate MAC can be used to investigate different financial inputs (e.g. fuel costs, equipment lifetime, discount rate, etc.) or to perform plant-specific analysis, regional analyses, or national analyses.
- Site-level roadmaps for transition to a predetermined emissions target can be developed using the model.
- The bottom-up approach used here captures the actual structure of the process and the abatement options are explicitly evaluated on their technical and economic merit.

Limitations:

- The model approach is that process- and sector-specific knowledge is required to develop the mass and energy balance and apply the process-integration techniques.
- The bottom-up approach requires individual models for each major sector to be developed and the results aggregated to provide a national-level estimate and potential pathways for emission reduction in the process heat sector.

What linkages are there to other modelling work?

There are no known linkages to other modelling work.

What questions have been looked at in the past?

Detailed models of milk powder processing have been developed and MAC curves generated. Higher-level models have been developed for other energy-intensive processes such as aluminium smelting, methanol synthesis, other dairy processes, and meat processing and rendering.

What areas are there for future development?

The approach will be applied to the remaining priority industry sectors.

Bibliography of recent work

For a full list of publications, see Table 7.

Supply and Demand Energy Model (SADEM)

Some of the information for this section is taken from Ministry of Business, Innovation and Employment (2016).

Who owns/operates the model?

SADEM is owned and operated by MBIE.

What is the scope and extent of the model?

SADEM is part of the suite of modelling tools used to explore the future demand for energy from the different New Zealand sectors.

How does the model work?

SADEM is an R-based program that econometrically estimates energy quantities across different fuel types and sectors, and brings everything together into a total picture of energy demand. Those estimates are then fed into GEM (a GAMS-based optimisation model developed by the EA; see above) to generate estimates of fuel price. These are fed back into the demand model, which impacts on quantity measures. The two systems iterate until they converge onto a consistent trajectory of fuel-quantity demands and price. This is something that MBIE is looking to update.

What datasets are used?

The model uses mainly MBIE fuel data, and some data from Stats NZ.

What are the strengths and limitations of the model?

Strengths:

- It projects energy demand for all sectors in the economy.
- It provides a central hub, coordinating electricity supply information from GEM and land transport demand information from the Vehicle Fleet Model (VFM).

Limitations:

- The PE nature of the model could be improved.
- Some of the econometrics underlying the demands could be updated.
- The modelling is of the energy sector only, not of the entire economy. The key drivers within this modelling are exogenous (e.g. GDP and oil price), meaning that secondary effects are not modelled (e.g. the potential link between the price of oil and GDP is not taken into account).

What linkages are there to other modelling work?

The supply-side electricity and electricity price component is derived from the GEM model using inputs consistent with SADEM.

What questions have been looked at in the past?

In the past, SADEM has been used to forecast energy supply, GHG emissions, fugitive emissions and energy intensity. A more in-depth overview of the issues the model has been used to explore can be found in Ministry of Business, Innovation and Employment (2016).

What areas are there for future development?

MBIE is currently in the process of reviewing and updating its energy modelling, including input data, assumptions and the underlying models used.

UniSyD

UniSyD is a detailed, user-friendly model of New Zealand's energy economy. The model has its origins in 2002, when it was commissioned to examine scenarios for a hydrogen economy, but has since been greatly expanded in scope and adopted in Scandinavia and Japan for modelling these national energy economies. Development of the model has proceeded with input from researchers from Unitec, Stanford University, University of Iceland, Kanagawa University, Asia Pacific Energy Research Centre (APERC), Aoyama Gakuin University and the Massachusetts Institute of Technology (MIT). For instance, the model implementation for the Nordic energy systems is being developed with the aim of identifying low-carbon energy system trajectories for five Nordic countries (Denmark, Finland, Iceland, Norway and Sweden), with an emphasis on the dynamics of alternative fuel markets.

Who owns/operates the model?

The model is jointly owned by Unitec and the University of Iceland. Kanagawa University is an associate partner. UniSyD may be available to entities that can commit to resourcing the ongoing development of the model subject to a confidentiality agreement.

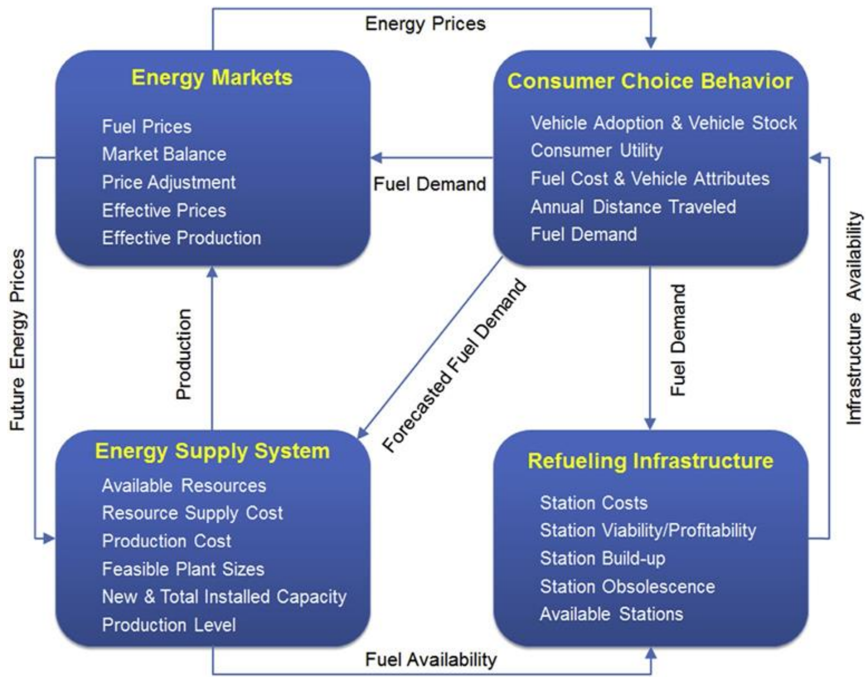
What is the scope and extent of the model?

The UniSyD family of models is available for New Zealand, Iceland and Japan, and a model is under development for Scandinavia. The model divides New Zealand into 13 distinctive geographical regions based on electricity authority and regional boundaries. It is characterised by specific identification of more than 2,000 variables that determine primary energy resource use, electricity generation and the composition of the vehicle fleet. The model transparently includes specific detail of current technologies and those emerging technologies thought to impact energy futures to 2060 and beyond. Outputs include future profiles of primary energy resource use, including viable renewables, fossil fuels and biomass; electricity generation in 13 regions; GHG emissions; capital investment; refuelling or recharging infrastructure propagation; and up to 14 different vehicle technologies in light and heavy fleets and new and imported vehicles.

How does the model work?

The relative prices of different technologies and feedstocks guide the modelled decision-making process of firms and consumers, whether the decision is the choice of new electricity generation capacity, battery charging or hydrogen-refuelling infrastructure, the amount of existing capacity to use for both electricity and hydrogen, or the preferred vehicle type (Figure 7).

Figure 7: Overview of UniSyD model



Source: Shafiei et al. (2017)

The transport fleet is divided into multiple fleets based on weight, with a choice of up to 14 vehicle technologies. A heavily researched non-linear vehicle choice algorithm determines the probability that consumers purchase new vehicles at each time step based on vehicle purchase price, fuel cost, emissions, annual maintenance cost, vehicle range, battery replacement cost for EVs, and fuel station availability (relative to conventional petroleum stations).

The model is developed using the system dynamics computer programming package Systems Thinking, Experimental Learning Laboratory with Animation (STELLA). The objects in the interface network diagram are each underpinned by equations defining the mathematical relationship between the variables. The primary exogenously defined variables are set in a separate control-panel level of the program, allowing for easy use of the model by policy-makers and other interested parties.

What datasets are used?

The datasets used involve supply infrastructure data, energy resources, vehicle attributes, consumer behaviour and socio-economic indicators. Supply infrastructure data include capital, fixed and variable costs; learning and economy of scale effects; conversion efficiencies; and emission factors. Energy resources include resource potential and resource supply curves. Vehicle attributes include capital, operation and maintenance costs; fuel economies; and driving range. Consumer behaviour includes vehicle attribute preferences and travel demand elasticities. Socio-economic indicators include GDP growth, population growth, maximum vehicles per capita, energy and emission tax rates, and international oil price.

What are the strengths and limitations of the model?

Strengths:

- There is global recognition of the robustness, utility and accuracy of the model.
- Programming takes place using a network interface that clearly shows relationship between variables.
- There is easy transportability between programmers.
- Vehicle fleet composition is determined by the model based on national economic criteria not specified by the user.
- Users can look at the value of any one of more than 2,000 variables at two-weekly time steps.
- A fast run time allows for the modelling of time steps of hours, as well as careful sensitivity analysis that balances supply and demand.
- The model has no links to other programs.
- More than 30 peer-reviewed publications provide endorsement of the model.

Limitations:

- The model is currently a PE model and therefore factors outside the energy sector do not influence model outputs.
- The model parameters require careful updating, which can be resource-intensive.

What linkages are there to other modelling work?

The UniTrac model has recently been designed as a small sub-set of the UniSyD model (see below)

What areas are there for future development?

Priorities for future development include:

- undertaking modelling at hourly time steps to examine effects of energy and electricity storage on national profiles; and
- inclusion of more detail for the industrial and agricultural sectors and shipping and rail in the transport sector.

Bibliography of recent work

For a partial list of publications, see Table 7.

UniTrac

UniTrac tracks the comparative ownership costs and emissions between advanced technology vehicles and conventional vehicles for successive owners of a single vehicle. Information here about the UniTrac model is taken from Leaver et al. (2018).

Who owns/operates the model?

UniTrac is owned jointly by Unitec and Kanagawa University.

What is the scope and extent of the model?

UniTrac is uniquely designed to track comparative ownership costs and emissions between advanced technology vehicles and conventional vehicles for successive owners of a single vehicle. The model has been configured for battery EVs and hydrogen-fuel-cell vehicles. Model outputs include emissions, fuel consumption and total cost of ownership. UniTrac has been applied to fleets in Japan and New Zealand.

How does the model work?

UniTrac calculates successive ownership costs for battery electric and hydrogen-fuel-cell light vehicles, and compares these costs with of conventional vehicles for successive owners. It uses a net present value analysis of capital cost, fuel and maintenance, interest and depreciation for multiple owners.

What are the strengths and limitations of the model?

Strength:

- The model is simple to maintain and operate.

Limitations:

- The vehicle fleet profiles are set by the user.
- The model examines vehicle costs in isolation from any other economic factors.

What linkages are there to other modelling work?

UniTrac was developed as a sub-set of UniSyD (see above).

What areas are there for future development?

The addition of multiple-ownership heavy vehicle fleets.

Bibliography of recent work

For a partial list of publications, see Table 7.

3.3 Overview of available energy- and multi-sector datasets

Energy- and multi-sector modellers rely on a number of datasets to both develop and run their models. Table 6 gives a partial list of datasets used in energy- and multi-sector models, showing who has developed the data and any additional information about the data. Datasets in Table 6 have been categorised as either observation datasets or projection datasets. Observation datasets are collections of historical observations (e.g. electricity generation by technology) and are used to calibrate models so that they reflect outcomes in a chosen year or years. Projection datasets include forecasts for certain variables (e.g. GDP) and are used as exogenous drivers/inputs for models.

Table 6: Datasets available for energy- and multi-sector models

Observation datasets		
Dataset	**Key characteristics**	**Models using the data**
Stats NZ's IO table	Sectoral output and interlinkages between suppliers and users of goods and services, and each industry's use of factors of production, including energy	MNZG and ESSAM
Ministry for the Environment (2017), along with data on fuel use by broad industry from MBIE	Emissions in each industry are driven by its energy use	MNZG and ESSAM
MBIE, New Zealand energy statistics (https://www.mbie.govt.nz/info-services/sectors-industries/energy/energy-data-modelling/statistics)	Energy balance tables by broad industry	UniSyD
MBIE, New Zealand energy greenhouse gas emissions (https://www.mbie.govt.nz/info-services/sectors-industries/energy/energy-data-modelling/publications/energy-greenhouse-gas-emissions)	Industry-sector GHG emissions	UniSyD
MOT, New Zealand vehicle fleet statistics (https://www.transport.govt.nz/resources/vehicle-fleet-statistics)	Vehicle fleet profiles	UniSyD
Stats NZ's environmental-economic accounts	Emissions by broad industry	MNZG and ESSAM

Elasticities sourced from CoPS	How firms and households respond to changes in relative prices through behavioural parameters	MNZG
EECA Energy End-Use Database (2014)	Estimates process heat energy demand	Process Heat Emissions Reduction
Hydrological Modelling Dataset (HMD)[10]	Hydrological datasets for New Zealand, which include data on infrastructure and hydro constraints, flows, storage and spill	DOASA
Modified EECA Heat Plant Database (2016)	Heat plant information, energy by sector (including direct heat use), GIS information on individual sites	Process Heat Emissions Reduction
Projection datasets		
Treasury estimates of New Zealand's long-run growth from its long-term fiscal model	Economic growth and emissions for 111 industries	MNZG
The world economy in 2050: a tentative picture (Fouré et al., 2010)	Global GDP by country/region	CliMAT-DGE
World energy outlook (International Energy Agency, 2013)	Global energy and efficiency improvements by country/region	CliMAT-DGE

4 Setting the agenda for future multi-sector mitigation modelling

4.1 Priority policy questions where modelling is needed

Under the Paris Agreement, New Zealand must transition toward a net-zero-emissions economy. As a matter of both near-term urgency and enduring need, building on a sound foundation of existing work, improved modelling would assist New Zealand to design an effective portfolio of policies and measures to reduce emissions and manage the distributional effects on regions, sectors, communities and households. More specifically, models are required to set emission-reduction goals, and in the shorter term, emission budgets, ETS caps and price safeguards. These decisions need to take into account changes in technologies, policies and markets, both in New Zealand and internationally.

[10] Freely available at https://www.emi.ea.govt.nz/Environment/Datasets/HydrologicalModellingDataset

At a more detailed level, modelling is needed to help improve the understanding of:

- New Zealand's domestic mitigation potential and costs, and how they are distributed across sectors and actors;
- how the New Zealand economy and emissions will respond to technological innovations and structural changes, including stranding of assets;
- New Zealand's consumption emissions as well as production emissions;
- the impacts of different emission-reduction targets and emission budgets on New Zealand's economic growth and broader measures of well-being (including at the level of communities and households);
- emission price pathways consistent with achieving different domestic emission-reduction targets and budgets;
- the potential value of alternative transition pathways and leaving pathway options open;
- the sensitivity and resilience of alternative transition pathways to risks, uncertainties and system shocks;
- the value of co-benefits (economic, environmental and social) from alternative mitigation options and policies;
- the costs and benefits of investment in domestic mitigation compared to purchasing international mitigation;
- how the New Zealand economy will be affected by changes in international technologies, policies and markets;
- alternative options for recycling New Zealand ETS auction revenue to the economy;
- energy and emission benchmarking of key commodities produced in New Zealand;
- risks and costs of emissions leakage from New Zealand's EITE producers;
- effectiveness of alternative policies to address disproportionate or undesirable impacts of mitigation policies across sectors and actors; and
- interactions between market-based mechanisms (e.g. the New Zealand ETS) and directive regulations and policies (e.g. emission standards, renewable energy targets, technology targets) in capped and uncapped sectors.

There are four categories of questions that recent modelling exercises relevant to the design and evaluation of climate change mitigation policy have addressed: historical analyses, projections and policy analyses, measuring the feasibility of targets, and evaluating the value of options.

- Historical analyses evaluate previous policies or other historical changes. Examples of historical analyses include: reporting the effects of government policies and measures on New Zealand's GHG emissions included in national communications to the UNFCCC; and estimating the impacts of mitigation policies on EITE sectors.

- Projections and policy analyses estimate future expected outcomes given policy or other changes. Examples of model projections and policy analyses include: estimating New Zealand's GHG emissions through 2030 under current policies and measures; and the economic impacts of 2030 and 2050 climate change targets.
- Modelling exercises that are related to the feasibility of targets assess the potential for the intentional outcomes of a policy or other change to be met. Examples of modelling related to feasibility of targets include: costs and volumes of abatement available in the energy sector and industrial processes and product use (IPPU) sector; the GHG mitigation potential of known practices and technologies in the agricultural sector; estimating the mitigation potential of each sector; and compatibility of goals for low emissions and low poverty.
- Modelling exercises on the value of options evaluate the costs and benefits of policy or other change to manage uncertainty. Examples of modelling related to the value of options include: the impact of short-term pathways on long-term costs; the implications of 100 percent renewables electricity (ease of achievement, risk of poor outcomes); and the value of the learning externalities from early adoption.

4.2 Specific data and modelling development needs

During the workshop, participants focused on two key development needs for modelling: improving datasets; and building New Zealand's domestic modelling capability to address the types of policy questions identified above.

Participants emphasised the importance of addressing dataset deficiencies and accessibility. They suggested that there is high quality of data for the electricity sector, but data for other sectors could be improved. Managing confidentiality, commercial sensitivity and quality assurance of data can be problematic. In the context of modelling, different levels of data complexity or certainty may be required to answer different types of questions.

Enabling modellers to apply high-quality, transparent and consistent datasets, preferably from a centralised and easily accessible platform, would improve the comparability of modelling outputs. It would also be useful for modellers to be able to access a repository of commonly applied assumptions and future scenarios. Sustained and dependable funding from public sources is needed to improve the collection and sharing of data in the public domain. Gaps and uncertainties in datasets need to be clearly identified. The issue of data collection and reporting is relevant to the review of environmental reporting by the Parliamentary Commissioner for the Environment. Stats NZ has an important role to play.

While the energy- and multi-sector models in use today produce valuable outputs, they also have limitations, which affect their ability to help inform the challenging policy questions identified above. Drawing from the workshop discussions, New Zealand's technical modelling capability would benefit from strengthening in the following areas:

- understanding the role of uncertainty in the modelling and assumptions, and what it means for interpreting the results;
- assessing emission price responsiveness of different sectors and actors;
- accommodating technological innovations and emission prices that go beyond the historical ranges used to set models' current response parameters (e.g. elasticities of substitution);
- assessing interactions between demand-side and supply-side technology changes and policy interventions;
- assessing transitional pathways over time, not just equilibrium states;
- covering a range of distributional effects at a high level of granularity (e.g. regional, sectoral and sub-sectoral, and within groupings of businesses and households);
- accounting for complex interactions within and between sectors, especially between the energy and land-use sectors;
- accounting for the impacts of "step changes" in disruptive technologies or policies (e.g. when a government changes), which may involve "tipping points" (social or economic) instead of gradual changes;
- accounting for interactions between the New Zealand economy and overseas markets, and climate change policies in those markets;
- assessing a broad range of co-benefits from mitigation options (e.g. water quality, air quality, biodiversity, other natural resource conservation, health, energy security, energy affordability, regional development, new market development, etc.);
- assessing cumulative mitigation policy impacts on supply chains;
- accounting for realistic behaviour by producers and consumers, including learning processes and "irrational" decision-making; and
- supporting more effective, integrated cost–benefit analysis of alternative emission-reduction targets and budgets.

4.3 Improving climate change mitigation modelling in New Zealand

Workshop participants considered the more general question of how we could improve the process of climate change mitigation modelling in New Zealand, and develop a more strategic approach as a modelling community. The following ideas and areas for improvement were raised in discussions.

4.3.1 Improving the transparency, credibility and comparability of models and their outputs

Policy-makers, researchers and other stakeholders would benefit from clear and accessible documentation of how different models operate, what they can contribute, what their limitations are, what datasets they use, and how their outputs can be evaluated and compared to those from other models. Models both inside and outside of government should be validated using domestic and international peer review processes. Assumptions and elasticities of substitution used in CGE models should be made more transparent so that users can know how to understand and compare results. Allowing open access to models would improve transparency.

4.3.2 Building underlying knowledge

More basic research is needed to enhance our understanding of the system dynamics that are reflected in models. We need to improve how we manage uncertainty. Real options are important but complex to model with constraints. Potentially, multi-stage stochastic programming methods could help with this. In these methods, producers and consumers make decisions under uncertainty about future technology and policy outcomes, rather than certainty about future outcomes. Models are usually designed to examine the relationships between certain elements and complexity is often added to models to increase precision, granularity and realism; but a simpler model may sometimes work better.

4.3.3 Improving model linkages

Different types of models have different strengths and capabilities, and linking models can be used to compensate for deficiencies and improve outcomes. For example, CGE models can be linked with electricity models to improve the representation of electricity generation in the CGE models. In turn, carbon prices and input prices estimated by CGE models can be used as exogenous inputs to electricity models. Enabling multiple modellers to collaborate or work in parallel in addressing challenging policy questions, instead of selecting one winning bidder, can produce additional insights, support validation of model outputs and broaden domestic modelling capability.

4.3.4 Increasing international collaboration

New Zealand should also continue to explore opportunities for international collaboration to adapt international models for use in New Zealand, and engage international modelling experts in building New Zealand's modelling capacity and peer reviewing its models. In this connection, the Joint Research Centre, a European Commission research centre that provides independent scientific advice and support to European Union policy, has developed a suite models for climate policy analysis. Two examples include the General Equilibrium Model for Energy–Economy–Environment (GEM-E3; https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/gem-e3-model-documentation), an economy-wide model; and the Prospective

Outlook on Long-term Energy System (POLES; https://ec.europa.eu/jrc/en/poles) model, a global technology-rich energy-system model. For some applications, the GEM-E3 and POLES are linked (e.g. see Vandyck et al., 2016). Also, Resources for the Future has developed a micro-simulation module that can be connected to a CGE model to estimate the impacts of climate policies on different household types (Williams et al., 2014).

4.3.5 Considering the impact of domestic policies in a global context

As other countries are also formulating policies to reduce emissions, New Zealand-focused models need to consider how domestic polices will affect the competitiveness of New Zealand's exports, and how polices in other countries will impact New Zealand. This can be accomplished by either estimating how policies in other countries will impact international prices, and/or developing global models that represent New Zealand and its key trading partners and competitors. As most global models focus on emissions-abatement options in energy production (and not agriculture), creating global models may require bespoke developments.

4.3.6 Building sufficient time and funding for the development of modelling expertise, and model building and analyses into the decision-making processes

Modelling needs should be integrated into planning and budgeting processes for policy development. Rushed and underfunded modelling is more likely to produce poor results. Early engagement between modellers, policy-makers and stakeholders can help with setting the parameters for modelling studies, including defining key assumptions and selecting scenarios.

4.3.7 Communicating modelling results effectively

Modellers need to do a better job of explaining model capabilities, assumptions, results and limitations in ways that meet the needs of key audiences, such as policy-makers, media and business stakeholders. The outputs from modelling need to be relevant to the policy questions under consideration and packaged in a way that enables practical applications by decision-makers. Effective communication of uncertainty is especially important. Decision-makers need to understand the difference between modelling to generate forecasts versus the modelling of exploratory scenarios.

5 Conclusions: what are our main priorities for the future?

As New Zealand charts its course toward a low-emission economy, the quality of energy-sector and multi-sector modelling is becoming increasingly important. This paper has outlined why models are useful for answering complex questions, provided a stocktake of energy- and multi-sector models used for climate change mitigation modelling in New Zealand, and made suggestions to improve future modelling work. These suggestions identified priority policy questions that the modelling community should address; proposed desirable data and model developments; and suggested improvements in the processes used for climate change mitigation modelling in New Zealand.

Many of the suggested improvements could be realised by creating an integrated framework for climate change mitigation modelling in New Zealand. This framework would regularly bring together a suite of models and a network of researchers to assess climate change mitigation policies. Core elements of the framework would include a central repository of data, common input assumptions and scenarios, and a “dashboard” that synthesises results from different models, allowing decision-makers to understand and apply the insights from the models more easily.

The framework would also have several other benefits. First, it could be used to improve linkages among models and ultimately allow each model to capitalise on the strength of other models in the framework. Second, enabling modellers to access high-quality datasets and apply consistent assumptions and scenarios would improve transparency and facilitate comparison of model outputs. Third, the framework would provide a centralised, formal channel for international collaboration.

Overall, sustained investment in a modelling framework will create an “ecosystem” for climate change mitigation modelling in New Zealand. In addition, it would help to ensure that New Zealand’s models are fit for purpose and ready to deploy when the policy demand becomes urgent.

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Appendix

Table 7: Recent publications using energy- and multi-sector models

Model	References
Biomass Value Chain Model	Samsatli, S., Samsatli, N. J. & Shah, N. (2015). BVCM: a comprehensive and flexible toolkit for whole system biomass value chain analysis and optimisation–mathematical formulation. *Applied Energy*, 147, 131–160. Suckling, I. D., De Miguel Mercader, F., Monge, J. J., Wakelin, S. J., Hall, P. W. & Bennett, P. J. (2018). *The New Zealand Biofuels Roadmap summary report*. Rotorua: Scion. https://www.scionresearch.com/__data/assets/pdf_file/0005/63293/Biofuels_summary_report.pdf Suckling, I. D., De Miguel Mercader, F., Monge, J. J., Wakelin, S. J., Hall, P. W. & Bennett, P. J. (2018). *The New Zealand Biofuels Roadmap technical report*. Rotorua: Scion. https://www.scionresearch.com/__data/assets/pdf_file/0017/63332/Biofuels_TechnicalReport.pdf
CliMAT-DGE	Daigneault, A. & Fernandez, M. (2014). MfE GHG emissions reduction policy scenario. Landcare Research Report LC1966 for the Ministry of the Environment. Daigneault, A. & Fernandez, M. (2016). The costs of achieving a global climate change mitigation target: an integrated assessment model inter-comparison. Paper presented at the 19th Annual Conference on Global Economic Analysis, 15–17 June 2016, Washington, DC. Daigneault, A., Lennox, J., Turner, J., Reisinger, A. & Jhunjhnuwala, K. (2013). GHG emissions policy impacts on global land-use sector: a dynamic general equilibrium analysis. Paper presented at the New Zealand Climate Change Conference, 4–5 June 2013, Palmerston North. Daigneault, A., Fernandez, M. & Wright ,W. (2015). Economic modelling of New Zealand's INDC for the post-2020 Climate Change Agreement: quality report. Landcare Research Report LC2106 for the Ministry for the Environment. Fernandez, M. & Daigneault, A. (2016.) Emissions trading and the economic impact of the Paris Agreement on New Zealand. *Compendium: Cuadernos de Economía y Administración*, *3(5),* 31–43. Fernandez, M. & Daigneault, A. (2016). The Paris Agreement and its impact on cattle and food sectors of New Zealand. *New Zealand Journal of Agricultural Research*, *59(4)*, 436–443 https://doi.org/10.1080/00288233.2016.1215335 Lennox, J., Daigneault, A., Jhunjhnuwala, K., Turner, J. & Reisinger, A. (2013). *Integrated assessment of trade-related impacts of global climate change and climate policies*. MPI Technical Paper 2014/34. Wellington: Ministry for Primary Industries. Lennox, J., Turner, J., Daigneault, A. & Jhunjhnuwala, K. (2013). Regional, sectoral and temporal differences in carbon leakage. Paper presented at the 57th AARES Annual Conference, 5–8 February 2013, Sydney.
CRAGE	Ferris, M. C. & Philpott, A. B. (2018). Dynamic risked equilibrium. Under Review. *Operations Research*. Kok, C., Philpott, A. B. & Zakeri, G. (2018). Value of electricity transmission expansion when market agents are risk averse. Under Review. *Operations Research*. These papers can be downloaded from www.epoc.org.nz/publications

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HydrovSPD	Porter, N. R. (2014). Intra-day uncertainty and efficiency in electricity markets. Master's thesis, University of Auckland. Downloadable from http://www.epoc.org.nz/ publications.html Presentations from the EOOC Winter Workshop 2018 are downloadable from http://www.epoc.org.nz/ww2018.html
Process Heat Emissions Reduction	Atkins, M. J., Neale, J. R., Wu, Y. & Walmsley, M. R. W. (2018). Regional and national greenhouse gas emissions reduction planning*. Chemical Engineering Transactions*, *70*, 19–24. https://doi.org/10.3303/CET1870004
UniSyD	Shafiei, E., Davíðsdóttir, B., Leaver, J., Stefansson, H. & Asgeirsson, E. I. (2017). Energy, economic, and mitigation cost implications of transition toward a carbon-neutral transport sector: a simulation-based comparison between hydrogen and electricity. *Journal of Cleaner Production*, *141*, 237–247. https://doi.org/10.1016/j.jclepro.2016.09.064 Shafiei, E., Leaver, J. & Davíðsdóttir, B. (2017). Cost-effectiveness analysis of inducing green vehicles to achieve deep reductions in greenhouse gas emissions in New Zealand. *Journal of Cleaner Production*, *150*, 339–351. https://doi.org/10.1016/ j.jclepro.2017.03.032 Plus 33 other quality-assured publications
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