Economics Working Paper Series
Faculty of Business, Economics and Law, AUT

The Climate PoLicy ANalysis (C-PLAN) Model, Version 1.0

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2021/04

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Niven Winchester[†,‡] and Dominic White[*]

Abstract

This paper documents Version 1.0 of the Climate PoLicy ANalysis (C-PLAN) model and presents results for the model's baseline and a policy scenario. The C-PLAN model is a global, recursive dynamic computable general equilibrium (CGE) model tailored to the economic and emissions characteristics of New Zealand. Distinguishing features in the model include methane-reducing technologies for livestock, bioheat from forestry residues, and explicit representation of output-based allocations of emissions permits. The model was built for New Zealand Climate Change Commission (CCC) to inform policy advice provided to the government. The computer code for the model and instructions for reproducing results used by the CCC are publicly available. It is hoped that the C-PLAN model will assist transparency in setting climate policies, help build capacity for climate policy analysis, and ultimately set the foundations for future climate policy initiatives in New Zealand and other countries.

Keywords: Climate change mitigation; Computable general equilibrium; Replication; Transparency.

JEL classifications: C68, Q40, Q54, Q58.

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1. Introduction

The Paris Agreement, which entered into force on 4 November 2016, aims to limit global warming to well below 2 degrees Celsius (°C) compared to pre-industrial levels. To achieve these goals, the Agreement requires countries to submit nationally determined contributions (NDCs) outlining how they will reduce greenhouse gas (GHG) emissions. It also invited countries to develop and submit long-term strategies for reducing GHG emissions to provide vision and direction for setting NDCs (UNFCCC, 2021).

To help meet its climate goals, Aotearoa/New Zealand passed the Climate Change Response (Zero Carbon) Amendment Act 2019 (New Zealand Government, 2019). The Act set new targets for domestic GHG emissions in 2050, required the government to develop and implement policies for climate change adaptation and mitigation, and established the Climate Change Commission (CCC). A key purpose of the CCC is to provide independent, evidence-based advice to the New Zealand government on climate issues. To meet this objective, the CCC commissioned a suite of new modelling tools for climate policy analysis. This paper describes the Climate PoLicy Analysis (C-PLAN) model, a recursive dynamic computable general equilibrium (CGE) model, developed under this process. The code for the model is freely available (for noncommercial) research and education purposes from the CCC. Instructions to reproduce results in this paper that were also used in the CCC's draft advice to government on climate action (CCC, 2021a) are included as supplementary files augmenting this manuscript.

CGE models consider the whole economy and interactions among sectors and have been widely used to evaluate climate change mitigation policies - see Barbatunde (2017) for a review of CGE analyses of climate change mitigation policies and Sue Wing (2009) for a practical illustration of the use of CGE models for climate policy analysis. Notably, CGE models for climate policy analysis include (1) the Massachusetts Institute of Technology Economic Projection and Policy Analysis (MIT-EPPA) model (Paltsev et al., 2005; Chen et al., 2016), and the European Commission's General Equilibrium Model for Economy-Energy-Environment (GEM-E3) (Capros et al., 2013). Although these models represent multiple regions, analyses using these models typically focus on major countries/regions and/or global outcomes. For example, Jacoby et al. (2017) use the MIT-EPPA model to compare carbon prices and welfare costs from Paris pledges in eight large countries/regions. Vandyck et al. (2016) use the GEM-E3 model to analyse the impact of Paris pledges on GHG emissions and energy and economic outcomes in 25 countries/regions and the world.

Inspired by the MIT-EPPA and GEM-E3 models, the C-PLAN model is a global CGE model tailored to the economic and emissions characteristics of New Zealand. A key feature of New Zealand is that a high proportion of gross GHG emissions are from agriculture and forestry. For example, in 2016, the share of gross emissions attributable to agriculture and forestry was 53.1% in New Zealand, 20.4% in Australia, 11.4% in the European Union (EU), and 6.4% in the United States (US) (Ge and Friedrich, 2020). As a result, the sectoral aggregation in C-PLAN represents several agricultural activities and related sectors (e.g., dairy farming and dairy processing) as separate sectors, and includes new technologies for abating emissions in these sectors. By releasing model code that replicates results used for policy advice, the C-PLAN modelling initiative also assists transparency in climate policy formulation and helps to build capacity for future climate policy analyses, both in New Zealand and other countries.[1]

This paper has six further sections. The next section provides an overview of the C-PLAN model. Section 3 details the structure of the model, including equilibrium conditions, production functions, new technologies and dynamic processes. Calibration of the model is discussed in Section 4. Section 5 outlines a baseline scenario and a policy scenario implemented in the C-PLAN model. Results from the two scenarios are presented and discussed in Section 6. The final section offers concluding remarks and suggestions for further research.

2. Overview of the C-PLAN model

The C-PLAN model was inspired by the MIT-EPPA model (Paltsev et al., 2005; Chen et al., 2016) and the European Commission's GEM-E3 model (Capros et al., 2013). It builds on science in these (and other) models, tailors the modelling framework to New Zealand, and includes innovative features. Version 1.0 of the C-PLAN model identifies two regions (New Zealand and an aggregate Rest of the World), seven GHG categories, 38 production sectors, and three sources of final demand. The model is recursive dynamic and is solved annually from 2014 to 2050. The GHG categories represented in C-PLAN are (1) carbon dioxide (CO_2) emissions from the combustion of coal, (2) gas combustion CO_2 emissions, (3) oil combustion CO_2 emissions, (4) process and other CO_2 emissions, (5) methane (CH_4) emissions, (6) nitrous oxide (N_2O) emissions, and (7) aggregate emissions of fluorinated gases (F-gases).

The 38 sectors represented in the C-PLAN model and their abbreviations are listed in Table 1. There are six sectors for agriculture, forestry, or fishing; 12 sectors related to energy extraction, production and/or distribution; 11 manufacturing sectors; three sectors for construction and services; five commercial

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[1] The Climate Mitigation, Adaption and Trade in Dynamic General Equilibrium (CliMAT-DGE) (Fernandez and Daigneault, 2015) was previously developed by Manaaki Whenua – Landcare Research for New Zealand climate policy analysis. However, as this model is specified as a forward-looking model, the representation of sectors, new technologies and policies must be simplified so that the model is solvable. Moreover, the code for the CliMAT-DGE model is not publicly available.

transport sectors; and one household transport sector. The C-PLAN model also includes three final demand sources: household consumption, government expenditure, and investment.

Table 1. Sectors represented in the C-PLAN model.

Agriculture, forestry, and fishing		**Manufacturing**	
rmk	Dairy farming	crp	Chemical, rubber, and plastic products
b_s	Beef and sheep farming	nmm	Non-metallic minerals (e.g., cement)
oap	Other animal products	nfm	Non-ferrous metals (e.g., aluminum)
hor	Horticulture	i_s	Iron and steel
frs	Forestry	fmp	Fabricated metal products
fsh	Fishing	mil	Dairy processing
		mtp	Meat products
Energy extraction, production & distribution		ofd	Other food products
col	Coal mining	w_p	Wood and paper products
cru	Crude oil extraction	mvh	Motor vehicles and parts
oil	Refined oil products	omf	Other manufacturing
gas	Natural gas extraction and distribution		
oxt	Other mining	**Construction and services**	
ecoa	Coal electricity	cns	Construction
egas	Gas electricity	afs	Accommodation and food services
enuc	Nuclear electricity*	ser	Other services
ehyd	Hydro electricity		
ew_s	Wind and solar electricity	**Commercial transport**	
eoth	Geothermal and other electricity	rtp	Road transport
tnd	Electricity transmission and distribution	wtp	Water transport – domestic
		wtpi	Water transport – international
		atp	Air transport – domestic
		atpi	Air transport – international
		Household transport	
		hht	Household transport

Note: * Nuclear electricity is only represented in the Rest of the World.

Opportunities for abating emissions in the model include: (1) substitution between fossil fuels in energy production (e.g., replacing coal with gas), (2) price-induced efficiency improvements (e.g., installing a more energy efficient boiler), (3) replacing more CO_2 intensive commodities with less CO_2 intensive commodities (e.g., replacing steel and cement with wood products in construction), and (4) replacing conventional technologies and fuels with advanced, low-carbon technologies and fuels (e.g., replacing internal combustion engine vehicles with electric vehicles, and replacing coal with biomass).

3. Model structure

3.1. Equilibrium conditions and the solution method

General equilibrium models consider equilibrium in all markets simultaneously and explicitly represent income-expenditure relationships. The central elements in a general equilibrium model are: (1) firms that maximize profits, (2) households that maximize utility, and (3) markets that determine prices such that supply equals demand for all commodities and primary factors. The C-PLAN model solves for a general equilibrium in each year modelled. For ease of exhibition but without loss of generality, this sub-section sets out general equilibrium conditions for a single region when primary factors are perfectly mobile across sectors, and there is no international trade, government sector, or investment (i.e., all production is consumed in the current period).[2]

Firm behaviour

In each sector, a representative firm maximizes profits by choosing its output level (*y*), and use of intermediate inputs (*x*) and primary factors (*k*). Suppose there are *I* sectors/commodities (indexed interchangeably by *i* and *j*) and *F* primary factors (indexed by *f*). The profit maximization problem for a firm representing industry *i* is:

$$\max_{y_i, x_{ji}, k_{fi}} \pi_i = p_i y_i - \sum_{j=1}^{J} p_j x_{ji} - \sum_{f=1}^{F} w_f k_{fi}$$

$$\text{such that } y_i = \varphi_i(x_{1i}, \ldots, x_{Ji};\ k_{1i}, \ldots, k_{Fi}) \tag{1}$$

where π_i is the profit of firm *i*, p_i is the price of commodity *i*, y_i is the output of commodity *i*, x_{ji} is use of commodity *j* as an intermediate input in sector *i*, w_f is the unit return to factor *f*, k_{fi} is use of factor *f* by sector *i*, and φ_i is the production function for sector *i*.

The solution to the profit maximization problem yields, for each representative firm, demand functions for intermediate inputs and primary factors as functions of product prices, commodity prices, and output.

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[2] See Lanz and Rutherford (2016) for a description of general equilibrium equations and conditions when these assumptions are relaxed.

$$x_{ji} = x_{ji}(p_1, \dots, p_J;\ w_1, \dots, w_F;\ y_i) \tag{2}$$

$$k_{fi} = k_{fi}(p_1, \dots, p_J;\ w_1, \dots, w_F;\ y_i) \tag{3}$$

As in the MIT-EPPA model, production is represented by constant elasticity of substitution (CES) functions that exhibit constant returns to scale (CRTS). As a result, the unit intermediate ($\bar{x}_{ji}$) and factor ($\bar{k}_{fi}$) demand functions can be represented as:

$$\bar{x}_{ji} = \frac{x_{ji}}{y_i} = \bar{x}_{ji}(p_1, \dots, p_J;\ w_1, \dots, w_F) \tag{4}$$

$$\bar{k}_{fi} = \frac{k_{fi}}{y_i} = \bar{k}_{fi}(p_1, \dots, p_J;\ w_1, \dots, w_F) \tag{5}$$

Additionally, CRTS production technologies imply that in equilibrium, firms make zero economic profits. This implies that, in each sector, the commodity price equals unit cost:

$$p_i = \sum_{j=1}^{J} p_j \bar{x}_{ji} - \sum_{f=1}^{F} w_f \bar{k}_{fi} \tag{6}$$

Consumer behaviour

In each region, a representative consumer chooses consumption (*d*) of each commodity to maximize utility, subject to their budget constraint. The consumer's income is derived from their ownership of production factors. The utility maximization problem is:

$$\begin{gathered} \max_{d_i}\ u(d_1, \dots, d_I) \\ \text{such that } m = \textstyle\sum_{f=1}^{F} w_f K_f^* = \sum_{i=1}^{I} p_i d_i \end{gathered} \tag{7}$$

where d_i is the consumption of commodity *i*, m is income, and K_f^* is the consumer's endowment of commodity *f*. The solution to the utility maximization problem yields Walrasian/Marshallian demand functions as follows:

$$d_i = d_i(p_1, \dots, p_J;\ w_1, \dots, w_F;\ K_1^*, \dots, K_F^*) \tag{8}$$

Market clearing

The final set of conditions for general equilibrium include market clearing conditions for commodities and primary factors. For each good, the commodity market clearing condition sets production equal to consumption plus the use of the commodity as an intermediate input across all sectors.

$$y_i = d_i + \sum_{j=1}^{J} x_{ij} = d_i + \sum_{j=1}^{J} \bar{x}_{ij} y_j \tag{9}$$

The factor market clearing condition sets the endowment/supply of each factor equal to the use of that factor across sectors:

$$K_f^* = \sum_{i=1}^{I} k_{fi} \tag{10}$$

Table 2. Equations in a general equilibrium model

Element	Equation	Equations/ variables
	Commodity Markets	
Demand	$c_i = c_i(p_1, \dots, p_I;\ m)$	*I* equations
Zero profit	$p_i = \sum_{j=1}^{J} p_j \bar{x}_{ji} - \sum_{f=1}^{F} w_f \bar{k}_{fi}$	*I* equations
Market clearing	$y_i = d_i + \sum_{j=1}^{J} \bar{x}_{ij} y_j$	*I* equations
	Factor Markets	
Demand	$k_{fi} = k_{fi}(r_1, \dots, r_F;\ y_i)$	*F*×*I* equations
	$\bar{k}_{fi} = \frac{k_{fi}}{y_i} = \bar{k}_{fi}(r_1, \dots, r_F)$	*F*×*I* equations
Market clearing	$K_f^* = \sum_{i=1}^{I} k_{fi}$	*F* equations
	Consumer Income	
Income	$m = \sum_{f=1}^{F} r_f K_f^*$	1 equation
Endogenous variables	$c_1, \dots, c_I;\ y_1, \dots, y_I;\ k_1, \dots, k_F;\ \bar{k}_1, \dots, \bar{k}_F;$ $p_1, \dots, p_I;\ r_1, \dots, r_F; m$	3*I* + 2*FI* + *F*+ 1 variables
Exogenous variables	$K_1^*, \dots, K_F^*;$	F variables

Equilibrium

The equations that describe equilibrium are summarized in Table 2. There are $3I + 2FI + F + 1$ endogenous variables and an equal number of equations; however, a consequence of Walras' law is that one of the equations is not independent of the other equations in the system. The solution to this problem is to fix the price of one commodity or factor equal to one (known as *numéraire* commodity/factor) and express all other prices relative to that price. Assigning a *numéraire* community/factor is consistent with there being no money illusion (i.e., only relative prices matter).

Once a *numéraire* commodity/sector is chosen, there are $3I + 2FI + F$ endogenous variables and $3I + 2FI + F$ independent equations. As the supply and demand functions in both product and factor markets are typically related to all the prices in the system, equilibrium is derived by simultaneously solving the set of non-linear equations.

Solution method

The C-PLAN model is specified and solved as a mixed complementarity problem (MCP) (Mathiesen, 1985; Rutherford, 1995). This formulation allows the equilibrium conditions to be specified as a system of weak inequalities and complementary slackness conditions between equilibrium variables and equilibrium conditions (Böhringer et al., 2003). In a general equilibrium MCPs, activity levels (production and demand) and commodity and factor prices are non-negative. The zero profit/unit price conditions in MCP form are:

$$-p_i \geq \sum_{j=1}^{J} p_j \bar{x}_{ji} - \sum_{f=1}^{F} r_f \bar{k}_{fi}$$

$$y_i \geq 0 \qquad (11)$$

$$y_i \left\{-\left(p_i - \sum_{j=1}^{J} p_j \bar{x}_{ji} - \sum_{f=1}^{F} r_f \bar{k}_{fi}\right)\right\} = 0$$

Combined, the conditions stipulate that if output is positive ($y_i > 0$), profit must be zero ($p_i = \sum_{j=1}^{J} p_j \bar{x}_{ji} - \sum_{f=1}^{F} w_f \bar{k}_{fi}$), and if profit is negative ($-p_i > \sum_{j=1}^{J} p_j \bar{x}_{ji}$), no production takes place ($y_i = 0$). A key benefit from the MCP formulation of the zero profit conditions is that it allows technologies that do not currently operate (because they are unprofitable and/or not available) to be included in the model and potentially operate in future years, depending on economic conditions, policies, and technology constraints. For example, it is possible to specify that a particular low-carbon technology is available in a future year at a specified cost (and possibly subject to deployment constraints), and the model will determine the quantity of output (if any) from the technology endogenously.

The factor market clearing conditions in the MCP format are:

$$K_f^* - \sum_{i=1}^{I} k_{fi} \geq 0 \qquad (12)$$

$w_f \geq 0$

$r_f(K_f^* - \sum_{i=1}^{I} k_{fi}) = 0$

Under these conditions, if the return to a factor is positive ($w_f > 0$), factor supply must equal factor demand ($K^* - \sum_{i=1}^{I} k_{fi}$), and if there is excess supply for a factor ($K^* - \sum_{i=1}^{I} k_{fi} \geq 0$), the return to that factor is zero ($w_f = 0$). The MCP formulation of factor market clearing conditions allows the model to represent stranded assets. For example, if policies reduce demand for a particular type of capital such that demand exceeds supply, the return to that capital will be zero. Commodity market clearing conditions in the MCP format are analogous to those for factor market clearing conditions.

As only very simple CGE models can be solved algebraically, the C-PLAN model is solved numerically. The model is coded using the Mathematical Programming Subsystem for General Equilibrium (MPSGE) (Rutherford, 1999), a subsystem of the Generalized Algebraic Modeling System (GAMS) mathematical modelling language (GAMS, 2021), and solved using the PATH solver (Ferris and Munson, 2021).

3.2 Production

Production techniques in C-PLAN are represented by a series of nested CES functions. These functions provide a flexible method to represent substitution between different inputs used by sectors. Input substitution possibilities for each sector are determined by the nesting structure used for that sector, assigned elasticity parameters, and input cost shares in the benchmark data. A unique production function is calibrated for each sector, but some sectors share a common nesting structure. Nesting structures are defined for five sectoral groups: (1) agriculture and forestry sectors, (2) construction, (3) electricity sectors, (4) fossil fuel extraction sectors, and (5) other sectors.

The nesting structure for most sectors is depicted in Figure 1.[3] In the energy nest, there is substitution between coal and gas and between a coal-gas aggregate and refined oil according to the elasticity parameter σ_{FE}. There is also substitution between aggregate fossil fuels and electricity according to σ_{ENE}. In the capital-labour nest, substitution between capital and labour is governed by σ_{KL}. The energy and capital-labour aggregates are combined in a further CES nest with elasticity parameter σ_{E-KL}. Price-induced substitution from energy to capital-labour in this nest captures endogenous energy efficiency improvements. Energy, capital, and labour are combined with intermediate inputs (except energy commodities) in a Leontief nest (i.e., there are no substitution possibilities between these aggregates). Non-energy intermediate inputs (1,…, *N*) are also combined in a Leontief nest.

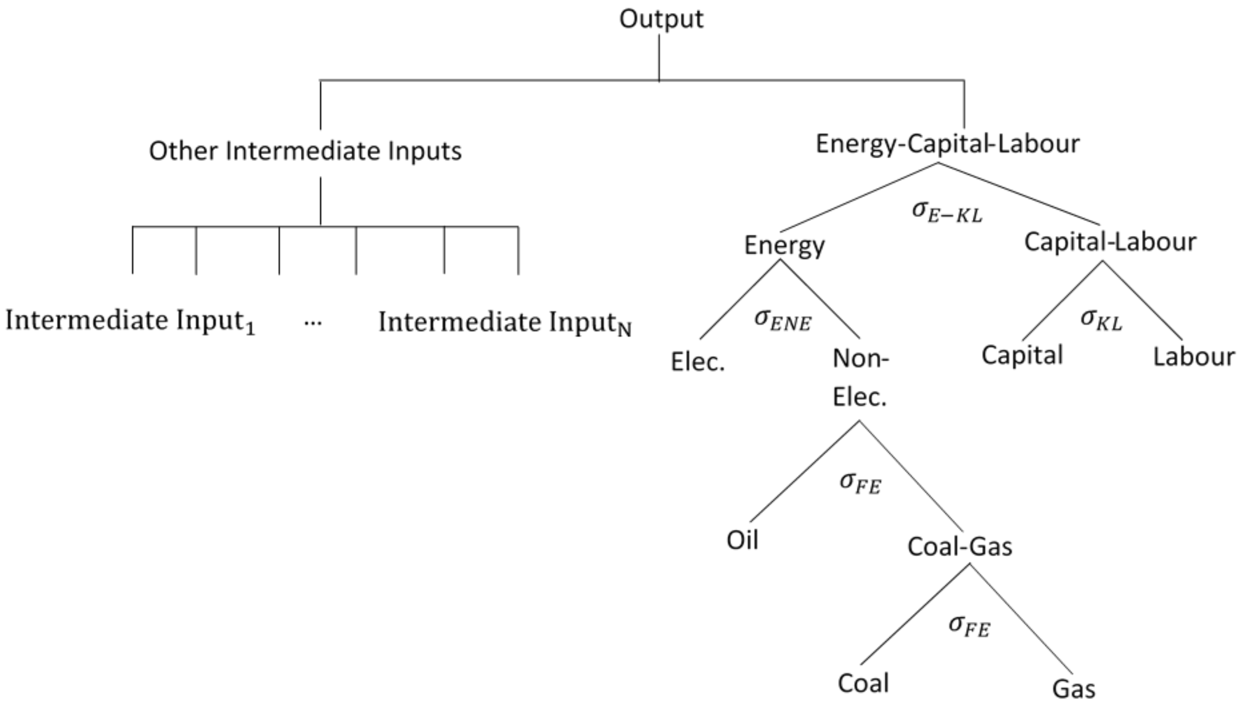

Figure 1. Production nest for all sectors, except those specified in footnote 3.

Note: Vertical lines in the input nest signify a Leontief or fixed coefficient production structure where the elasticity of substitution is zero.

There are constraints on the output of some sectors in the model (fishing; other mining; chemical, rubber and plastic products; non-metallic minerals; non-ferrous metals; iron and steel; construction; domestic and

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[3] Sectors with alternative production structures include agricultural sectors; forestry; fishing; coal mining; refined oil products; other mining; natural gas extraction and distribution; electricity generation technologies; chemical, rubber and plastic products; non-metallic minerals; non-ferrous metals; iron and steel; construction; domestic and international water transport; and international air transport.

international water transport; and international air transport). These limits represent the impact of either physical resource constraints (e.g., resources for the other mining sectors) or policies and changes in market conditions not explicitly included in the model (e.g., plans to close New Zealand's only aluminum smelter). For these sectors, there is an additional top-level Leontief nest between a resource-specific factor and all other inputs (not shown in Figure 1).[4] This specification allows the maximum output of each sector to be controlled by the endowment of the resource specific factor in each period.

The production nest for the agriculture and forestry sectors is depicted in Figure 2. The nesting structure allows the potential for endogenous yield improvements through two channels. First, if $\sigma_{IL} > 0$, farmers can use more intermediate inputs, such as fertilizer, to increase output from a given amount of land. Second, if $\sigma_{AGR} > 0$, more labour and capital can be used to increase output from a fixed amount of land.

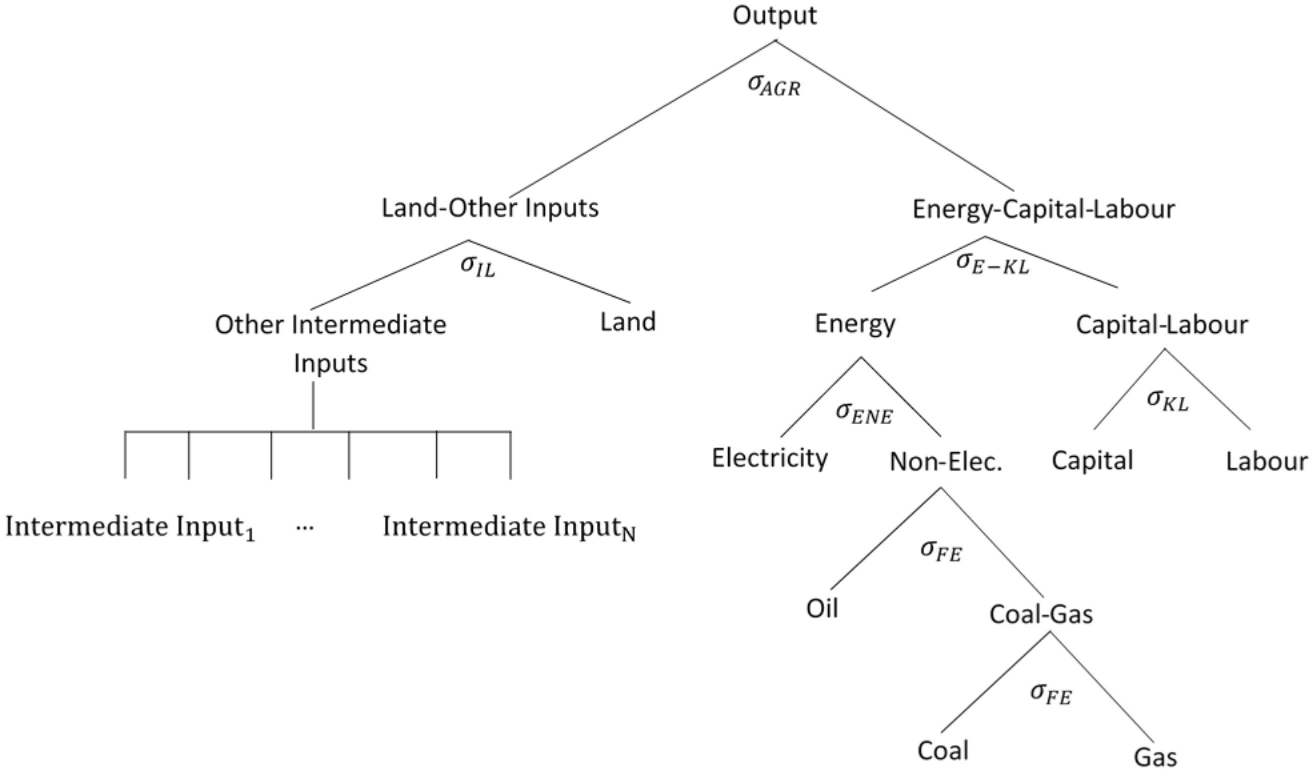

Figure 2. Production nest for agriculture and forestry.

Note: See notes for Figure 1.

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[4] There are payments to a sector-specific resource in our benchmark data for fishing and other mining sectors. For other output-controlled sectors, we reassign 5% of capital payments in each sector to a sector-specific resource.

The nesting structure for the construction sector, following Winchester and Reilly (2020), allows for substitution between wood products and other building materials, as shown in Figure 3. Building materials are separated from other intermediate inputs in the top level of the production nest. Wood products trade off with other building materials according to elasticity parameter σ_{BM} and other building materials are combined in a Leontief nest. A further Leontief nest is used to combine building materials with other inputs. As wood products are less emissions intensive than other building materials, substitution towards wood products provides an additional emissions abatement option in the model.

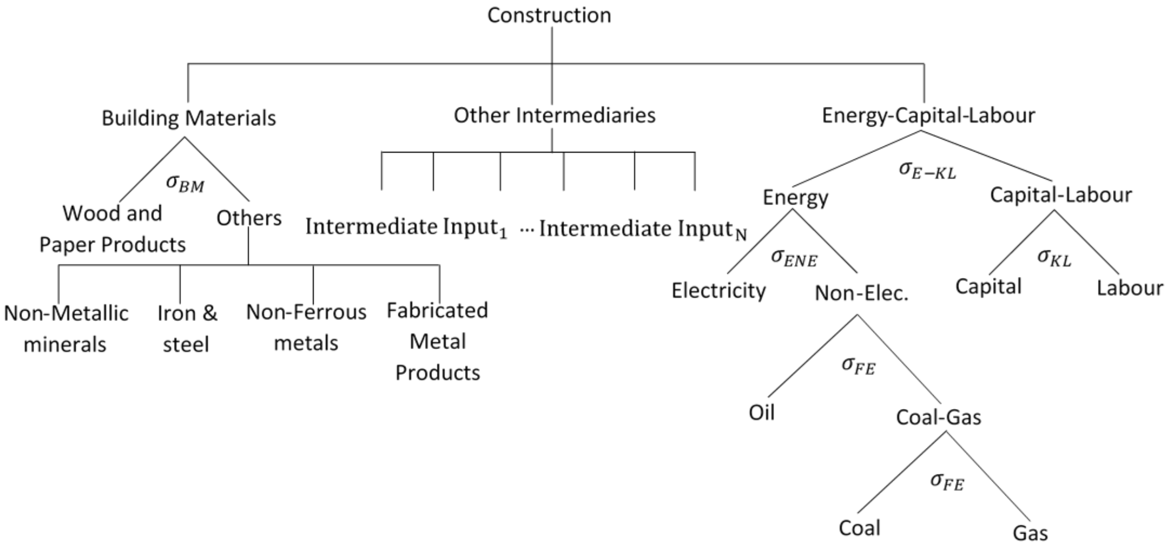

Figure 3. Production nest for construction.

Note: See notes for Figure 1.

The nesting structure for fossil fuel extraction sectors (coal, crude oil, and gas) is depicted in Figure 4. In the top level of this nest, sector-specific resources trade off with all other inputs according to elasticity parameter σ_R. This specification imposes resource constraints on fossil fuel production. If $\sigma_R > 0$, reflecting graded resources where the most easily accessible quantities are extracted first, more fuel can be produced from the same resource but at a higher marginal cost. If $\sigma_R = 0$, the maximum amount of fuel extraction is determined by the endowment of the fossil fuel resource and the unit input requirements for this resource.

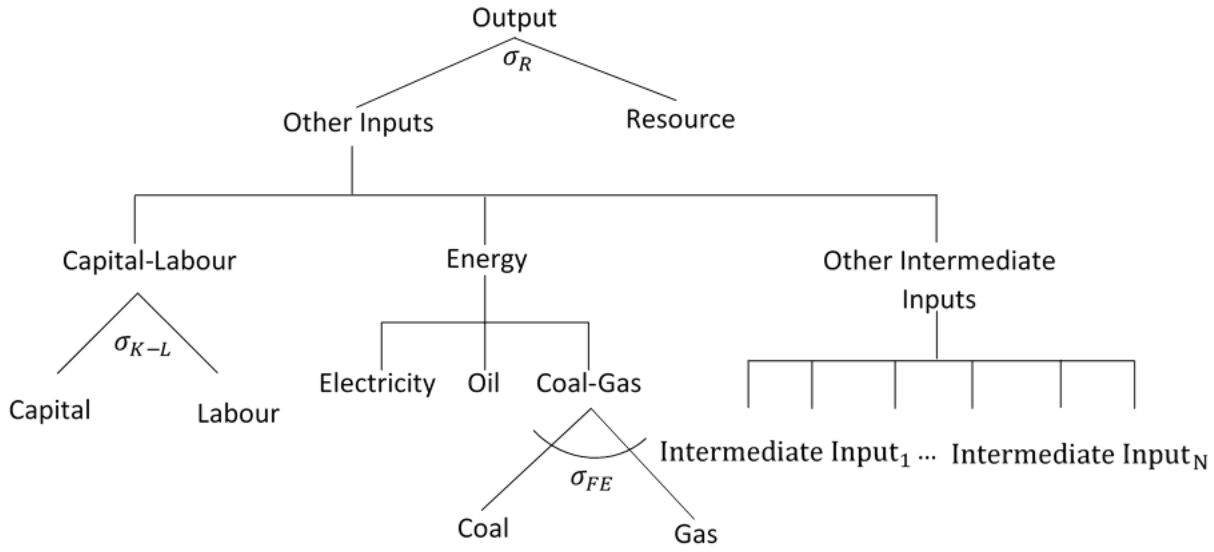

Figure 4. Production nest for fossil fuel extraction sectors (coal, crude oil, and gas).

Note: See notes for Figure 1.

The production nesting structure used for electricity technologies is shown in Figure 5a. The top-level nest combines a technology specific factor (TSF) with other inputs according to the elasticity parameter σ_{TSF}.[5] This nesting structure assists the targeting of output from each technology to projections from another source, such as an electricity model. For electricity generation technologies with $\sigma_{TSF} = 0$, for each technology, maximum output is determined by the endowment of the TSF relative to unit input requirements for this factor. This specification is used to model electricity generation technologies that are unlikely to respond to price changes during the sample period, such as hydroelectricity. For technologies with $\sigma_{TSF} > 0$, output is endogenous in the model, (except when endowments of the TSF factors are calculated endogenously so the model solves for a desired amount of production). For fossil fuel electricity technologies, there is substitution between fuels and capital-labour to allow for price-induced energy efficiency improvements.

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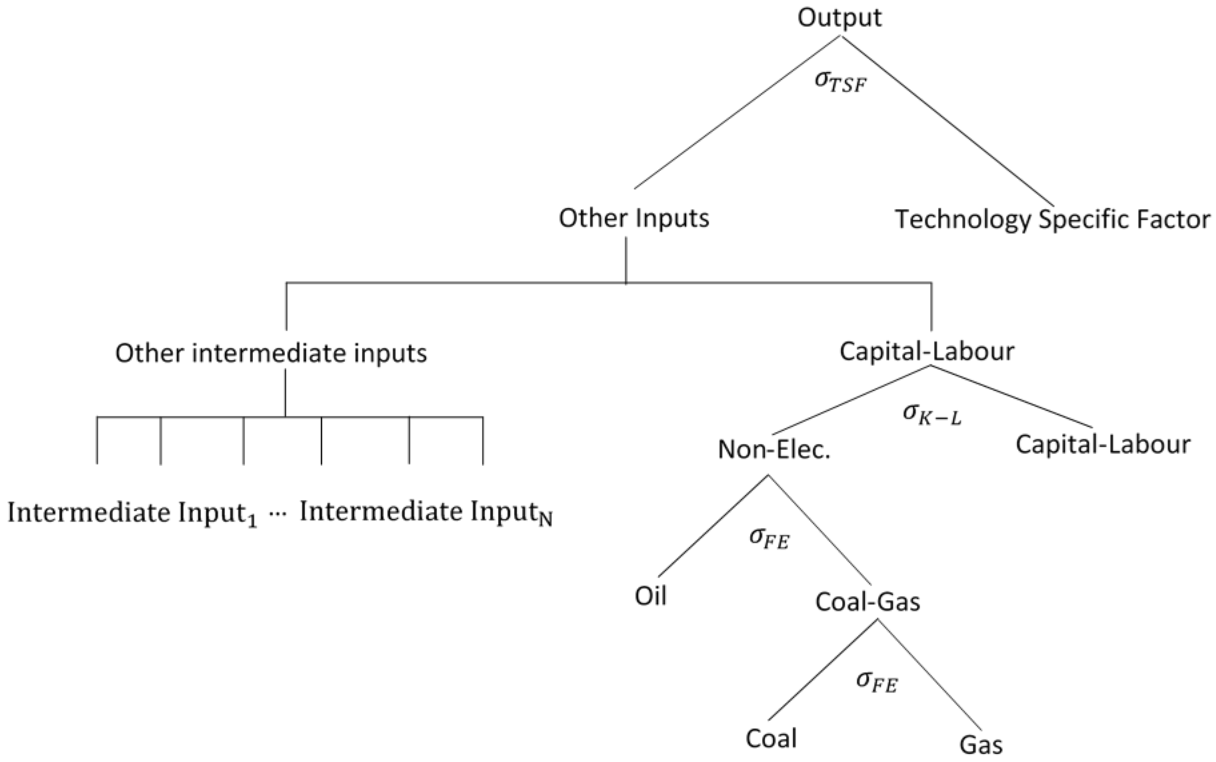
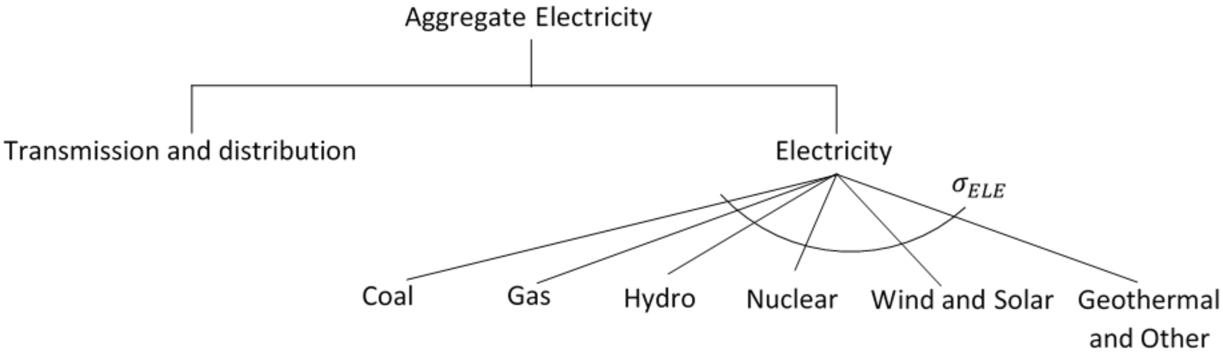
[5] Payments to the TSFs are not included in the database used to calibrate the model. To create such payment, for each electricity technology, we reassign 5% of capital payments to TSF payments.



(a) Electricity technologies



(b) Aggregate electricity

Figure 5. Production nests for (a) electricity technologies, and (b) aggregate electricity.

Note: See notes for Figure 1.

Electricity generation technologies are combined with each other along with transmission and distribution to form an aggregate electricity commodity. As illustrated in Figure 5b, transmission and distribution services are used in fixed proportions with total electricity. The aggregate electricity commodity created by this production nest is used as an intermediate input by other sectors and is purchased by households.

3.3 Final Demand

In each region, a representative agent allocates expenditure across private/household consumption, government consumption, and investment according to the CES function depicted in Figure 6.

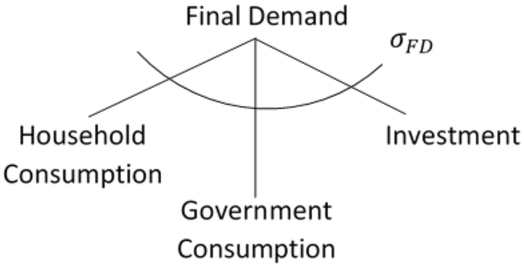


Figure 6. Production nest for final demand.

Note: See notes for Figure 1.

As shown in Figure 7, the utility function for household consumption in each region is also a series of nest CES functions, with some exceptions to allow income elasticities of demand to differ across commodities. Key features of the household consumption nest include (1) substitution between energy commodities, (2) substitution between energy and other non-transport commodities, and (3) substitution possibilities in the consumption of transport services. In the transport nest, consumers can choose between commercial transport (e.g., taxis, buses, and airplanes) and household transport (travel in privately-owned motor vehicles) with substitution between these options governed by σ_{hht}. In the commercial transport nest, the representative consumer can choose between road transport, air transport, and water transport. Household transport is 'produced' by purchasing output from the services sector (e.g., vehicle maintenance and insurance) and vehicle services, which are CES aggregates of output from the refined oil (e.g., gasoline/petrol and diesel) and motor vehicles sectors. Substitution between refined oil products and motor vehicles are governed by the elasticity parameter $\sigma_{oil-mvh}$. This allows consumers to respond to rising oil prices (e.g., due to a carbon price) by spending more on motor vehicles and less on fuel per unit of household transport, representing a price-induced preference for more fuel-efficient vehicles.

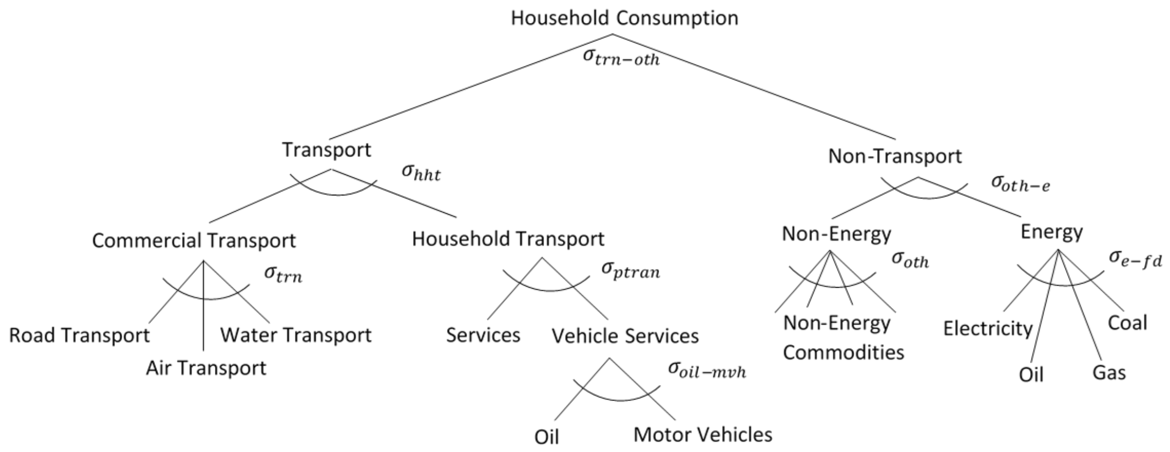


Figure 7. The nesting structure for household consumption.

Note: See notes for Figure 1.

Government consumption and investment expenditures are each represented by a single-level CES function. The government consumption and investment aggregates do not include purchases of energy commodities.

Income elasticities of demand

A shortcoming with CES utility functions is that the income elasticities of demand are equal to one for all goods, which is at odds with empirical observations. Accordingly, for some commodities, the Linear Expenditure System derived from Stone-Geary preferences (Geary, 1950; Stone, 1954) is used to simulate non-homothetic preferences with income elasticities of demand that are less than one (Chen, 2017). The commodities with Stone-Geary preferences include road transport, air transport, and household transport.

3.4 International trade

International trade in the C-PLAN model is modelled using the Armington approach (Armington, 1969) and explicitly includes transport costs. As illustrated in Figure 8, each commodity purchased in an economy (either as an intermediate input or for final demand) is a CES combination of the domestic variety and an aggregate imported commodity that is itself a CES aggregation of imports from different regions (including transport costs). Imports and transport sourced from different regions (*r1*,…, *rn*) tradeoff with one another in a further CES nest. Imports from each region are combined with transport services in a Leontief nest, where transport services are a further Leontief aggregation of global transport services (t_1,…, t_n). Transport services used for international trade are drawn from a global pool, where each transport service is a CES aggregation of production of that service in each region, as illustrated in Figure 9.[6] Substitutability between varieties for each commodity is controlled by σ_{MD} and σ_{MM}.

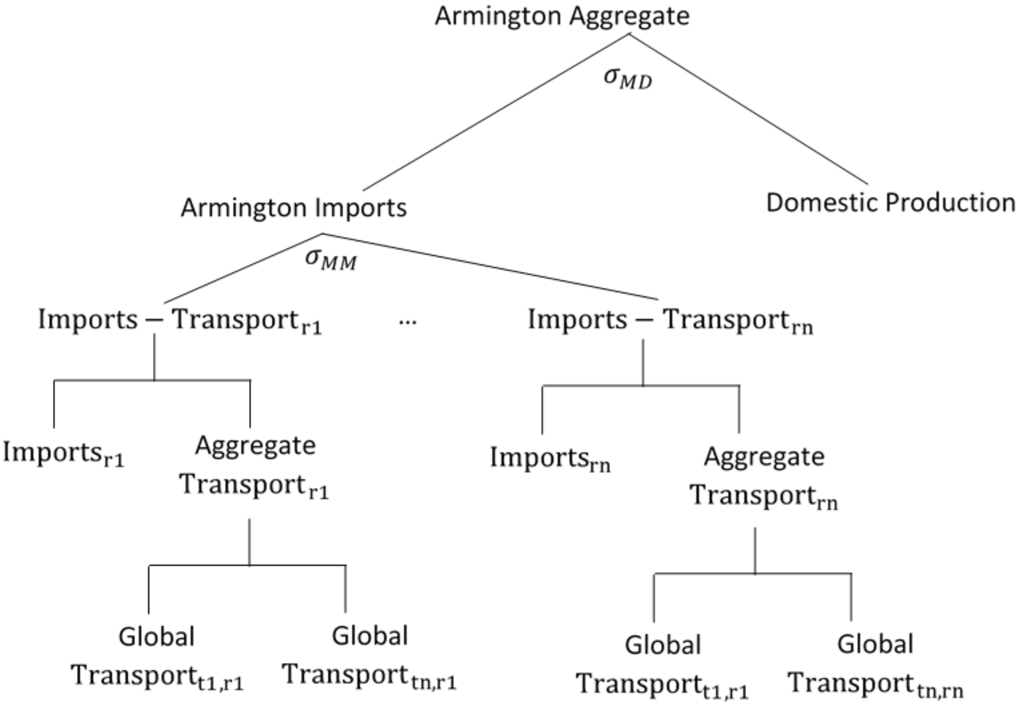


Figure 8. The nesting structure for imported and domestic varieties of commodity *i*.

Note: See notes for Figure 1.

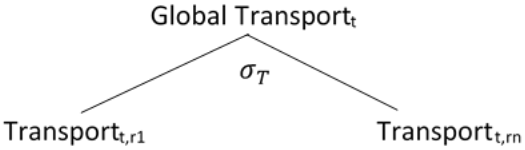


Figure 9. The nesting structure for global transport.

Note: See notes for Figure 1.

3.5 Emissions and carbon prices

GHG emissions in the model are linked to either inputs of fossil fuels (coal, gas, and refined oil) or sectoral output. For each fossil fuel, CO_2 emissions from burning fuels are constant per unit of fuel, so

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[6] Nuno-Ledesma and Villoria (2019) provide details on the estimation of international transport margins in the GTAP Database.

less fuel must be used to reduce emissions. GHG emissions linked to output are either CO_2, CH_4, N_2O or F-gases. Non-CO_2 emissions are measured in CO_2 equivalent (CO2e) units using global warming potential (GWP) weights.[7] If there is not an emissions trading system (ETS), in each sector, these emissions are constant per unit of output. When an ETS policy operates, there is substitution between output and emission permits, reflecting opportunities for producers to abate emissions by spending more on other inputs.

When an ETS operates, producers and consumers are required to purchase a permit for each tonne of CO_2e emitted directly due to their actions (e.g., dairy farmers are required to purchase permits for CH_4 emissions from dairy cows, and households are required to purchase permits for CO_2 emissions from gas used for home heating). An ETS cap is imposed by limiting the number of permits available. If the emissions cap is binding, permits are scarce and the shadow value for permits calculated by the model is analogous to an emissions price that would develop under an ETS.

Outcomes in the model are influenced by the allocation method in addition to the emissions cap. If permits are grandfathered or auctioned, the representative consumer is endowed with a quantity of permits equal to the emissions cap. The revenue from the permits represents a lump sum transfer to the consumer from profits (grandfathering) or additional government revenue (auctioning).

Under an output-based (free) allocation of emission permits, producers are given permits to cover a proportion (β) of emissions per unit of output (e) in a (historical) benchmark year. Output-based allocations are modelled in C-PLAN by specifying a joint production function where firms produce βe emissions permits per unit of output. The quantity of emissions endowed to the representative consumer (representing permits grandfathered or auctioned) is chosen endogenously in the model so that the number of endowed and produced permits is equal to the emissions cap.

3.6 Dynamic processes

Elements in the C-PLAN model which that are important for determining how economies evolve over time include: (1) capital accumulation, (2) labour force growth and labour productivity growth, (3) autonomous energy efficiency improvements, and (4) the availability and scope for advanced technologies.

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[7] GWP weights measure the ability of non-CO_2 gases to trap heat in the atmosphere relative to the heat-trapping capability of CO_2 over a 100-year period (IPCC, 2014).

Capital accumulation and capital productivity

The data used to calibrate the model for the benchmark year includes payments to capital currently employed in each sector.[8] In subsequent years, in each region, capital accumulation is equal to investment in the previous period minus depreciation. The C-PLAN model distinguishes between sector specific capital (that can only be used in the sector where it is currently employed) and mobile capital (that can be used in any sector). Sector specific, or 'fixed', capital in sector *i* in period t, K_{it}^{F}, is equal to:

$$K_{it}^{F} = (1 - \delta_i)\varphi_i K_{it-1}^{A} \tag{13}$$

where δ_i is the depreciation rate in sector i, φ_i is the proportion of capital employed in sector *i* in period *t* – 1 that becomes specific to that sector, and K_{it-1}^{A} is aggregate (sector specific and mobile) capital employed in sector *i* in period *t–1*.

Total mobile capital in an economy in period *t*, K_t^{M}, is equal to investment in period *t-1*, I_{t-1}, plus the sum of mobile capital net of depreciation across sectors.

$$K_t^{M} = I_{t-1} + \sum_{i=1}^{N} (1 - \delta_i)(1 - \varphi_i) K_{it-1}^{A} \tag{14}$$

Total capital in sector *i* in period *t* is equal to sector specific capital and mobile capital:

$$K_{it}^{A} = K_{it}^{F} + \gamma_{it} K_t^{M} \tag{15}$$

where γ_{it} is the share of economy-wide mobile capital used in sector *i* at time *t*.

In each period, K_{it}^{F} and K_t^{M} are carried over from the previous period and γ_{it} is determined endogenously based on each sector's demand for capital. If the amount of capital employed in sector *i* is less than K_{it}^{F}, there are stranded assets in that sector and $\gamma_{it} = 0$.

Changes in capital productivity in the C-PLAN model are specified using a productivity multiplier, τ_t, that is applied to both sector-specific and mobile capital in all sectors. In the baseline/reference scenario, τ_t values are determined endogenously in the model to target external gross domestic product (GDP) projections. Baseline estimates for τ_t are used as exogenous inputs for subsequent scenarios and GDP is endogenous in these scenarios.

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[8] Capital stocks consistent with capital payments can be calculated by setting the rate of return, defined as the sum of the rates of interest and depreciation, equal to the flow of capital services to the underlying capital stock (Paltsev et al. 2005, p. 26).

Labour force growth and labour productivity

The effective labour force in the model is a function of the number of workers in in the labour force and the productivity of those workers. The effective labour force in the model in period *t*, LE_t, is:

$$LE_t = LE_{t-1}(1 + g_t^{LF} + g_t^{LP} + g_t^{LF} g_t^{LP}) \tag{16}$$

where g_t^{LF} and g_t^{LP} are the growth rates for the labour force and labour productivity respectively.

Autonomous energy efficiency improvements

A persistent trend in developed countries is that energy efficiency has improved at constant or falling energy prices (Webster et al., 2008). This trend is represented in CGE models by exogenous time-trends in the input coefficients for energy or fossil fuels (Paltsev et al, 2005). The C-PLAN model follows this approach by including Autonomous Energy Efficiency Improvement (AEEI) parameters that scale energy inputs required per unit of output when fuels or electricity are used in non-primary energy sectors.

Specifically, the scalar applied to inputs of energy type *e* per unit of output for sector *i* in period *t*, γ_{eit}, is:

$$\gamma_{eit} = \gamma_{eit-1}(1 + g_{eit}^{AEEI}) \tag{17}$$

where g_{eit}^{AEEI} is the growth rate for energy inputs *e* used in sector *i* in period *t* to produce a unit of useable energy for that sector ($-1 < g_{eit}^{AEEI} \leq 0$).

3.7 Advanced technologies

Advanced technologies in the C-PLAN model represent lower-emissions techniques for producing commodities. They do not operate in the benchmark year but are available in specified future years. Key components for advanced technologies are cost markups, and TSF input-requirements. For each technology, the cost markups represent production costs using the advanced technology relative to conventional production at benchmark (constant) input prices. Cost markups are typically greater than one, so providing the technology is available, advanced technologies will only be used if relative input costs for conventional production increase by a sufficient amount (e.g., due to a carbon price). Most advanced technologies require inputs from a TSF (in additional to capital, labour, and intermediate inputs). As a result, endowments of TSFs can be assigned in the model to reflect deployment and/or market penetration constraints.[9]

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[9] See Morris et al. (2019) and Weitzel et al. (2019) for detailed discussions of the representation of advanced technologies in economy-wide models.

As shown in Table 3, advanced technologies in C-PLAN include electric road transport, electric household transport, dairy farming with a methane-reducing technology, beef and sheep farming with a methane-reducing technology, geothermal electricity with carbon capture and storage (CCS), electric heat for selected sectors (horticulture, dairy processing, meat products, other food products, wood and paper products, and other manufacturing), and bioheat from forestry waste for selected sectors (horticulture, meat products, other food products, wood and paper products, and other manufacturing). If they operate, output from advanced technologies substitute for an existing commodity (e.g., electric road transport can replace conventional road transport) or for inputs in certain sectors (e.g., electric heat is a substitute for the coal-gas aggregate in the production of wood and paper products).

Table 3. Advanced technologies and their key characteristics.

Technology	Substitute for	Available from
Electric road transport	Road transport	2015
Electric household transport	Household transport	2015
Dairy farming with reduced methane	Dairy farming	2030
Beef and sheep farming with reduced methane	Beef and sheep farming	2030
Geothermal electricity with CCS	Geothermal electricity	2028
Electric heat	Coal-gas aggregate in selected sectors	2020
Bioheat	Coal-gas aggregate in selected sectors	2020

Note: Electric road transport and electricity household transport are available in the baseline and policy scenarios. Other advanced technologies are only available in policy scenarios.

Electric vehicles

As the share of electric vehicle travel kilometers (VTKs) in 2014 was only 0.01%, we ignore travel by electric vehicles in the benchmark year and model transport by electric vehicles as advanced technologies. The production structure for electric road transport is illustrated in Figure 10. Electricity is the only component in the energy nest and a TSF for this technology is included with other inputs in the top-level of the nest. As $\sigma_{TSF} > 0$, in each period, output of this technology can increase beyond that permitted by the TSF endowment for this technology but at an increasing marginal cost.

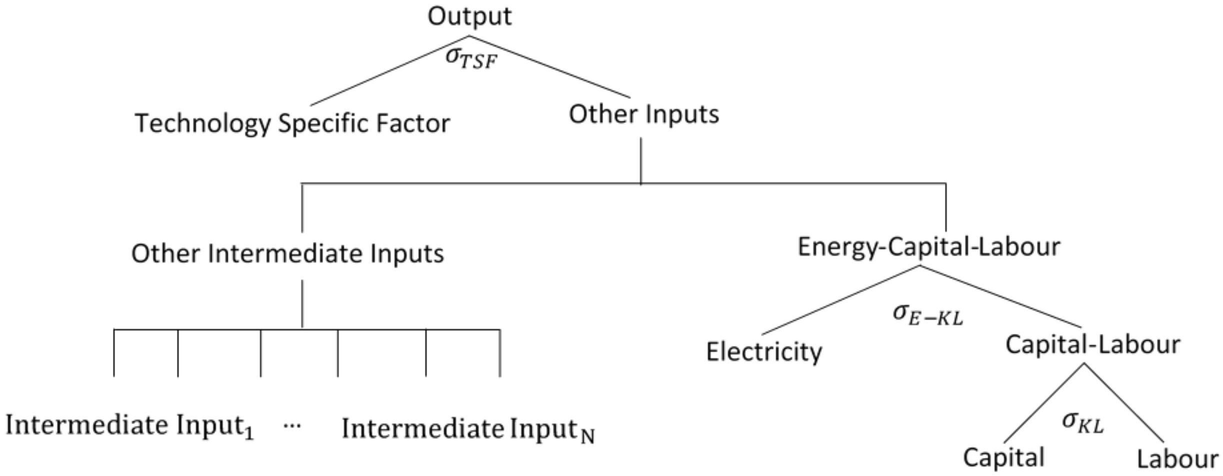

Figure 10. Production nest for electric road transport.

Note: See notes for Figure 1.

As shown in Figure 11, the production structure for electric household transport includes a TSF and other inputs in a top-level nest. Like the production function for conventional household transport (from vehicles with internal combustion engines), services and motor vehicles are the other inputs required for electric household transport. As for electric road transport, $\sigma_{TSF} > 0$ and electricity costs are assigned based on electricity requirements per VTK for commercial transport from the Energy and Emissions in New Zealand (ENZ) model (CCC, 2021b, Appendix 1).[10]

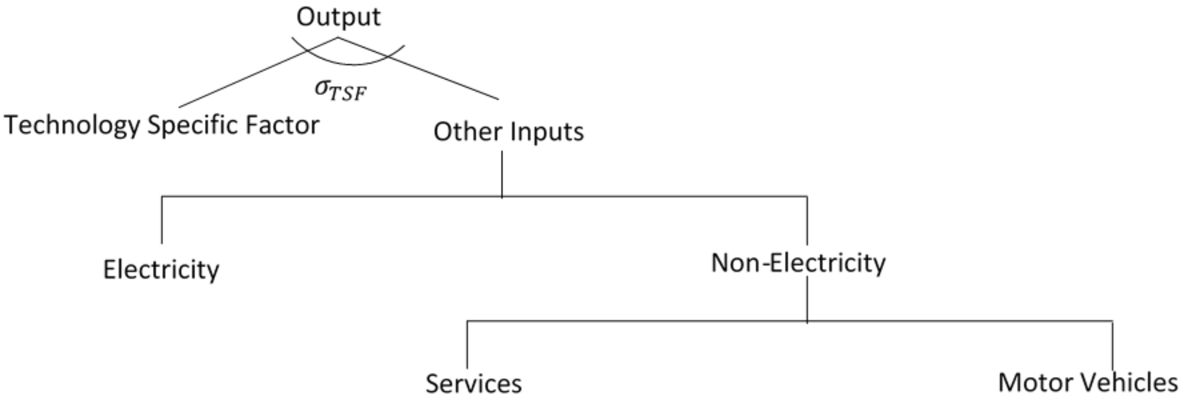

Figure 11. Production nest for electric household transport.

Note: See notes for Figure 1.

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[10] See Productivity Commission (2018) for additional documentation on the ENZ model.

Dairy farming and sheep and beef farming with a methane-reducing technology

Methane-reducing technologies for dairy farming and sheep and beef farming are included in the model by specifying additional production functions for these sectors with lower methane intensities than conventional farming. As illustrated in Figure 12, the production structure for reduced-methane farming is the same as for conventional farming (see Figure 2) with the addition of a TSF requirement. TSF inputs are combined with other inputs in a series of Leontief nests, so maximum production from each reduced methane technology is determined by the TSF endowment for that technology. As the effectiveness of the methane-reducing technology improves over time (and the cost of using the technology is constant), the cost per tonne of CO_2e abated falls each year.

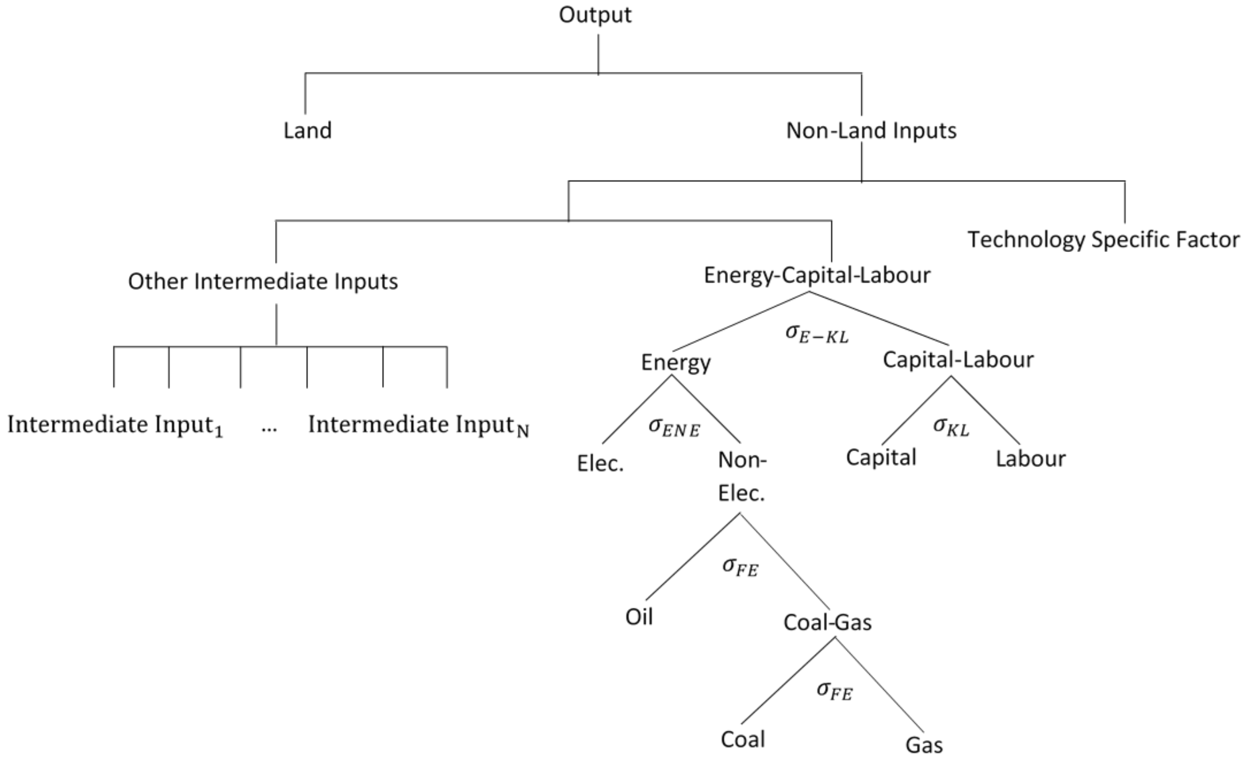

Figure 12. Production nest for dairy farming and sheep and beef farming with a methane-reducing technology.

Note: See notes for Figure 1.

Geothermal electricity with CCS

Geothermal electricity with CCS uses an identical production structure to conventional geothermal electricity but with additional capital and labour costs. As the availability of CCS does not impact the availability of geothermal resources, the TSF for conventional geothermal electricity can also be used in geothermal electricity with CCS but sector-specific capital cannot move between the two geothermal electricity technologies.

Electric heat and bioheat

Electric heat is a perfect substitute, on a usable energy-equivalent basis, for the coal-gas aggregate in the production of horticulture, dairy processing, meat products, other food products, wood and paper products, and other manufacturing. Bioheat from forestry residues is also a perfect substitute for the coal-gas aggregate and can be used in the horticulture, meat products, other food products, wood and paper products, and other manufacturing sectors. As shown in Figure 13, the availability of forestry residues for each sector is represented by a TSF and fuel for bioheat is produced by using road transport and services to collect and process forestry residues. There are no substitution possibilities between bioheat TSFs and other inputs, so endowments of bioheat TSFs determine the maximum amount of bioheat use in each sector. Bioheat TSF endowments increase when there is more forestry production, so the potential for bioheat is greater in scenarios with more forestry production than in scenarios with less forestry production.

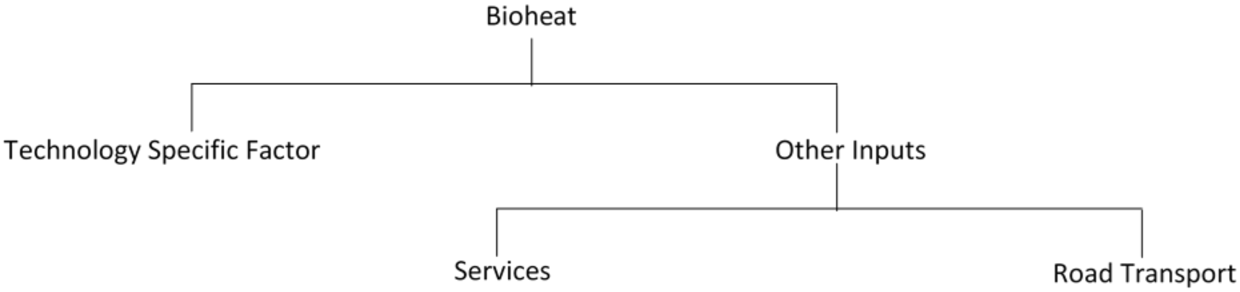

Figure 13. Production nest for bioheat.

Note: See notes for Figure 1.

3.8 Model closures

As in all CGE models, several relationships must be specified to 'close' the model. In each period, labour is perfectly mobile across sectors, the supply of labour is fixed and the economy-wide wage adjusts to clear the labour market (i.e., there is full employment). In capital markets, in each period the supplies of sector specific capital and mobile capital are exogenous and capital rental rates are endogenous (and the supply of each capital type is updated after each solve period). The supplies of each land type, resource specific factors, and TSFs are also constant in each year and unit returns for these factors are endogenous.

Turning to macroeconomic closures, in each year, the current account balance is fixed at the level in the benchmark year. Government spending and net tax revenue are endogenous with government surpluses or deficits passed on to consumers as (implicit) lump sum transfers. Investment in each period is endogenous and is equal to domestic savings minus the current account balance.

4. Model calibration

4.1 Economic data

The core economic dataset used to calibrate the C-PLAN model is Version 10 of the GTAP-Power Database (Peters, 2016; Chepeliev, 2020). This database extends the standard GTAP Database (Aguiar et al., 2016; Aguiar et al., 2019) to represent electricity generation and transmission and distribution in greater detail and provides a snapshot of the global economy in 2014 (and some previous years). The GTAP-Power Database is distributed as Header Array (HAR) files and represents 78 sectors and 141 countries/regions. We use a modified version of the GTAPinGAMS package provided by Lanz and Rutherford (2016) to (1) convert the HAR files to GAMS Data Exchange (GDX) files, and (2) aggregate the data to the sectors listed in Table 1 and a New Zealand-Rest of the World regional aggregation. The mapping from sectors represented in the GTAP Database to C-PLAN sectors is reported in Appendix A.

The air transport and water transport sectors in the GTAP-Power Database include both domestic and international activities. As emissions from fuel used for international aviation and marine transport (so-called international bunker fuels) are excluded from domestic targets, we augment the GTAP data to separately represent domestic and international components of the air transport and water transport sectors. For each transport mode, this is accomplished by assigning production and input use shares across domestic and international components so that they match emissions shares reported by (MfE, 2019a).

The GTAP-Power Database includes all purchases of goods and services but it does not record what those purchases are used for. We create the household transport aggregate described in Section 3.3 by assuming that 99% of household purchases of refined oil products and all household purchases of motor vehicles are used for transport. We also disaggregate household purchases of services into those for transport (e.g., insurance, maintenance, and licensing) and those for other activities based on estimates by the New Zealand Automobile Association (2018).

Table 4. GHG emissions by sector in the C-PLAN model in 2014, $MtCO_2e$.

	CO_2				CH_4	N_2O	f-gases	Total
Sector	Oil	Gas	Coal	Other				
rmk	0.464	0.002	0.048	0.583	15.000	3.192		19.288
b_s	0.336	0.004	0.059	0.401	14.403	1.892		17.096
oap	0.062	0.001	0.010	0.018	0.666	0.019		0.776
hor	0.222	0.003	0.004	0.097	0.022	1.858		2.206
frs	0.144	0.035	0.020	0.004	0.014			0.217
fsh	0.170	0.145	0.004		0.000	0.001		0.322
col	0.000	0.000	0.118		0.225			0.344
cru	0.000	0.064		0.308	0.005			0.378
gas	0.000	0.638		0.298	0.402	0.000		1.338
oxt	0.481	0.027	0.002		0.001	0.007		0.518
oil	0.768	0.111			0.000	0.001		0.879
ecoa			1.214			0.007		1.221
egas		3.022			0.002			3.024
eoth				0.646	0.166			0.811
tnd	0.000							0.000
crp	0.096	1.303	0.028	0.254	0.127	0.001		1.809
nmm	0.044	0.067	0.337	0.830				1.279
nfm	0.043	0.069	0.004	0.538	0.000	0.000	0.073	0.728
i_s	0.052	0.113	0.033	1.732	0.000	0.000		1.930
fmp	0.020	0.017	0.005	0.320	0.000	0.001		0.362
mil	0.099	0.554	1.209		0.003	0.005		1.869
mtp	0.004	0.014	0.334		0.001	0.001		0.354
ofd	0.013	0.263	0.115		0.001	0.002		0.393
w_p	0.074	0.334	0.050		0.031	0.049		0.540
mvh	0.005	0.000	0.001					0.006
omf	0.093	0.037	0.021	0.041	0.000	0.058	1.320	1.571
rtp	6.656	0.044	0.001		0.007	0.055		6.762
wtp	0.319	0.000	0.001		0.001	0.002		0.323
wtpi	0.927				0.002	0.008		0.938
atp	0.846	0.000			0.000	0.007		0.853
atpi	2.575				0.000	0.021		2.597
cns	0.351	0.022	0.002		0.001	0.002		0.378
afs	0.028	0.088	0.003					0.118
ser	0.304	0.272	0.104		4.070	0.119		4.869
c	0.064	0.276	0.026		0.075			0.441
hht	6.349					0.092		6.441
Total without bunker fuels	18.108	7.526	3.753	6.070	35.225	7.372	1.394	79.446
Total with bunker fuels	21.611	7.526	3.753	6.070	35.227	7.401	1.394	82.981

4.2 GHG Emissions

Emissions in the model's benchmark year are calibrated to match 2014 emissions in New Zealand's GHG Inventory 1990–2017 (MfE, 2019a).[11] This process involved, for each C-PLAN sector, allocating Greenhouse Gas Inventory emissions classifications to one of the following categories: CO_2 emissions from coal, CO_2 emissions from gas, CO_2 emissions from oil, CO_2 process emissions; CH_4 emissions; N_2O emissions; and emissions of F-gases. The mapping of GHG Inventory emissions to C-PLAN sectors is reported in Appendix B.

Gross GHG emissions by sector and emissions category are presented in Table 4. Major emission sources include CH_4 emissions from dairy farming (19.2% of domestic emissions) and sheep and beef farming (18.5%), CO_2 emissions from combusting refined oil products in road transport (8.5%) and household transport (8.1%), CH_4 emissions from (waste) services (5.2%), N_2O emissions from dairy farming (4.0%) and beef and sheep farming (2.4%), and CO_2 emissions from burning gas for electricity generation (3.9%). Grouping sectors, 51.1% of domestic emissions are from agriculture, forestry and fishing; 18.4% are from transport; 16.5% are from manufacturing and mining; 7.4% are from services; and 6.5% are from electricity. Emissions from 2015 onward are endogenous in the model.

4.3 Elasticities of substitution

Elasticities of subsitution parameters in the C-PLAN model are reported in Table 5. Most values are informed by those used in the MIT EPPA model (Paltsev et al., 2005; Chen et al., 2016), which are in turn sourced from econometric estimates or expert elicitation. Values for the elasticity of substitution between capital and labour in production (σ_{KL}), which differ across sectors, are sourced from the GTAP Database (Aguiar et al., 2019). Values for the elasticities of substitution in the trade specification (σ_{MD} and σ_{MM}), which differ across commodities, are sourced from Hertel et al. (2007). The elasticity of substitution parameter values, in partnerhsip with the CES nesting structures and benchmark cost/expenditure shares, influence how consumers and producers respond to relative price changes.

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[11] In addition to being reported in MfE (2019), New Zealand's GHG emissions are available are also accessible via an interactive tool at https://emissionstracker.mfe.govt.nz/#NrAMBoEYF12TwCIByBTALo2wBM4eiQAc2RSW0QA. The data are also available in a spreadsheet form at https://www.mfe.govt.nz/sites/default/files/media/Climate%20Change/time-series-emissions-data-by-category.xlsx.

Table 5. Elasticity parameter values in the C-PLAN model.

Parameter	**Elasticity of subsitution between/among…**	**Value(s)**
Elasticities of substitution in production functions		
σ_{E-KL}	Energy and capital/labour	0.6
σ_{KL}	Capital and labour	0.2 – 1.7
σ_{ENE}	Electricity and non-electricity commodities	0.5
σ_{FE}	Fossil fuels for energy use	1
σ_{AGR}	Land-other inputs and energy-capital-labour in agriculture production	0 – 0.05
σ_{IL}	Land and intermediate inputs in agricultural production	0 – 0.01
σ_{BM}	Wood and paper products and other building materials	0.5
σ_{R}	Resource inputs and other inputs in fossil fuel extraction and output-constrained sectors	0 – 0.2
σ_{TSF}	Technology specific factors and other inputs	0 – 0.15
σ_{ELE}	Electricity technology in supplied/aggregate electricity	∞
Elasticities of substitution in final demand		
σ_{FD}	Household consumption, government consumption, and investment	0.25
$\sigma_{trn-oth}$	Transport and non-transport goods in household consumption	0.75
σ_{hht}	Household purchases of commercial and own-supplied transport	0.5
σ_{trn}	Household purchases of commercial transport services	1
σ_{ptran}	Household purchases of services and vehicles for own-supplied transport	0.1
$\sigma_{oil-mvh}$	Household purchases of refined oil and motor vehicles for own-supplied transport	0.25
σ_{oth-e}	Household purchases of non-energy and energy commodities	0.25
σ_{oth}	Household purchases of non-energy commodities	0.5
σ_{e-fd}	Household purchases of energy commodities	0.4

5. The baseline and policy scenarios

This section outlines a baseline scenario and a policy scenario. The baseline and policy scenarios are, respectively, equivalent to the ‘Current Policy Reference’ and ‘Target Pathway 1’ scenarios used in the

CCC's draft advice to government on climate action (CCC, 2021a). Instructions for reproducing the results for the scenarios, that are also reported in Section 6, are included in the supplementary materials for this manuscript.[12]

5.1 The baseline scenario

Dynamic CGE models typically generate a baseline scenario that produces numerical projections consistent with future changes in socioeconomic drivers and use this baseline as a reference for evaluating the impacts of policies of interest (Dellink et al., 2020). This approach is followed in the C-PLAN model. Exogenous drivers in the C-PLAN baseline include projections for GDP, the labour force, electricity generation, and oil prices; current policies; resources constraints; and expected technology developments. In each year, subject to some constraints, emissions and sectoral output are endogenous in the baseline. Assumptions and drivers for New Zealand in the baseline scenario are outlined below.

GDP, the labour force, and labour productivity

GDP and labour force growth rates in the baseline match those in the central assumptions used for New Zealand's fourth biennial report under the United Nations Framework Convention on Climate Change (MfE, 2019b). Annual GDP growth is 2.15% in 2025 and declines gradually to 1.58% by 2050. Labour force growth is 0.97% in 2025 and declines to 0.39% in 2050. Labour productivity increases at 1.2% per year in all years throughout the economy.

Carbon prices and free allocations of emission permits

Carbon prices and the free allocation of output-based emission permits are based on the 'With existing measures' scenario in New Zealand's Fourth Biennial Report (MfE, 2019b). The carbon prices apply to most sectors and emissions sources in all years. In a notable exception, the carbon price is applied to CH_4 emissions from agriculture from 2026 onward (but not in previous years). The carbon price rises from \$3.37/tCO2e in 2015 to \$35 in 2021 and is constant at this value through to 2050. Free, output-based permits are allocated to dairy processing, meat processing, horticulture, and certain energy-intensive sectors (refined oil products; chemical, rubber and plastic products; non-metallic minerals; non-ferrous metals; and wood and paper products). For most sectors, permit allocation per unit of output falls from 100% of the surrender obligation (at 2016 emission intensities) in the period 2015-2020 to 33% in 2050.

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[12] Detailed results for the scenarios are also published by the CCC at https://www.climatecommission.govt.nz/get-involved/sharing-our-thinking/data-and-modelling/. They can be accessed by selecting from the side menu 'Macroeconomic modelling results and dataset' and then clicking on 'C-PLAN results dataset for 2021 draft advice.xlsx'.

Electricity generation

Electricity generation by technology in the baseline scenario matches estimates by the ENZ model (CCC, 2021b, Appendix 1). Total electricity generation increases from 42.2 terawatt-hours (TWh) in 2014 to 61.0 TWh in 2050. Coal electricity ceases in 2023 and electricity from (aggregate) wind and solar generation increases from 2.2 TWh in 2014 to 22.6 TWh in 2050. Hydro electricity is stable at around 24.2 TWh per year.

Electric vehicles

Electric vehicle use in the baseline scenario is informed by estimates from the ENZ model. The proportion of VTKs by electric vehicles rises over time and by 2050 it is 91.1% of total household VTKs and 54.7% of total VTKs in commercial transport. For both electric road transport and electric household transport, TSF endowments are assigned in each period to target desired output levels from these sectors.

Autonomous energy efficiency improvements

There are no autonomous energy efficiency improvements for fuels used in electricity. In domestic and international air transport, the energy efficiency of refined oil use improves by 1.25% per year. In all other sectors, energy efficiency improves by 1% per year for all energy types (coal, gas, refined oil, and electricity).[13]

Oil prices

Following an approach commonly used in other CGE models (Foure et al., 2020), oil resources are endogenously chosen to target specified crude oil prices. Oil prices in the baseline scenario are guided by the International Energy Agency's World Energy Outlook 2019 (IEA, 2019). It is difficult to implement large fluctuations in oil prices in CGE models (Bekkers et al., 2020; p. 312) so the oil prices imposed in the baseline decrease by a constant amount each year between 2014 and 2024. From 2024 onwards, the price of crude oil, in 2014 US dollars, is $56.60 per barrel.

Forestry land and forestry CO_2 sequestration

Forestry land and CO_2 sequestered by forests are exogenous in the baseline and are based on Ministry for Primary Industries (MPI) projections used in New Zealand's Fourth Biennial Report (MfE, 2019b). In the baseline, land used for managed forest increases from 1.81 million hectares (Mha) in 2014 to 2.82 Mha in

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[13] See Chateau et al. (2020) for a discussion on the impact of energy efficiency parameters on CGE baselines.

2050. Forests sequester 12.3 $MtCO_2$ in 2014, 5.7 MtCO2 in 2025, and 22.2 $MtCO_2$ in 2050. Forestry CO_2 sequestration is consistent with expected changes in land use for managed and native forest, but native forest land is not represented in the C-PLAN model. Forestry land use and CO_2 removals from forestry in each year are reported in Appendix C.

Agriculture land use

Land use for dairy and beef and sheep farming are based on MPI projections used in New Zealand's Fourth Biennial Report (MfE, 2019b) and were updated by the CCC to reflect recent afforestation projections (which decrease the land available for other uses). The land use projections account for the impact of (1) the National Policy Statement for Freshwater Management (prior to changes to this policy announced in 2020) (MfE, 2017), (2) the One Billion Trees Programme (MPI, 2020), and (3) the New Zealand ETS under current policies. Given these estimates, (equal) proportional changes in land used for other animal products and horticulture are derived residually to match estimates of total agricultural land estimated by MPI for the Fourth Biennial Report. Under these assumptions, between 2014 and 2050, dairy land increases from 1.75 to 1.78 Mha, beef and sheep land decreases from 8.46 to 5.78 Mha, land for other animal products decreases from 0.250 to 0.248 Mha, and horticulture land decreases from 0.269 to 0.266 Mha. Agriculture land use by activity in each year is reported in Appendix C.

Forestry and agriculture yields

Guided by MPI's estimates for the Fourth Biennial report (MfE, 2019b), the yield on land used for dairy farming decreases by 5.0% between 2014 and 2031 and then increases back to its 2014 level by 2050, and the yield on beef and sheep land increases by 19% between 2014 and 2050. Yields on land for other animal products, horticulture, and forestry are assumed to increase by 1% per year.

Autonomous decreases in non-combustion emissions (except F-gases) per unit of output

Autonomous decreases in non-CO_2 emission intensities for dairy farming, beef and sheep farming, other animal products, and horticulture are derived from MPI projections for New Zealand's Fourth Biennial Report (MfE, 2019b). For CH_4 emissions from the services sector, which includes waste, autonomous improvement values are chosen so that baseline estimates for these emissions are similar to those projected in New Zealand's Fourth Biennial Report. For other non-CO_2 GHGs, autonomous decreases in emissions per unit of output are 0.3% per year. Under these assumptions, between 2014 and 2050, autonomous decreases in non-CO_2 emission intensities are 7.4% for dairy farming and 12.7% for beef and sheep farming, other animal products and horticulture; the CH_4 intensity of services (which includes waste) falls by 59.9%; and emissions intensities for other non-CO_2 emissions (except F-gases) falls by 10.3%.

Autonomous decreases in F-gases per unit of output

Autonomous decreases in F-gases per unit of output from the other manufacturing sector are calibrated to match projections by MfE (2020) and are consistent with New Zealand's commitments under the Kigali Amendment to the Montreal Protocol. This calibration results in the F-gas intensity of other manufacturing output falling by 62.9% between 2014 and 2050.

Restricted output for certain sectors and income elasticities of demand

Reflecting regulatory and resource constraints and an analysis of market conditions by the CCC, output of the fishing; chemical, rubber and plastic products; non-metallic minerals; iron and steel; and crude oil sectors cannot exceed observed output in 2014. The maximum output of non-ferrous metals is constrained from 2021 onward in anticipation of the Tiwai Point Aluminium Smelter closing (as announced in July 2020). Guided by the Ministry of Transport projections (MoT, 2019), domestic water transport can grow by a maximum of 30% between 2014 and 2050. Growth in output of international air transport, international water transport, and other mining cannot exceed GDP growth. Finally, linear expenditure system parameters – which control income-induced demand responses for road transport, air transport, and household transport – are assigned so that consumption of these commodities is similar to projections by the Ministry of Transport (MoT, 2019).

Rest of world baseline inputs

In the rest of the world, the baseline is calibrated using GDP forecasts from OECD (2018), electricity projections by EIA (2017), and electric vehicle projections from BNEF (2020) and OECD (2017). For fossil fuels used in electricity generation, there are autonomous energy efficiency improvements of 0.3% per year, while these improvements are 1% per year for fossil fuels used in other sectors. There are also autonomous decreases in non-fossil fuel CO_2 emissions per unit of output of 0.3% year in all sectors. To broadly represent climate policies in the rest of the world, consistent with limiting global warming to 1.5 – 2.0 degrees Celsius, a carbon price is applied to all GHGs from 2020 onward (in the baseline and the policy scenarios). The carbon prices, in 2014 USD, rises linearly from $8 in 2020 to $250 in 2050.

5.2 A policy scenario

The Zero Carbon Act sets separate emissions targets for different baskets of gases. It aims to reduce emissions of biogenic methane to 24–47% below 2017 levels by 2050, including to 10% below 2017 levels by 2030; and reduce net emissions of all other GHGs to zero by 2050. Accordingly, in the policy scenario, we constrain emissions using two separate ETSs: one ETS is specified for methane from dairy farming, beef and sheep farming, and services (waste); and the other includes all other GHGs in all sectors. Both ETSs begin in 2022 and the baseline carbon prices are applied in previous years. Emissions caps for each basket of gases were determined by the CCC. The biogenic methane ETS caps these emissions at 24% below the 2017 level in 2050 and interpolates emission caps for the years 2022 to 2049 so that emissions decline over time. The cap on gross emissions in the other GHGs ETS is equal to the removal of emissions by forestry in 2050, so net emissions are zero in this year. Caps on other GHG emissions for the years 2022 to 2049 are interpolated so that gross (and net) emissions fall over time. There is no trading between the two ETSs and no international trading of emissions permits.

Some sectors receive free, output-based permit allocations based on emissions per unit of production in the model's benchmark year (2014). Output-based permit allocation rates in the policy scenario are displayed in Appendix D. For the biogenic methane ETS, in 2022, dairy farming and beef and sheep farming receive 96.2% of permits required per unit of output (at 2014 emission intensities). This free allocation rate falls over time and is 31.9% in 2050. For the other GHGs ETS, free permits are provided for high energy intensive sectors (refined oil products; chemical, rubber and plastic products; non-metallic minerals; non-ferrous metals; iron and steel; and wood and paper products) and medium energy intensive sectors (horticulture, dairy processing, and meat products). High energy intensive sectors receive free permits for 97.8% of emissions per unit of output (at 2014 emissions intensities) in 2022, with the free allocation rate falling to 1.1% by 2049 and 0% by 2050. For medium energy intensive sectors, the free allocation rate falls from 96.2% in 2022 to 4.2% in 2040 and 0% in subsequent years.

Electric vehicles are available in both the baseline and policy scenarios, but bioheat, electric heat, geothermal electricity with CCS, and the methane-reducing technology are only available in the policy scenario. The methane-reducing technology is available in 2030 and subsequent years for both dairy farming and sheep and beef farming. In 2030, if used, the technology reduces methane emissions per unit of output by 10% relative to 2014 emissions. The effectiveness of the technology increases by one percentage per year and by 2050 it reduces emissions per unit of output by 30%. The methane-reducing technology can be applied to a maximum of 75% of dairy output and to a maximum of 40% of sheep and beef output in all years that it is available.

A longstanding characteristic of New Zealand land markets is that land use change is insensitive to product and land prices (Kerr and Olssen, 2012). Accordingly, productive land use in the policy scenario is the same as in the baseline scenario. However, in the policy scenario, slightly more land is used for native forests and less for other uses (neither of which are included in the model) relative to the baseline scenario. This difference results in a small increase in CO_2 forestry removals in the policy scenario relative to the baseline scenario.

Table 6. Summary results for 2035 and 2050.

	2035		2050	
	Baseline	**Policy**	**Baseline**	**Policy**
GDP and welfare				
GDP, billion 2017$	396.0	395.4	512.1	510.4
GDP, % change*	-	-0.15	-	-0.34
Consumer welfare, billion 2017$	190.4	190.2	247.0	246.3
Consumer welfare, % change*	-	-0.10	-	-0.26
CO2 prices, 2017$/tCO₂e				
Biogenic methane ETS	-	114.68	-	53.44
Other GHGs ETS	-	120.81	-	337.79
GHG emissions, MtCO₂e				
Biogenic methane	30.21	28.77	29.06	25.27
Other GHGs, gross	41.50	36.06	34.83	24.25
Forestry removals	12.12	13.39	22.19	24.25
Other GHGs, net	29.38	22.67	12.64	0.00
Electricity and vehicles				
Electricity production, TWh	45.72	45.59	61.02	61.11
Percent of travel from EVs				
Road transport	12.60	13.52	54.72	64.42
Household transport	31.48	33.42	91.17	100.00

Note: * Percent change relative to the baseline scenario in the specified year.

6. Results

A summary of results in 2035 and 2050 for the baseline and policy scenarios is presented in Table 6 and additional results are reported in Figures 14 to 17. In the baseline scenario, biogenic methane emissions and other GHGs emissions both decrease over time (Figure 14). For biogenic methane, the decrease is driven by autonomous decreases in GHG intensities and the land use assumptions for dairy and beef and sheep farming. Increased use of electric vehicles, constraints on some energy-intensive sectors, and autonomous improvements in energy efficiency are key reasons for the decrease in gross emissions of other GHGs. Emissions sequestered by forestry rise over time so net emissions of other GHGs fall by a larger amount than gross emissions (Table 6). In the policy scenario, emissions for each GHG group equal the emissions cap for that group. Both emissions caps are tightened over time so that by 2050, biogenic methane emissions are 13% lower than baseline emissions in that year, and gross other GHG emissions are 30% lower.[14] By design, net emissions of other GHGs are zero in 2050.

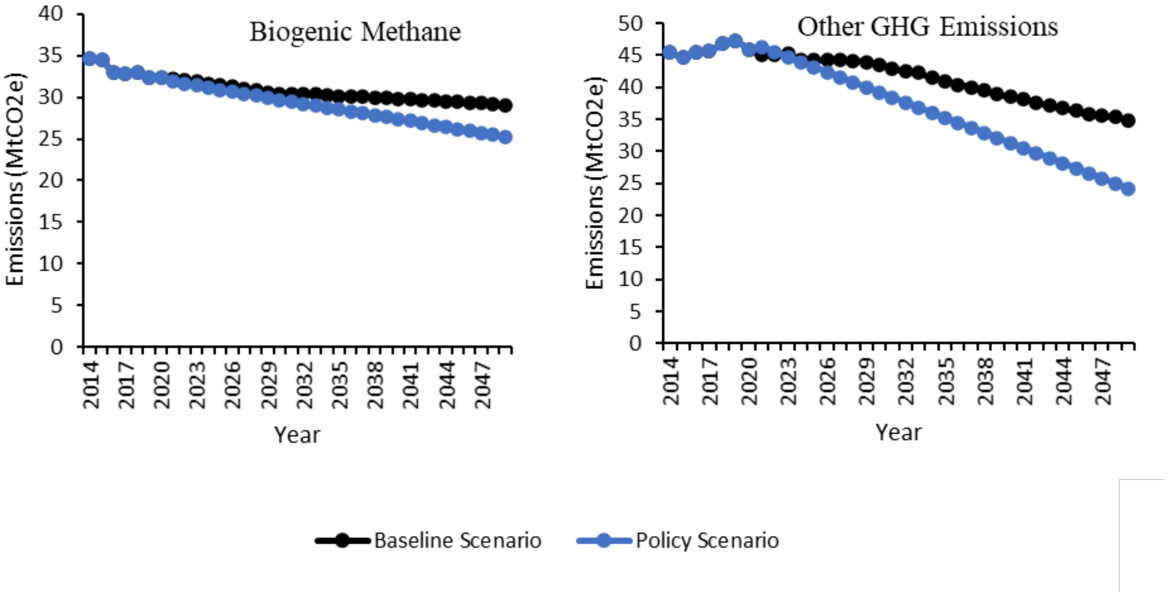

Figure 14. Biogenic methane and other GHG emissions in the baseline and policy scenario.

Gross emissions from each sectoral group fall over time in the baseline scenario, except for those from other commercial (mainly air) transport, services, and other household consumption (Figure 15). In the policy scenario in 2050, the largest absolute decreases in gross emissions relative to baseline emissions in that year are in agriculture and forestry (4.6 MtCO$_2$e), manufacturing and mining (4.5 MtCO$_2$e), and road transport (2.4 MtCO$_2$e). There is a large proportional decrease in 2050 electricity emissions in the policy scenario relative to the baseline (51.3%) but the absolute decline in emissions is only 1.0 MtCO$_2$e.

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[14] In 2022 and 2023, the cap on other GHGs is higher than in the baseline scenario; however, the emissions cap is binding as the baseline includes a \$35/tCO$_2$ price on most GHGs (that is not included in the policy scenario after 2021).

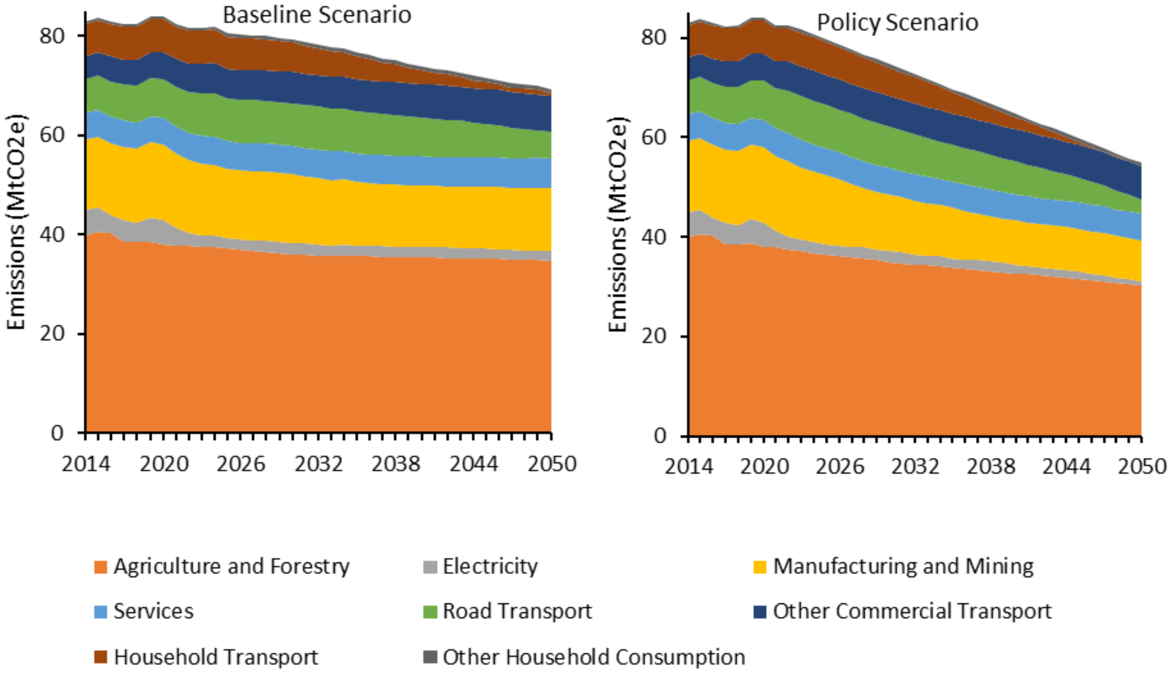

Figure 15. Gross emissions from sectoral groups, MtCO$_2$e.

There is a steep rise in the carbon price for biogenic methane between 2030 and 2035 as the biogenic methane cap becomes more stringent and the methane-reducing technology has limited effectiveness in reducing emissions (Figure 16). After 2035, the increasing efficacy of the methane-reducing technology lowers the biogenic methane price despite the tightening of the emissions cap. The carbon price for other GHGs rises gradually over time, as the economy grows and the cap on these emissions is tightened, from \$8.96/tCO$_2$e in 2022 to \$337.79/tCO$_2$e in 2050.

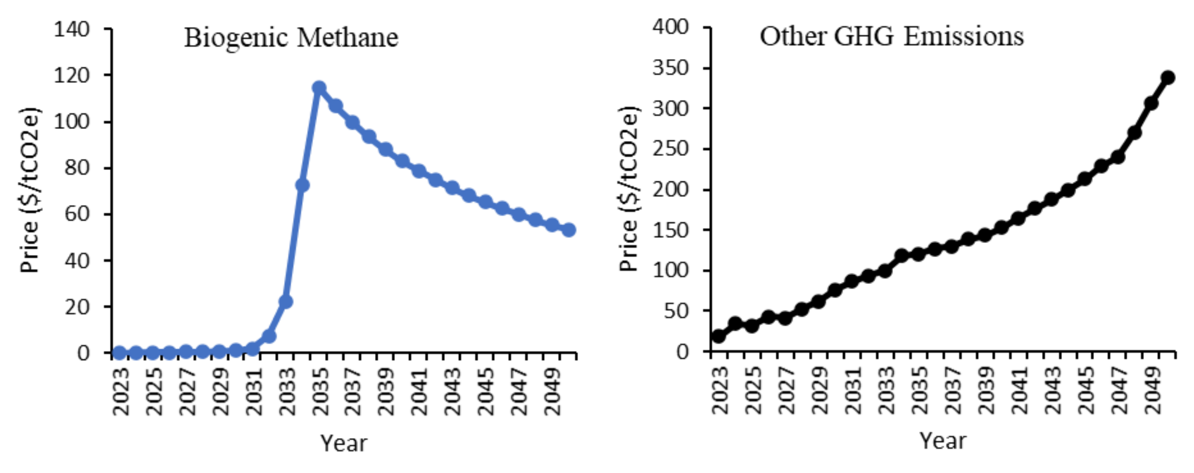

Figure 16. CO_2 prices in the policy scenario, $/$tCO_2e$.

In the baseline scenario, annual electricity generation increases from 47.3 TWh in 2020 to 61.0 TWh in 2050 (Figure 17). During this period, electricity generation from wind and solar increases from 2.3 to 22.5 TWh and generation from geothermal increases from 9.5 to 12.7 TWh; hydroelectric generation is constant at 24.2 TWh per year; gas electricity falls from 5.6 to 1.4 TWh; and, reflecting existing regulations, coal electricity is phased out by 2023. In the policy scenario, in 2050, relative to the baseline, gas electricity falls by 33.1% and wind and solar and geothermal (from conventional and with CCS sources) generation increases by 1.9% and 1.03% respectively (and there is no change in hydro generation).

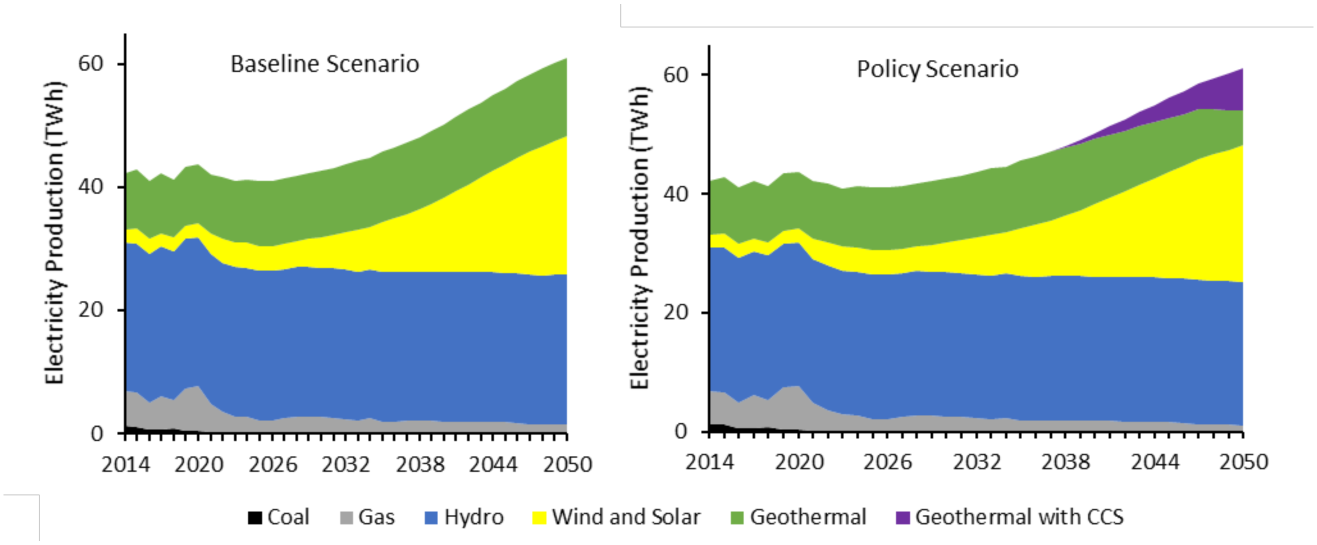

Figure 17. Electricity generation in the policy scenario, TWh per year.

GDP in the policy scenario is 0.15% lower than in the baseline scenario in 2035 and 0.34% lower in 2050 (Table 6). A key reason for the modest GDP impacts is that emissions are falling in the baseline scenario so the impact of the carbon prices on economic activity diminish over time. Proportional changes in consumer welfare, assessed using the equivalent variation in consumer income measure, are also modest (Table 6).

7. Conclusions

This paper set out Version 1.0 of the C-PLAN model, a global recursive dynamic CGE model for climate policy analysis tailored to New Zealand. Key features of the model include a detailed representation of agricultural sectors, methane-reducing technologies for dairy farming and beef and sheep farming, geothermal electricity with CCS, bioheat for industrial sectors, electric vehicles for commercial and household transport, and explicit representation of free, output-based permit allocations.

The C-PLAN model is built to help shape the CCC's advice on GHG emission targets and climate policies to the New Zealand Government. The model is open source and available from the CCC. The open-source code includes instructions for replicating the results for the scenarios used to inform the CCC's 2021 Draft Advice for Consultation and the results described in this paper. It is hoped that this modelling initiative assists transparency in climate policy development and helps build capacity for future evidence-based climate policy decisions.

Prominent CGE models for climate policy analysis have been development for several decades and continue to be extended. For example, the first version of the MIT-EPPA model (Yang et al., 1996) was developed in mid 1990s and is currently in its seventh major development cycle. The C-PLAN model has benefited from development in models such as the MIT-EPPA and GEM-E models, but there is significant scope for future research using the C-PLAN model. Possible developments include (1) modelling endogenous changes in land use for forestry and agricultural uses, (2) improving the representation of road transport options, (3) enhancing the linking between C-PLAN and electricity models to better represent the supply response of electricity generation technologies to carbon prices, (4) examining the sensitivity of the policy scenario to alternative baseline assumptions, (5) a more sophisticated representation of non-homothetic preferences, and (6) a more detailed regional aggregation and calibration to evaluate the impact of climate policies in specific countries/regions on New Zealand.

Acknowledgements

Development of the C-PLAN model was funded by the Climate Change Commission. The authors thank Sean Buchanan, Stuart Evans, Chris Holland, Anita King, Ralph Samuelson, Matthew Smith, and Paul

Young for assistance with calibrating the new technologies and developing the baseline and policy scenarios. Any errors are the authors' responsibility.

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Appendix A: Mapping from GTAP to C-PLAN sectors

Table A1. Mapping from GTAP to C-PLAN sectors.

C-PLAN sector	GTAP sector(s)
Dairy farming	Dairy farming (rmk)
Beef and sheep farming	Cattle, sheep, wool, goats, horses (ctl, wol)
Other animal products	Swine and poultry (oap)
Horticulture	Wheat, barley, corn, oats, fruits and vegetables (pdr, wht, gro, osd, c_b, pfb, ocr, v_f)
Forestry	Forestry, logging and related service activities (frs)
Fishing	Fishing, fish farming and related services (fsh)
Coal	Mining and agglomeration of hard coal, lignite and peat (col)
Oil	Extraction of crude oil (cru)
Gas	Extraction of natural gas (gas)
Coal electricity	Coal electricity (coalbl)
Gas electricity	Gas electricity (gasbl, gasp)
Hydro electricity	Hydro electricity (hydrobl, hydrop)
Wind electricity	Wind electricity (oilbl, oilp)
Solar electricity	Solar electricity (solarp)
Geothermal electricity	Geothermal electricity (otherbl, oilbl, oilp))
Petroleum products	Refining of crude oil, petroleum products (p_c)
Mining of metal ores	Mining of ores for iron, copper, gold etc. and gems (omn)
Dairy products	Processing of raw milk (mil)
Meat products	Processing of meat (cmt, omt)
Other food processing	Processing of fruits and vegetables, and beverages (vol, pcr, sgr, ofd, b_t)
Wood	Wood and wood products (lum)
Paper and paper products	Production of paper and paper products, publishing (ppp)
Textiles, clothing and footwear	Textiles, wearing apparel, leather products (tex, wap, lea)
Chemical, rubber & plastic products	Chemical, rubber and plastic products (crp)
Cement manufacturing	Cement, plaster, lime, gravel, concrete (nmn)
Non-ferrous metals	Production and casting of copper, aluminium, zinc, lead, gold, and silver (nfm)
Iron and steel	Iron and steel (i_s)
Other manufacturing	Fabricated metal products, transport equipment, electrical equipment and machinery (i_s, fmp, mvh, otn, ele, ome, omf)
Trade	Retail and wholesale trade, hotels and restaurants (trd)
Road transport	Road, rail, pipelines, auxiliary transport activities (otp)
Water transport	Water transport (wtp)
Air transport	Air transport (atp)
Construction	Building houses factories offices and roads (cns)
Services	Financial Intermediation, insurance, real estate (cmn, ofi, isr, obf, ros, osg, dew)

Appendix B: Mapping from New Zealand GHG Inventory classifications to C-PLAN sectors

Table B1. Mapping from New Zealand GHG Inventory classifications to C-PLAN sectors.

C-PLAN sector	New Zealand GHG Inventory classifications
Dairy farming (rmk)	Agriculture livestock enteric fermentation: dairy cattle methane emissions; and agriculture livestock manure management for dairy cattle.
Beef and sheep farming (b_s)	Agriculture enteric fermentation: sheep emissions and non-dairy cattle emissions; and agriculture manure management: non-dairy cattle emissions and sheep emissions.
Other animal products (oap)	Agriculture enteric fermentation: swine emissions and other livestock emissions; and agriculture manure management: swine emissions, other livestock emissions, and N20 and non-methane volatile organic compounds (NMVOC) emissions.
Horticulture (hor)	Agricultural soil and crop residues emissions, and field burning of agricultural residues emissions.
Fishing (fsh)	Energy fuel combustion fishing emissions.
Agriculture, forestry and fishing (rmk, b_s, oap, hor, frs, fsh)	Energy in other sectors: agriculture and forestry emissions; agricultural soils emissions (other than crop residues), agriculture liming emissions, and agriculture urea application emissions.
Coal mining (col)	Energy fugitive emissions from fuels: coal mining and handling.
Crude oil extraction (cru)	Energy fugitive emissions from fuels: oil and natural gas; and other emissions from energy production oil emissions.
Refined oil products (oil)	Energy fuel combustion: petroleum refining emissions.
Natural gas extraction and distribution (gas)	Energy fugitive emissions from fuels: oil and natural gas; and other emissions from energy production: natural gas emissions, and venting natural gas emissions.
Crude oil extraction and natural gas extraction and distribution (cru and gas)	Energy fugitive emissions from fuels: oil and natural gas; and other emissions from energy production: flaring oil and natural gas emissions, and venting oil and natural gas emissions.
Other mining (oxt)	Energy manufacturing industries and production: mining (excluding fuels) and quarrying emissions.
Coal, gas and geothermal electricity, and electricity transmission and distribution (ecoa, egas, eoth, tnd)	Energy fuel combustion from energy industries: public electricity and heat production.
Geothermal electricity (eoth)	Energy, oil, natural gas, and other emissions from energy production: geothermal emissions.
Chemical rubber and plastic products (crp)	Energy manufacturing industries and construction: chemical emissions; and industrial processes and product use: chemical industry emissions.
Non-metallic minerals (nmm)	Industrial processes and product use: mineral industry cement production emissions, mineral industry lime, and other process uses of carbonates production emissions.

C-PLAN sector	New Zealand GHG Inventory classifications
Non-ferrous metals (nfm)	Industrial processes and product use: metal industry aluminium production emissions, and metal industry lead production emissions; and energy manufacturing industries and construction: non-ferrous metals emissions.
Iron and steel (i_s)	Energy manufacturing industries and construction: iron and steel emissions; and industrial processes and product use: metal industry iron and steel production emissions.
Meat products, dairy processing, and other food products (mtp, mil and ofd)	Energy manufacturing industries and construction: food and beverages emissions.
Wood and paper products (w_p)	Energy manufacturing industries and construction: pulp paper and print emissions.
Other manufacturing (omf)	Industrial processes and product use: product uses as substitutes for ozone-depleting substances (ODS), other product manufacture and use, and non-energy products from fuels and solvent use emissions; and energy manufacturing industries and construction: textile and leather gaseous fuels emissions, textile and leather solid fuels emissions, and textile and leather liquid fuels emissions.
Fabricated metal products, wood and paper products, construction, and motor vehicles and parts (fmp, w_p, cns, and mvh)	Energy manufacturing industries and construction: non-metallic minerals emissions, other manufacturing of machinery emissions, and other emissions.
Accommodation and food services (afs and ser)	Waste emissions and energy: commercial/institutional emissions.
Road transport (rtp)	Energy in transport: road transport emissions without cars or motorcycles, railway emissions, and other transportation emissions.
Domestic water transport (wtp)	Energy in transport: domestic navigation emissions.
International bunkers water transport (wtp)	Energy in international bunkers: international navigation emissions.
Domestic air transport (atp)	Energy in transport: domestic aviation emissions.
International bunkers air transport (atp)	Energy in international bunkers: international aviation emissions.
Household transport (hht)	Residential energy and emissions; and energy in transport: road transport car emissions, and road transport motorcycle emissions.

Appendix C: Land use and forestry removals

Table C1. Land use (Mha) and forestry CO_2 removals ($MtCO_2$).

Year	Land use, Mha							Forestry removals, $MtCO_2$
	Dairy Farming	Beef & sheep farming	Other animal products	Horticulture	Forestry	New native forests*	Change in other uses*	
2014	1.746	8.463	0.250	0.269	1.815	0.000	1.592	12.297
2015	1.746	8.463	0.250	0.269	1.814	0.000	1.888	13.254
2016	1.752	8.165	0.250	0.265	1.814	0.001	2.050	13.156
2017	1.729	8.027	0.250	0.263	1.820	0.003	1.977	11.513
2018	1.755	8.081	0.250	0.249	1.822	0.004	2.137	9.628
2019	1.755	7.904	0.250	0.261	1.841	0.007	2.194	8.846
2020	1.747	7.833	0.250	0.262	1.866	0.015	2.191	7.352
2021	1.750	7.800	0.247	0.266	1.893	0.025	2.204	6.212
2022	1.755	7.744	0.248	0.266	1.921	0.035	2.256	5.756
2023	1.759	7.647	0.249	0.267	1.945	0.040	2.301	5.337
2024	1.763	7.568	0.249	0.268	1.968	0.043	2.348	5.394
2025	1.767	7.492	0.249	0.267	1.991	0.046	2.398	5.705
2026	1.771	7.413	0.249	0.267	2.015	0.048	2.433	6.432
2027	1.777	7.347	0.248	0.266	2.039	0.051	2.481	7.294
2028	1.781	7.271	0.246	0.265	2.064	0.054	2.521	8.188
2029	1.783	7.204	0.245	0.263	2.090	0.057	2.560	8.979
2030	1.787	7.134	0.244	0.262	2.117	0.060	2.600	9.583
2031	1.790	7.066	0.242	0.260	2.144	0.063	2.635	10.139
2032	1.792	6.997	0.242	0.260	2.172	0.066	2.671	10.632
2033	1.793	6.928	0.243	0.261	2.201	0.070	2.692	10.913
2034	1.795	6.872	0.243	0.261	2.231	0.073	2.721	11.258
2035	1.795	6.810	0.243	0.261	2.262	0.077	2.753	12.123
2036	1.796	6.742	0.244	0.262	2.293	0.080	2.786	13.050
2037	1.797	6.673	0.244	0.262	2.325	0.084	2.811	14.583
2038	1.798	6.609	0.244	0.263	2.359	0.087	2.836	15.589
2039	1.799	6.547	0.244	0.262	2.393	0.091	2.860	16.615
2040	1.799	6.484	0.244	0.263	2.427	0.095	2.885	17.598
2041	1.798	6.420	0.245	0.264	2.463	0.099	2.910	18.119
2042	1.797	6.357	0.245	0.264	2.499	0.103	2.937	18.450
2043	1.796	6.290	0.245	0.264	2.536	0.107	2.955	18.698
2044	1.794	6.231	0.246	0.264	2.574	0.111	2.977	18.950
2045	1.793	6.168	0.246	0.265	2.613	0.116	2.998	19.404
2046	1.791	6.106	0.246	0.265	2.652	0.120	3.019	19.941
2047	1.788	6.044	0.246	0.265	2.692	0.125	3.039	20.507
2048	1.785	5.981	0.247	0.266	2.733	0.129	3.059	21.067
2049	1.783	5.918	0.247	0.266	2.774	0.134	3.076	21.622
2050	1.782	5.855	0.247	0.266	2.816	0.138	3.101	22.188

Note: Native forest land and changes in land to other uses are not represented in the C-PLAN model.

Appendix D: Allocation of free emission permits

Table D1. Proportion of free emission permits per unit of output (at 2014 emission intensities).

Year	Biogenic methane ETS	Other GHGs ETS	
	Dairy, beef & sheep farming	High energy intensive sectors	Medium energy intensive sectors
2022	0.962	0.978	0.967
2023	0.953	0.967	0.950
2024	0.943	0.956	0.933
2025	0.933	0.944	0.917
2026	0.908	0.906	0.858
2027	0.884	0.867	0.800
2028	0.859	0.828	0.742
2029	0.835	0.789	0.683
2030	0.810	0.750	0.625
2031	0.786	0.711	0.567
2032	0.761	0.672	0.508
2033	0.737	0.633	0.450
2034	0.712	0.594	0.392
2035	0.687	0.556	0.333
2036	0.663	0.517	0.275
2037	0.638	0.478	0.217
2038	0.614	0.439	0.158
2039	0.589	0.400	0.100
2040	0.565	0.361	0.042
2041	0.540	0.322	0
2042	0.516	0.283	0
2043	0.491	0.244	0
2044	0.467	0.206	0
2045	0.442	0.167	0
2046	0.417	0.128	0
2047	0.393	0.089	0
2048	0.368	0.050	0
2049	0.344	0.011	0
2050	0.319	0	0

Supplementary material for the Climate PoLicy ANalysis (C-PLAN) Model, Version 1.0

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This document contains supplementary material for the documentation of Version 1.0 of the Climate PoLicy ANalysis (C-PLAN) model. This document has three sections. Section S1 outlines requirements for running the model. Section S2 explains how to run scenarios. The final section outlines the file structure used for the C-PLAN model.

S1. Requirements for running the C-PLAN model

To use the C-PLAN model, users should first obtain the model files from the New Zealand Climate Change Commission (CCC) and sign the licensing agreement under which the model is distributed. The CCC's website is https://www.climatecommission.govt.nz/. To run the model, users will need the following software and database licences:

- A licence for the General Algebraic Modeling System (GAMS) that includes licences for (1) the GAMS Base Module, (2) the Mathematical Programming System for General Equilibrium analysis (MPSGE) subsystem, and (3) the PATH solver. Information about GAMS licences is available at https://www.gams.com/.
- A licence for Version 10 of the Global Trade Analysis Project (GTAP) Database. If users have a licene for this database, the CCC will distribute a version of the model that includes the data file `cplan1.gdx` in the inputs directory. This file is an aggregation of the GTAP Database and is required to run the C-PLAN model. Licensing information for the GTAP Database is available at https://www.gtap.agecon.purdue.edu/databases/default.asp.

To work with and understand the C-PLAN model, users should have a sound understanding of advanced microeconomic theory, especially general equilibrium theory; and knowledge of the GAMS and MPSGE programming languages.

S2. Running scenarios

Scenarios are simulated in the C-PLAN model by running the control files in the `case` folder. For example, running `baseline.gms` will simulate the baseline scenario, and running `policy_TP1.gms` will simulate the policy scenario (also known as Transition Pathway 1) discussed in the paper. The baseline scenario must be simulated before running the policy scenarios.

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Results for each scenario, in GAMS Data Exchange (GDX) format, are sent to the `results` folder when the GAMS simulation for the scenario is complete. Table S1 provides a mapping from C-PLAN control files to scenarios used in the CCC's 2021 Draft Advice for Consultation.[1] Running the scenarios in the `case` directory will reproduce the results published by the CCC. The C-PLAN model files have been tested with GAMS Version 30.3.0.

Table S1. C-PLAN control files to reproduce results for CCC scenarios.

C-PLAN file	CCC scenario name
`baseline.gms`	Current Policy Reference
`policy_TP1.gms`	Transition Pathway 1 (TP1): More removals
`policy_TP2.gms`	Transition Pathway 2 (TP2): Methane technology
`policy_TP3.gms`	Transition Pathway 3: (TP3) Less removals
`policy_TP4.gms`	Transition Pathway 4 (TP4): Faster reductions

S3. C-PLAN file structure

This section outlines the file structure used by the C-PLAN model. It provides a file structure list with a brief description of each file used in a baseline run of the model. Salient GAMS commands used in running the C-PLAN model are described in Table S2. The file structure is shown as a tree diagram in Figure S1.

Table S2: Index for GAMs commands described below.

Command	Description
`INCLUDE`	A command used to include the context of another file at the position of the input stream.
`GDXIN`	A command used to load specified items from a GDX file (data file).
`CALL`	A command used to execute another program during an input stream.

The text below shows the files called when the `baseline.gms` is simulated. The text includes a brief description of each file called.

1. `INCLUDE: Inputs\load.gms`: Code to load the core sets, defining the database and the data file.
    1.1. `INCLUDE: Inputs\order_sets.gms`: a list of the model sectors defined as a set to control the ordering of sectors.
    1.2. `GDXIN: Inputs\%data%.gdx:` the core economic dataset for the model.
    1.3. `INCLUDE: Inputs\sets.gms:` code defining (most) sets used in the model.

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[1] The results published by the CCC are available at https://www.climatecommission.govt.nz/get-involved/sharing-our-thinking/data-and-modelling/. They can be accessed by selecting from the side menu 'Macroeconomic modelling results and dataset' and then clicking on 'C-PLAN results dataset for 2021 draft advice.xlsx'.

  1.4. `INCLUDE: Inputs\parameters.gms`: code defining most of the parameters used by the model.
  1.5. `INCLUDE: Inputs\gtap10data.gms`: code to read the GTAP 10 dataset. This file defines the relevant parameters to read in the GTAP 10 data.
    1.5.1. `GDXIN: Inputs\%data%.gdx`: as described above.
    1.5.2. `INCLUDE: Inputs\disagg.gms`: code to disaggregate existing sectors.
  1.6. `INCLUDE: Inputs\calibrate\co2.gms`: code to calibrate CO_2 emissions in the model.
    1.6.1. `GDXIN: Inputs\calibrate\co2.gdx`: data for CO2 emissions from the combustion of fossil fuels.
  1.7. `INCLUDE: Inputs\oghg.gms`: code to assign other greenhouse gases in the model.
    1.7.1. `GDXIN: Inputs\calibrate\nonco2_nz.gdx`: data for other greenhouse gas emissions in New Zealand (process CO2 emissions, CH4 emissions, N2O emissions and F-gas emissions).
    1.7.2. `GDXIN: Inputs\calibrate\nonco2_world.gdx`: data for other greenhouse gas emissions in the Rest of the World.
  1.8. `INCLUDE: Inputs\elasticities.gms`: code to assign elasticities of substitution in the model.
  1.9. `INCLUDE: Inputs\calibrate\hht.gms`: code to breakout own-supplied transport from household consumption.
2. `INCLUDE: Inputs\ref_inputs.gms`: code to define reference inputs for New Zealand and the Rest of the World.
  2.1. `CALL: Inputs\calibrate\baseline_inputs.xlsx, worksheet: gams_econ (baseline_econ.gdx)`: baseline economic data for New Zealand.
  2.2. `CALL: Inputs\calibrate\baseline_inputs.xlsx, worksheet: gams_elec (baseline_elec.gdx)`: baseline electricity data for New Zealand.
  2.3. `CALL: Inputs\calibrate\baseline_inputs.xlsx, worksheet: gams_ev (baseline_ev.gdx)`: baseline data for electric vehicles in New Zealand.
  2.4. `CALL: Inputs\calibrate\baseline_inputs.xlsx, worksheet: gams_land (baseline_land.gdx)`: baseline land use and forestry removals of CO_2 data for New Zealand.
  2.5. `CALL: Inputs\calibrate\baseline_inputs_row.xlsx, worksheet: gams_econ (baseline_econ_row.gdx)`: baseline economic data for the Rest of World.

2.6. `CALL: Inputs\calibrate\baseline_inputs_row.xlsx, worksheet: gams_elec (baseline_elec_row.gdx):` baseline electricity data for the Rest of the World.

2.7. `CALL: Inputs\calibrate\co2prices_base.xlsx, worksheet: gams_prices (base_co2price.gdx):` baseline carbon prices in New Zealand.

2.8. `CALL: Inputs\calibrate\co2prices_base.xlsx, worksheet: gams_allocate (base_allocate.gdx):` baseline output-based emissions permit allocation rates in New Zealand.

2.9. `CALL: Inputs\calibrate\policy_inputs.xlsx, worksheet: gams_ghg (policy_ghg.gdx):` Emissions caps for New Zealand in policy scenarios.

2.10. `CALL: Inputs\calibrate\policy_inputs.xlsx, worksheet: gams_land (policy_land.gdx):` land use and forestry removals of CO_2 in New Zealand in policy scenarios.

2.11. `CALL: Inputs\calibrate\policy_inputs.xlsx, worksheet: gams_allocate (policy_allocate.gdx):` output-based emissions permit allocation rates in New Zealand in policy scenarios.

2.12. `CALL: Inputs\calibrate\ch4_vaccine.xlsx, worksheet: gams (ch4_vaccine.gdx):` methane vaccine efficiency and deployment rates in policy scenarios.

2.13. `GDXIN: Inputs\calibrate\baseline_econ.gdx:` as described above.

2.14. `GDXIN: Inputs\calibrate\baseline_elec.gdx:` as described above.

2.15. `GDXIN: Inputs\calibrate\baseline_ev.gdx:` as described above.

2.16. `GDXIN: Inputs\calibrate\baseline_land.gdx:` as described above.

2.17. `GDXIN: Inputs\calibrate\baseline_econ_row.gdx:` as described above.

2.18. `GDXIN: Inputs\calibrate\baseline_elec_row.gdx:` as described above.

2.19. `GDXIN: Inputs\calibrate\base_co2price.gdx:` as described above.

2.20. `GDXIN: Inputs\calibrate\base_allocate.gdx:` as described above.

2.21. `GDXIN: Inputs\calibrate\policy_ghg.gdx:` as described above.

2.22. `GDXIN: Inputs\calibrate\policy_land.gdx:` as described above.

2.23. `GDXIN: Inputs\calibrate\policy_allocate.gdx:` as described above.

2.24. `GDXIN: Inputs\calibrate\ch4_vaccine.gdx:` as described above.

2.25. `INCLUDE: Inputs\ref_calibrate.gms:` code to use the data described above, from `ref_inputs.gms`, to calculate inputs for the baseline scenario.

2.26. `INCLUDE: Inputs\luc_ref.gms:` code for land use and land use change in the baseline scenario.

2.27. `INCLUDE: Inputs\new_tech\new_technologies.gms:` code for include files for new technologies.

  2.27.1. `INCLUDE: Inputs\new_tech\nt_rtp1.gms:` code to add electric vehicles for commercial transportation.

  2.27.2. `INCLUDE: Inputs\new_tech\nt_hht1.gms:` code to add electric vehicles for own-supplied household transportation.

  2.27.3. `INCLUDE: Inputs\new_tech\nt_bh.gms:` code to add bioheat for specified sectors.

  2.27.4. `INCLUDE: Inputs\new_tech\nt_eh.gms:` code to add electrification of heat for specified sectors.

  2.27.5. `INCLUDE: Inputs\new_tech\nt_rmk1.gms:` code to specify production of raw milk with reduced methane emissions.

  2.27.6. `INCLUDE: Inputs\new_tech\nt_b_s1.gms:` code to specify production of beef and sheep with reduced methane emissions.

  2.27.7. `INCLUDE: Inputs\new_tech\nt_eoth_ccs.gms:` code to add geothermal electricity with CCS.

3. `INCLUDE: Inputs\policies.gms:` code for to turn off policy flags.
4. `INCLUDE: Inputs\calibrate\ref_policies.gms:` code for climate policies imposed in the reference scenario.
5. `INCLUDE: Inputs\build.gms:` code to run the model and store results.

5.1. `INCLUDE: Inputs\initial_values.gms:` code for initial values for baseline inputs and policy flags. This includes the installation of initial values to replicate the benchmark (in the first period only).

5.2. `INCLUDE: Inputs\model.gms:` code to specify the core computable general equilibrium model using the Mathematical Programming System for General Equilibrium (MPSGE)analysis.

5.3. `INCLUDE: Inputs\loop.gms:` code for the loop file to solve the model for each period and update certain parameters.

5.4. `INCLUDE: Inputs\refstore.gms:` code to store reference values for use in policy simulations.

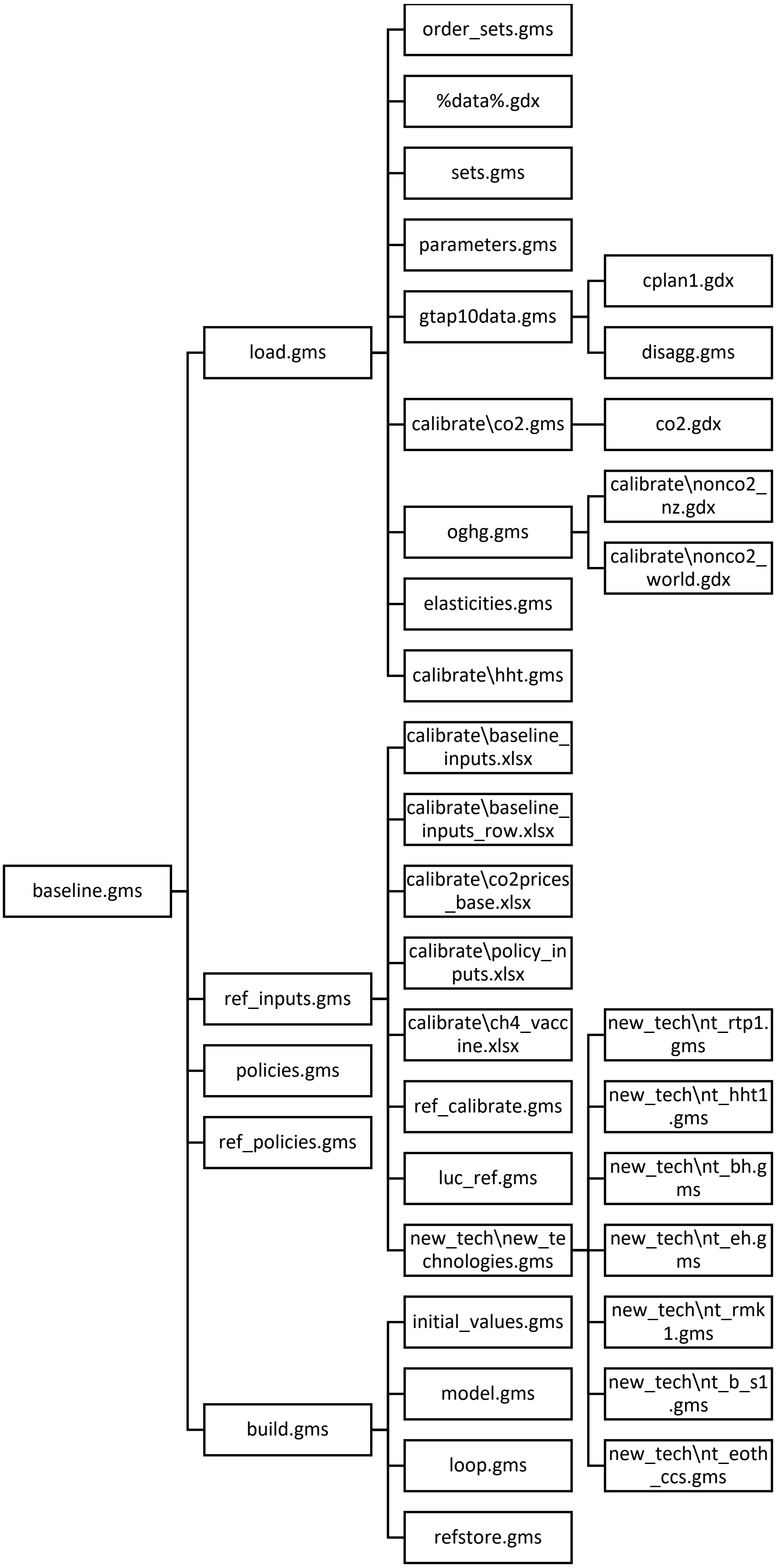

Figure S1. C-PLAN file structure as a tree diagram.