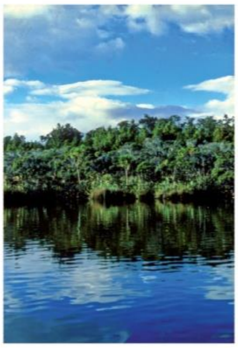

The Climate Mitigation, Adaptation and Trade in Dynamic General Equilibrium (CliMAT-DGE) Model

Technical Document

Landcare Research
Manaaki Whenua

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Contents

1 Introduction

Assessing the impacts of national and regional-level environmental policies on economic output and welfare often requires a comprehensive model that leads to meaningful costs estimates, especially under differing technological assumptions Policy makers and researchers require reliable estimates of the responses of the New Zealand and global economy to policies addressed to mitigate or cope to changing climatic conditions. The model should provide a level of regional disaggregation sufficient to represent countries and regional blocs, as well as explicit representation of relevant economic sectors. Computable General Equilibrium (CGE) models are typically employed for this type of analysis, as they provide a suitable framework to represent national-level economies and the complex interaction across sectors. The main virtue of the CGE approach is its micro-consistent representation of price-dependent market interactions (Böhringer et al. 2003).

The Climate Mitigation, Adaptation and Trade in Dynamic General Equilibrium (CliMAT-DGE) model, developed by Landcare Research, is a top-down dynamic, multi-sectoral and multiregional CGE model that describes the global economy and generation of greenhouse gas (GHG) emissions from energy and non-energy sectors. CliMAT-DGE represents a global dynamic economic model with a strong focus on New Zealand as a distinct region. Other global CGE models tend to aggregate New Zealand together with Australia (e.g. Babiker et al 2008) or Oceania (e.g. Golub et al. 2012).

CliMAT-DGE is based on the dynamic version of the MIT-EPPA model (Babiker et al. 2008, Paltsev et al. 2005). Though there are important differences in the modelling approaches which are described in this report.

This report documents the structure of CliMAT-DGE. Section 2 describes the production and consumption sectors, dynamic process, closure conditions, and aspects related to technological change, international trade, GHG, and GDP accounting. Section 3, which presents baseline calibration and comparisons with other CGE models, serves as a form of validity for the model’s output. Section 4 presents an illustrative policy scenario for reducing GHG emissions. Sections 5 and 6 discuss model extensions and future research.

2 The CliMAT-DGE Model

A CGE model represents the circular flow of goods and services in the economy (Fig. 1). The consumer sectors (households) supply factor inputs (labour, capital, land and other natural resources) to the producing sectors of the economy. Producers provide goods and services, given the technology to transform labour and capital into output. Households receive payments (income) in the form of wages and rent for the services provided to producers. These payments are then used to pay for goods and services (expenditures). This same representation holds for all regions where interactions among them occur via trade flows.

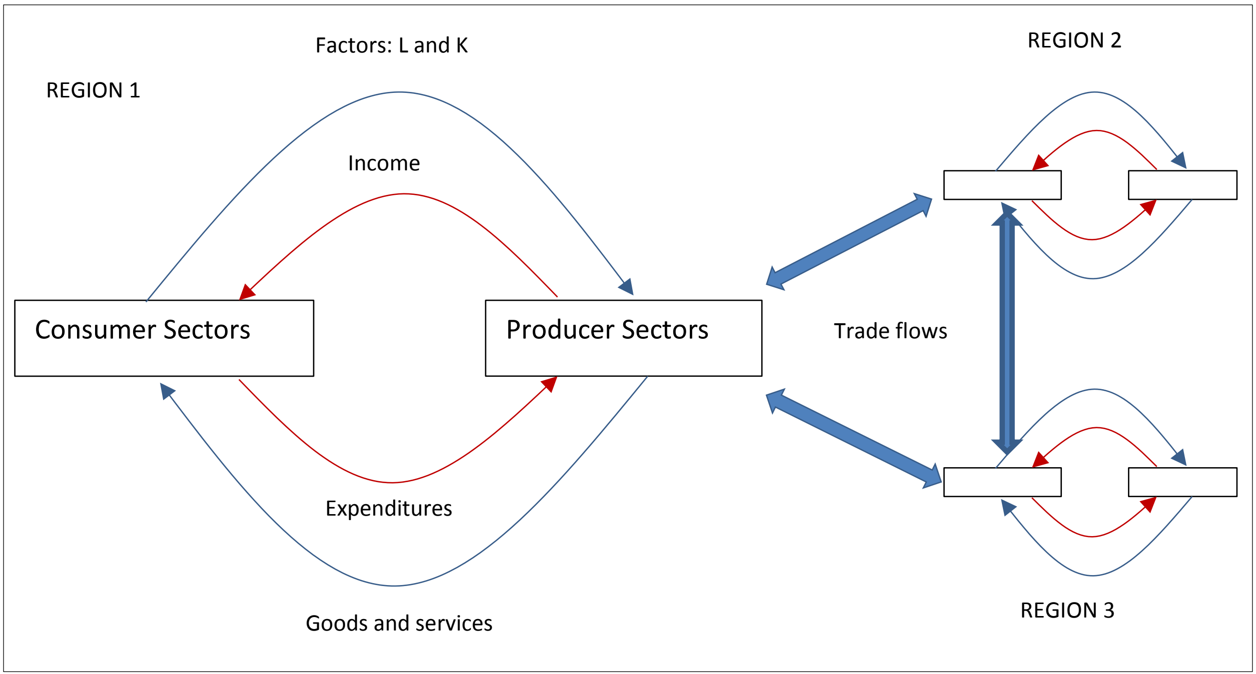

Figure 1: Representation of a General Equilibrium Model, adapted from Paltsev et al. (2005).

Consumers and producers behave rationally; that is, each agent solves her own optimisation problem and takes prices as given. Thus, prices provide information about the decision environment to reach equilibrium. Equilibrium is defined as the allocation of resources so that the actions of all agents are mutually consistent and can be executed simultaneously, for example, demand equals supply on all markets (Shoven & Whalley 1994; Dellink 2005). Supply of land, natural resources, and labour are assumed to be fixed in each period, whereas capital stocks accumulate through new investment and are reduced by depreciation as they are used over time. Capital can flow freely among regions to equalise the real rates of returns.

CliMAT-DGE uses the Global Trade Analysis Project (GTAP) dataset that accounts for 129 regions and 57 economic sectors.[1] The model was initially built on GTAP 7 but more recently updated to use GTAP 8. The base year of the benchmark projection is 2007 (the latest year included in GTAP); the model then develops a benchmark projection of the economic variables and GHG emissions (from human activities), and simulates scenarios to evaluate the impacts of mitigation policies. Based on long-run conditions and constraints on physical resources that restrict the opportunity set of agents, the model predicts the behaviour of the economy, energy use, and emissions by region and sector (Fæhn et al. 2013). CliMAT-DGE is coded using the Mathematical Programming System for General Equilibrium (MPSGE) package in GAMS (Rutherford 1999)

Sample aggregated sectors in CliMAT-DGE are listed in Table 1. Sectors related to land use can be defined covering any combinations of the GTAP agricultural and forestry sectors. Coal, oil, gas, petroleum refining, renewable electricity, and fossil electricity sectors are defined as separate sectors. Renewable and fossil electricity generation sectors are

[1] https://www.gtap.agecon.purdue.edu/databases/v8/

disaggregated from the single electricity GTAP sector. For this we allocate fossil fuel inputs to the fossil electricity sector, where the shares are estimated so that they equalize the market shares from IEA generation data (see the Appendix for further details).

Other sectors can be created from combinations of the remaining GTAP 8.1 sectors. More details on the sector aggregation of GTAP and CliMAT-DGE are in Appendix 2.

Table 1: Example of Aggregated Sectors in CliMAT-DGE

Primary Production Sectors	**Abbreviation**
Grains including rice	GRA
Other crops	CRO
Oil seeds and sugar cane	OSC
Plant based fibres	PFB
Bovine cattle, sheep and goats, horses	CTL
Raw milk	RMK
Forestry/Logs	FST/LGS
Secondary Energy Sectors	
Coal	COA
Oil	OIL
Gas	GAS
Petroleum, coal products	P_C
Fossil electricity	EFS
Carbon-free electricity	ECF
Manufacturing and Value-Added Sectors	
Food products	FOO
Harvested wood products	HWP
Energy-intensive manufacturing and	EMT
Non-energy-intensive manufacturing	NSV
Transport	TPT

Two or more regions can be defined covering any combination of the countries and aggregate regions in GTAP 8.1. A non-exhaustive list of sample regions where the model has proved to run successfully is presented in Table 2. Not all GTAP countries can be represented as a standalone region for two reasons. First, CliMAT-DGE uses projections from CEPII (Fouré et al. 2010) to construct the baseline balanced growth path (BGP); however, data are not available for some countries or regions listed in GTAP, which can inhibit model initialization. Second, methods that were used to construct CliMAT-DGE's energy market inhibit certain countries from being modelled as individual regions. Future development of CliMAT-DGE may improve the ability to model a more diverse set of countries/regions and aggregated sectors assumption.

Table 2: Examples of Aggregated CliMAT-DGE countries and regions

Individual Countries		
Australia	Great Britain	Mexico
Canada	Indonesia	Netherlands
China	Italy	Norway
Denmark	Ireland	New Zealand
Germany	Malaysia	USA

Regions	**Notes**
OECD	OECD + Singapore, Chile, Turkey, and Korea
MERCOSUR	Brazil, Argentina, Uruguay, Paraguay
EU28	European Union
CAFSU	Kazakhstan , Kyrgyzstan, Armenia, Azerbaijan, Georgia, Rest of Former Soviet Union
North America	USA, Canada and Mexico
ROW	Rest Of the World

CliMAT-DGE was designed with the flexibility to represent different aggregations of countries or regions, sectors, horizon lengths, and assumptions on economic growth, technological change, taxes, and subsidies. However, because of computation limitations the model typically solves with configurations of up to eight regions, 20 sectors, and time horizons of less than 100 years. Though the research interest may be in the medium-run (i.e. 30–50 years), simulations usually employ longer time horizons to minimise the impact of terminal conditions on the results.[2]

GHG emissions are expressed in carbon dioxide equivalents (CO_2e) based on their 100-year global warming potential (GWP). The GTAP 8.1 database initially listed the non-CO_2 GHGs – methane (CH4), nitrous oxide (N2O), and fluorinated gases (FGAS) – based on GWPs from the IPCC third assessment report (IPCC 2001). But in CliMAT-DGE the GWPs come from the fourth assessment report (IPCC 2007).[3]

2.1 Equilibrium Conditions

The CGE model is formulated as a mixed complementarity problem (MCP) (Mathiesen, 1985; Rutherford, 1999).In this formulation, an equilibrium is described by a set of prices, activity levels and incomes. These variables are paired respectively with equations that describe clearance of markets, zero excess profits of firms and income balance for households. These equations are derived under standard neoclassical assumptions of perfectly competitive markets, profit-maximising firms and utility-maximising households and an absence of scale economies.

[2] Sensitivity analysis has established that terminal conditions have minimal impact on estimates such as regional GDP and GHG emissions 10 years or more before the final period of model simulations.

[3] The AR4 GWP for CH4 is 25 and for N_2O is 298. The FGAS GWPs vary by gas.

1. **Zero Profit:** The zero profit condition requires that, in equilibrium, all opportunities to make profits must be exhausted so that profits are equal to zero for all sectors that produce a positive quantity of output. If profits are negative for any sector, then there should be no production at all. The intuition here is that if any firm is capable of reaping profits, then new firms will enter the market and compete. Thus, supply will increase and lead to price reductions. This lower price will then decrease the profits for both the old and the new firms. This process continues until the excess profits equal zero

2. **Market Clearing:** The market clearing condition means that a positive price exists for any good with supply less than or equal to demand. If a good has an excess supply, then its price should be zero. Specifically, for the primary production factors, demand of labour and capital must be equal to total endowments. For produced goods, supply is equal to the amount produced plus imports. Demand is made up of demand by other firms (intermediate deliveries) and demand by households plus exports

3. **Income-expenditure Balance:** The income-expenditure balance condition restricts the present value of current and future expenditure of each representative household to be equal to or less than the present value of the household's endowments of labour and other factors of production, plus the present value of indirect taxes less subsidies[4]. (see Fig. 1). As households always prefer more consumption to less, income is always completely exhausted by present consumption and saving for future consumption. Section 2.4 describes the forward-looking nature of the model and the possibility of running temporary current account imbalances.

2.2 Production

Firms are grouped together into production sectors. Producers operate under full competition and maximise profits, subject to their production technology, for given prices. As full competition and constant returns to scale are assumed, no excess profits can be reaped and the profit-maximization problem turns into a cost-minimization (Dellink 2005).

The way that agents in the model adjust to policy shocks are represented as elasticities of substitution (Dellink 2005). These elasticities of substitution are key parameters in production and utility functions as they summarize the technical ability or willingness to substitute inputs. For example, if a GHG restriction (e.g. a cap on regional emissions) increases the price of carbon-based inputs (e.g. fossil fuels), then, given the shares of energy on production, carbon content, and technology, production costs may rise. The extent of the cost increases will depend on the relative flexibility for an industry to substitute fossil fuels for other less GHG-intensive energy sources. Similarly, consumers' propensity to shift away from fossil fuels and to substitute for other less GHG-intensive goods is represented by the elasticity of substitution. Table 3 shows the values of substitution elasticities in all the production sectors. Some of these values were adapted from Paltsev et al. (2005)**.**

[4] CliMAT-DGE does not include a distinct government sector, so tax revenues accrue directly to the representative household.

All production sectors are modelled using nested Constant Elasticity of Substitution (CES) production functions. The nested-CES functions capture the potential substitution between production technologies. In order to link the production or consumption of a commodity with GHG emissions, the MPSGE code of the nesting structures includes the interaction between GHGs and sector commodities.

Figure 2 shows the nesting structure for the production sectors. For agriculture, land enters at the very top of the tree, where it is directly substitutable with a resource intensive bundle (energy-materials and value-added). This structure is more flexible than the one in Paltsev et al. (2005), for example, as agricultural intensification usually involves increased capital inputs along with increased use of fertilisers, pesticides, irrigation, sheds, etc., then the elasticity of substitution between land and other inputs in CliMAT-DGE is lower than in the EPPA model ($\sigma_{erva} = 0.35$ instead of $\sigma_{erva} = 0.7$) (Paltsev et al. 2005). In addition, land productivity can be differentiated by agro-ecological zone (AEZ),[5] and GHG mitigation occurs through the substitution of labour, capital, land-use, and energy for each of the agricultural terminal nodes.

In the case of the manufacturing and service sectors, there is a common nest structure for food products, harvested wood products, energy-intensive manufacturing, non-energy-intensive manufacturing, and transport. As in McKibbin and Wilcoxen (1999), we allow limited substitutability between the capital-labour-energy (KLE) bundle and the intermediate inputs (non-energy) bundle. This differs from EPPA (Paltsev et al. 2005), where these intermediate bundles are combined in fixed proportions.

Nearly all of the Armington trade elasticities are the same as EPPA, with the key exception being the value specified for thenon-energy sector domestic-import trade elasticities. In this case, EPPA varies the elasticity value between 2.0 and 3.0 depending on the sector while CliMAT-DGE simply applies the average value of 2.5 to all sectors except electricity. In both the case of EPPA and CliMAT-DGE the domestic-imports Armington trade elasticity value for electricity is 0.3.

[5] Note that this is typically aggregated to a single zone per country for computational ease.

Table 3: Reference values of production sector substitution elasticities

	Description	*Value*	*Notes*
	Energy Substitution Elasticities		
σ_{klem}	Capital-labour-energy and intermediates	0.25	
σ_{eva}	Energy-value Added	0.45	Manufacturing and Value-added
σ_{int}	Intermediate inputs	0.25	All sectors
σ_{enoe}	Electricity-Fuels aggregate	0.3 ; t = 1 0.65; t = 2 0.8; t = 3 1; t > 3	All sectors
		0.4 + 0.2$log(t)$	Non-energy intensive manufacturing
σ_{en}	Among fuels	0.5	All sectors
σ_{coa}	Coal	0	All sectors
σ_{gas}	Gas	0	All sectors
σ_{oil}	Oil	0	All sectors
σ_{PC}	Petroleum commodities, oil refining	0	All sectors
σ_{fuoco}	Fuels other than crude oil	0	Oil refining sector
σ_{s}	KLE-Intermediate inputs bundle	0	Oil refining sector
σ_{cog}	Coal-oil and gas	1	Electricity from fossil fuels
σ_{co}	Coal and oil	1	Electricity from fossil fuels
	Other Production Elasticities		
σ_{va}	Labour-Capital	1	All sectors
σ_{rva}	Land and inputs		Renewable energy
σ_{erva}	Energy-materials-land and value added	0.35	Agriculture
σ_{er}	Energy-materials and land	0.7	Agriculture
σ_{ae}	Energy and materials	0.3	Agriculture
σ_{GR}	Fuel-specific resources and other inputs	0.2 + 0.15$log(t)$	Coal, oil, gas and carbon-free electricity
σ_{c}	Intermediate inputs	0	Coal, oil, gas and carbon-free electricity
σ_{cons}	Energy and non-energy	0.6 + 0.1$log(t)$	Consumption
$\sigma_{c_{fuel}}$	Among fuels and GHG	0	Manufacturing and Value-added Agriculture Coal, oil, gas Consumption
$\sigma_{c_{nenr}}$	Non-energy sectors	0	All sectors
σ_{z}	Land	0	Agriculture
	Armington Trade Elasticities		
σ_{DM}	Domestic-imports	2.5	All sectors
		0.3	Electricity
σ_{MM}	Among imports from different regions	6	Oil
		5	Non-energy sectors
		5	Coal, gas and oil refining
		0.5	Electricity

For the primary Energy Sectors (Coal, Oil, and Gas), the nesting structure includes at the top nest a fuel specific resource, with σ_{GR} controlling the short run supply (i.e. the rate of production from the resource) (Paltsev et al. 2005).

The oil refining sector (P_C) has a Leontieff structure between the Capital-Labour-Energy bundle and the intermediate inputs bundle. Similar to the EPPA model, oil enters as an intermediate input and not as part of the energy nest. P_C goods are separated from a sub-nest of coal and gas. Coal and gas interact with $\sigma_{co} = 1$ to create a composite good that interacts with P_C with $\sigma_{en} = 0.5$. This structure reflects that P_C goods are mainly used for transport whereas the other fuels are mainly used for industrial heat or power.

The electricity sector consists of fossil-fuel sources and renewable sources (i.e. electricity generated from hydro, geothermal, nuclear, sola,r and wind generation), referred to in CliMAT-DGE as the carbon-free electricity sector (ECF). For the fossil electricity sector, all fossil fuels were combined in a single nest ($\sigma_{en} = 1$), simplifying the sub-nesting in EPPA. Since relatively small amounts of Oil and P_C are used in electricity generation, this is a simplification that should be relatively innocuous.

All types of electricity are perfect substitutes, that is, the model does not allow any user to choose what electricity should be consumed. Demand for carbon-free electricity is determined through the zero-profit condition for each generation technology with output all sold at the same market price, and the market clearing equation for electricity. The former is complementary to generation output levels while the latter is complementary to the electricity price. That is, generation adjusts for each technology so that there are zero profits, while prices adjust to clear the market.

More details on how the electricity sector is formulated are provided in Appendix 3.

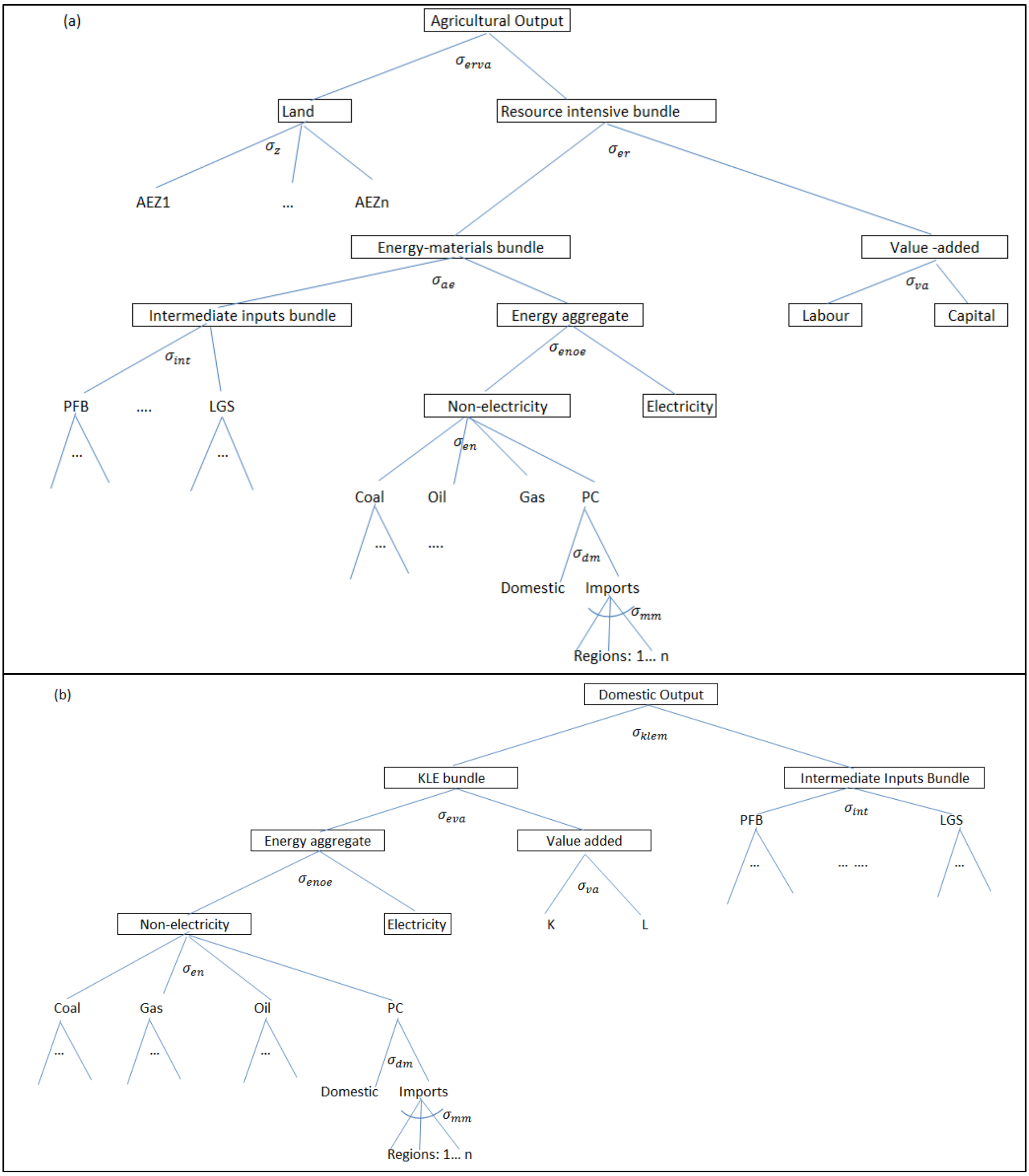

Figure 2: Structure Production Sectors: (a) Agriculture, (b) Manufacturing and Value-Added. Terminal nests with … indicate the same aggregation structure for imported goods as shown for the P_C sector. The Intermediate Inputs '…' represent the rest of primary production, manufacturing and value-added sectors listed in Table 1.

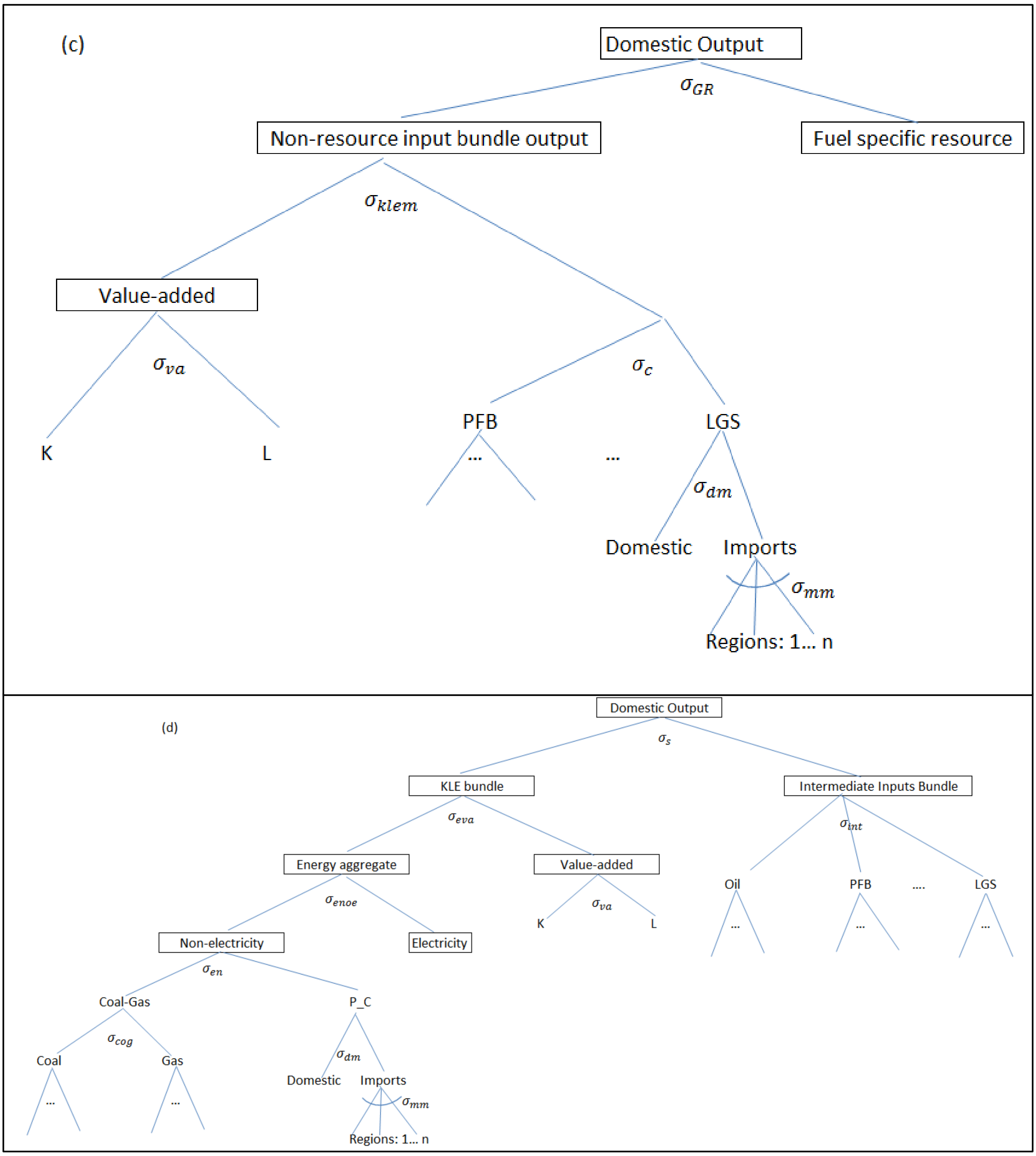

Figure 2 (cont.): Structure of Production Sectors: (c) Primary Energy Sectors (Coal, Oil and Gas), (d) Oil Refining Sector. Terminal nests with … indicate the same aggregation structure for imported goods as shown for the P_C sector. The Intermediate Inputs '…' represent the rest of primary production, manufacturing and value-added sectors listed in Table 1.

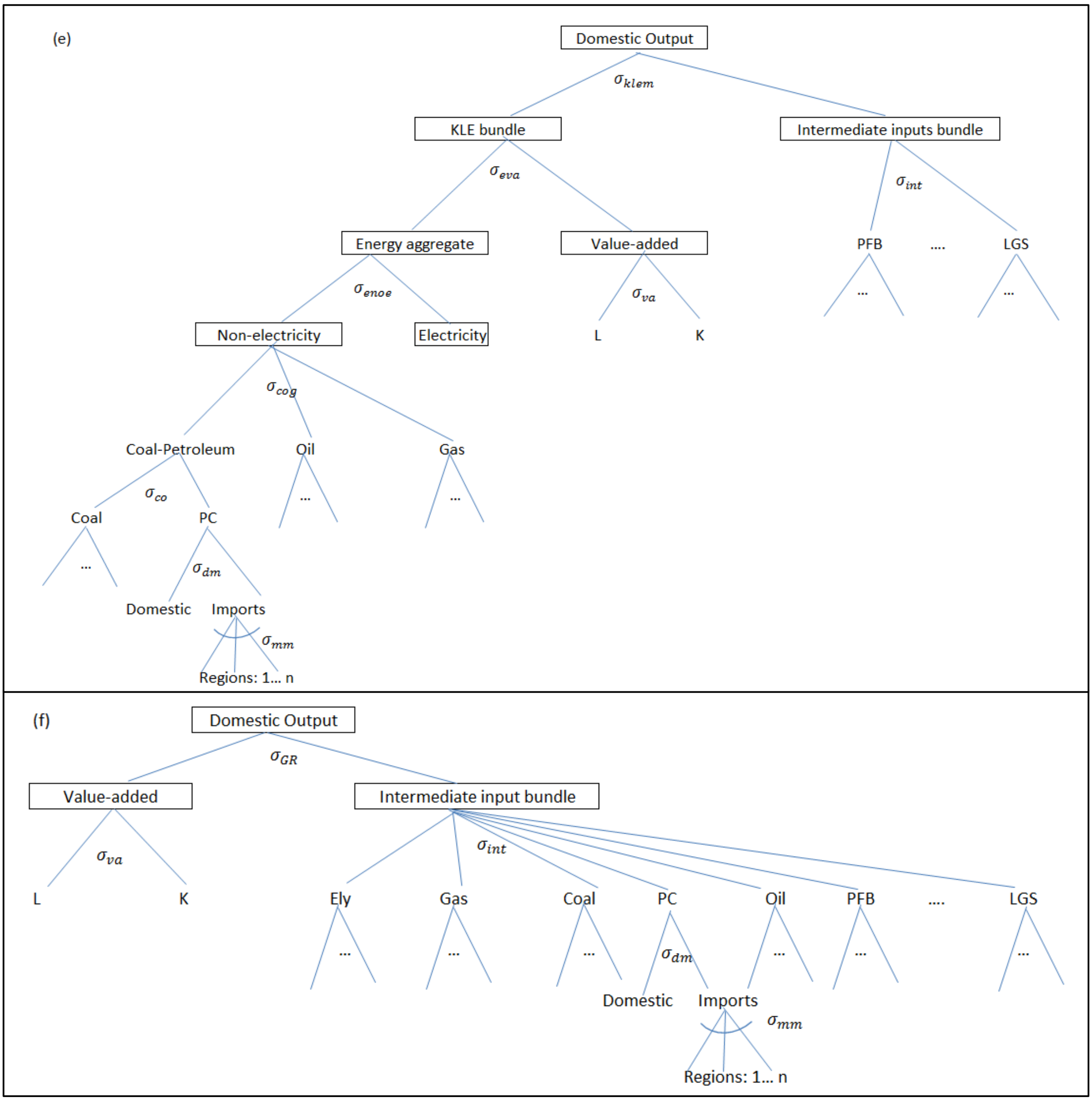

Figure 2 (cont.): Structure of Production Sectors: (e) Electricity from Fossil Fuels Sector, (f) Electricity from Renewables. Terminal nests with … indicate the same aggregation structure for imported goods as shown for the P_C sector. The Intermediate Inputs '…' represent the rest of primary production, manufacturing and value-added sectors listed in Table 1.

2.2.1 Backstop Technologies

CliMAT-DGE includes backstop technologies such as biomass and conventional electricity with carbon capture and storage and biofuels (Table 4). These technologies enter in the model solution if and when they become economically competitive with existing technologies. Similar to Paltsev et al. (2005), competitiveness of new technologies depends on the endogenously determined prices for all inputs, as those prices depend on depletion of resources, climate policy, and other forces driving economic growth such as the savings, investment, and the productivity of labour. The markups (i.e. relative increase) over conventional technology cost at benchmark prices are also in Table 4. The production structure of backstop technologies is in Figure 3.

The benchmark output for biofuels is equal to the output of petroleum activities, while the benchmark output for BEC and BFU is equal to electricity from fossil-fuel sources. Factor use is the product between markup factors, benchmark output and the factor shares for advanced technologies. For BEC and BFU, the share of capital and labour is 0.6 and 0.2, respectively. For CEC, the share of capital and labour is 0.66 and 0.22, respectively. There is no share for land or other resources.

Table 4: Backstop technologies in CliMAT-DGE

Technology	Description	Markups
BEC	Bioelectricity with carbon capture and storage	1.5 (McFarland et al. 2004)
CEC	Coal-fired electricity with carbon capture and storage	1. 5 (IPCC WGIII Annex III Report)
BFU	Biofuels processing	1.2 (By assumption)

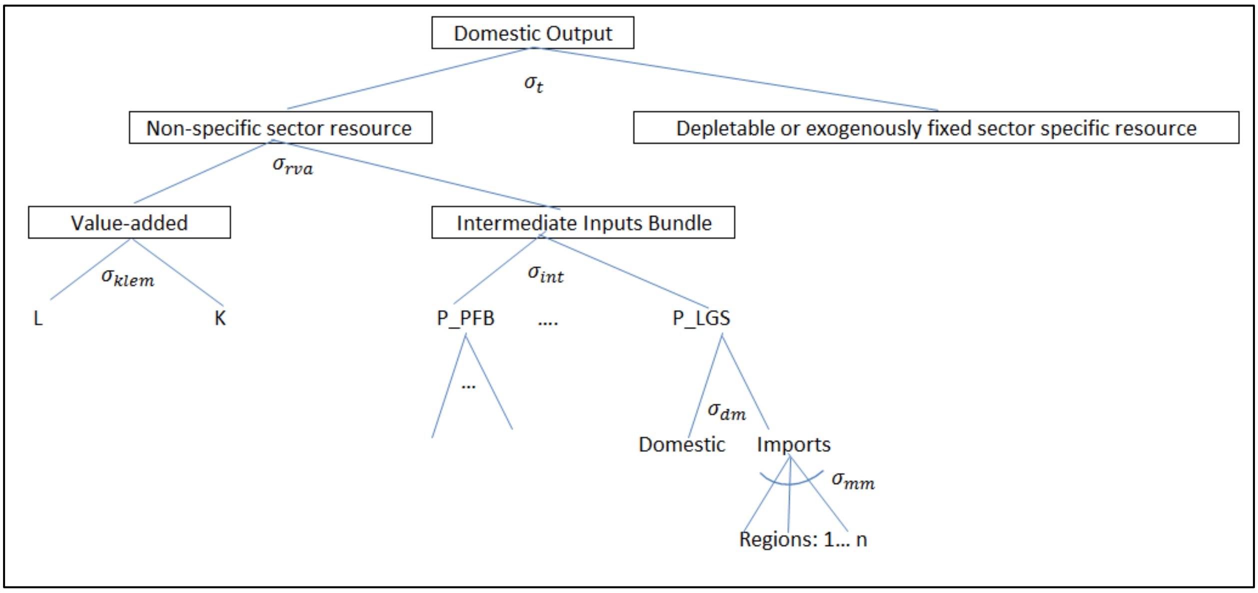

Figure 3: Structure of Backstop Technologies Sector. Terminal nests with … indicate the same aggregation structure for imported goods as shown for the LGS sector. For the Intermediate Inputs bundle '….' represent the rest of primary production, manufacturing and value-added sectors in Table 1.

2.3 Consumption

Households are aggregated into one representative agent. The representative agent is a macroeconomic account which describes the sources of aggregate income from factor incomes (endowments of capital and labour) and indirect taxes net of subsidies, and describes the allocation to aggregate domestic spending by private households and government (Burfisher 2011). For given prices and initial endowments, households maximise their utility subject to a budget constraint. Differences between income and expenditures are reflected in the budget deficit. The government is modelled as a passive entity that collects taxes and distributes the full value of the proceeds to the households, that is, CliMAT-DGE does not include an explicit government sector.[6] Thus, government and private consumption are not distinguished. The main welfare implication is that consumption levels in the model output are a composite of private and government consumption and it is implicitly assumed that preferences over private and public consumption goods are identical. Due to data restrictions, CliMAT-DGE does not the same structure at EPPA to model representative households EPPA, such as including disaggregating household transportation into purchased and own-supplied transport[7]. Future work could extend the level of household representation in CliMAT-DGE (e.g., skilled versus unskilled labour), provided globally-consistent data are available.

Similar to the production sectors, consumption is represented by a nested CES structure (Fig. 4). The elasticities of substitution possibilities between energy and non-energy goods are in Table 5. For the energy sector, energy may come from fossil fuels that may have domestic or foreign origin. For the non-energy sectors, there are limited substitution possibilities ($\sigma_{int} = 0.25$) among non-energy consumption goods (e.g. plant-based fibres, logs). The elasticity between non-energy inputs to consumption over time periods is a function of per capita income growth between periods and thus varies over time and regions. Consumption shares in each period are also updated as a function of per capita income growth between periods.

[6] N.B. EPPA models government in a similar manner (Paltsev et al 2005).

[7] N.B. The current representation of household consumption may overstate household substitution possibilities and understate welfare impacts from transport-related taxation (and similar policy measures) relative to other CGE models that have a more complex representation. Future sensitivity analysis will explore the impact of adjusting the elasticity of substitution to test the relative impacts of policy shocks on household consumption.

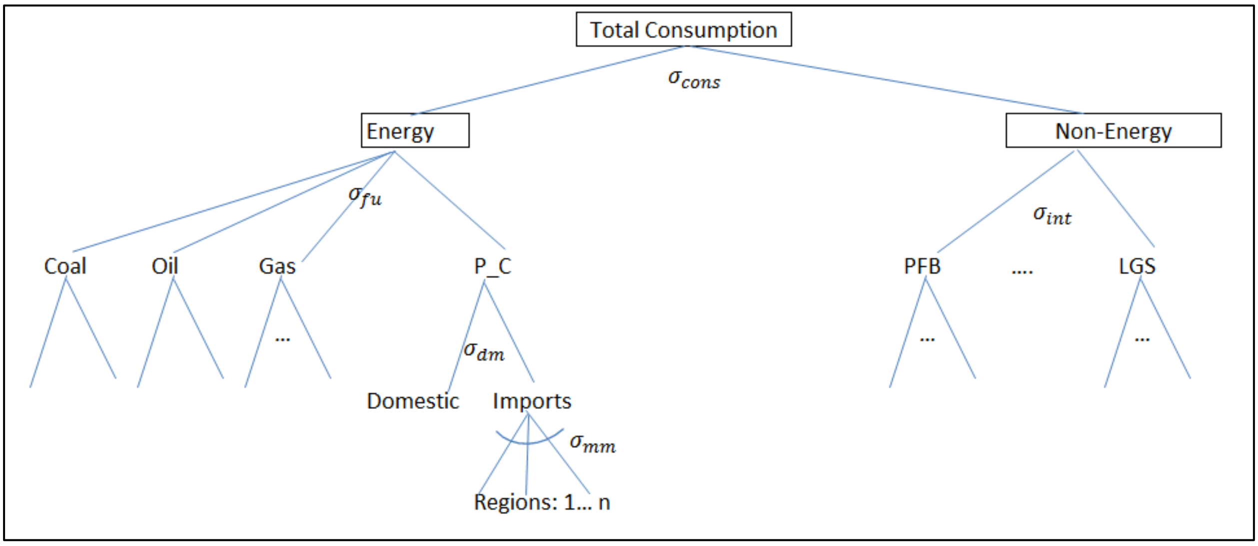

Figure 4: Structure of Consumption. Terminal nests with … indicate the same aggregation structure for imported goods as shown for the P_C sector. For the Intermediate Inputs bundle '…' represent the rest of primary production, manufacturing and value-added sectors in Table 1.

Table 5: Reference values of consumption sector substitution elasticities

	Description	
σ_{cons}	Energy and non-energy for households	0.6 + 0.1*log*(*t*)
σ_{enoe}	Electricity-Fuels aggregate	0.4 + 0.2*log*(*t*)
σ_{fu}	Among fuel sources	0.5
σ_{int}	Intermediate inputs	0.25
$\sigma_{c_{fuel}}$	Among fuels and GHG	0
$\sigma_{c_{nenr}}$	Non-energy sectors	0
σ_{MM}	Among import origins	2.5

2.4 Dynamic Process

The evolution of the economy in CliMAT-DGE follows a dynamic process. Key sources of growth over time are capital accumulation, labour supply and its productivity, energy productivity, stocks of natural resources, and backstop technologies for energy supply.

Dynamics in CliMAT-DGE follow a forward-looking behaviour where decisions made today about production, consumption, and investment are based on future expectations. The economic actors have perfect foresight and know exactly what will happen in all future periods of the model's time horizon. Thus, households are able to smooth their consumption over time so that the savings rate varies endogenously. It is assumed that consumers maximise their utility and producers maximise their profits while retaining full knowledge of all present and future prices.

As expectations about the future affect current behaviour of agents, the forward-looking approach adds flexibility to adjust savings and consumption over time to partially mitigate the negative impacts of an environmental policy in the short run. Therefore, the model is capable of addressing policy issues such as banking and borrowing of GHG allowances, international capital flows, and an optimal emissions abatement path[8] (Dellink 2005; Babiker et al. 2008).

2.4.1 Baseline calibration and projection

As in Babiker et al. (2008) the main issue to consider on calibration is the consistency among capital stock, capital earnings, interest rate, growth rate, and the rate of depreciation. In addition, as CliMAT-DGE uses CEPII data to construct the benchmark projections, it employs checks to ensure consistency. For this, tolerance levels are set at various stages of model calibration and policy scenario estimation. CliMAT-DGE starts with a basic CGE model for to rebalance economic identities (e.g. GDP, balance of trade) after GTAP original data are aggregated into the sectors of interest. Checks include that the balance of trade sums to zero, and factor use, international transport use, and intermediate inputs use balance with respect to the final demands. If checks are not passed, CliMAT-DGE automatically aborts calculations and indicates the failure to rebalance benchmark data.

Physical capital, K_{rt} , evolves through the creation of new capital from investments, I_{rt}, considering a constant depreciation rate, δ, at each period. The capital accumulation is represented as

$$K_{r,t+1} = (1-\delta)K_{rt} + I_{rt} \tag{2}$$

where r stands for country or region, t for time period. The initial level of the price of one unit of capital is:

$$p_t^K = (1+i)\big(1+\phi(\delta+g)\big) \tag{3}$$

Where i is the real interest rate, g is the annual growth rate of the economy, and ϕ is the adjustment cost parameter. For the benchmark, we i is equal to 5%, and the benchmark and g is equal to 1.8%[9]. The initial capital adjustment price, pa_t^K, is calculated as

$$pa_t^K = (\phi/2)(\delta+g)^2 \tag{4}$$

and the initial rate of return of capital, $\bar{r}^K$, as

$$\bar{r}^K = \frac{p_t^K(\delta+i)}{1+i} - pa_t^K \tag{5}$$

We set the initial quantity reference paths, qrf_{rt}, for the balanced growth path (BGP) projections as:

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[8] N.B. The path is only optimal in terms of cost-effectiveness unless climate impacts are also included.

[9] N.B: This assumption is relaxed after the benchmark calibration, thus allowing the growth rate to vary across model regions.

$$\mathrm{qrf}_{\mathrm{rt}} = (1+\mathrm{g})^{\mathrm{t}-1} \quad (6)$$

The BGP calibrates taking the depreciation rates as a residual from specifying the regional interest rates, and taking the growth rate in global GDP from 1995 to 2007. The BGP is defined as involving neither climate policies nor climate impacts.

The BGP serves two purposes. Firstly, solving the model requires making initial guesses for the values of all variables that are not "too far" from the actual solution of the model. For the BGP, we know the exact solution by construction. Secondly, if the model does not solve or gives a solution that is not the same as the BGP, this indicates a problem with the model structure or data that should be resolved.

Taking the BGP solution as initial guesses, the model is the resolved in several steps, incrementally altering the values of exogenous inputs to approach their baseline values[10]. This procedure is automated in the scenario script (Equation 8) so that the user specifies the number of incremental steps, τ. For labour productivity, we set regional labour endowments equal to the CEPII projections $(lprd_{CEPII})$ and adjust labour productivity in each region consistent with the growth rate $\left(\frac{qrf_{rt}}{lrf_{rt}}\right)$ where lrf_{rt} is the baseline indexed projections of active population (from CEPII).[11]

$$\text{labour productivity } = (1-\tau)\left(\frac{\mathrm{qrf}_{\mathrm{rt}}}{\mathrm{lrf}_{\mathrm{rt}}}\right) + \gamma(\mathrm{lprd}_{\mathrm{CEPII}}) \quad (8)$$

Once the model has been solved for an approximate baseline, we endogenously adjust the active population to reproduce the desired GDP projections. The solution for the baseline scenario is then estimated and stored at the end of this process so that it can be consistently compared against policy scenarios.

2.4.2 The infinite horizon and the terminal conditions

It is assumed that the representative household lives forever but for computational purposes the model must have a finite number of time steps. However, the finite horizon implies that the representative agent has no incentive to accumulate capital or consume beyond the terminal period. This terminal period behaviour can affect earlier periods as agents look forward and see the value of investment reduced because it will only be used through the terminal year. Similar to Lau et al. (2002) the terminal condition assigns a post-terminal growth rate to investments that assures a balanced investment growth without imposing a specific capital stock target or a specific exogenous growth rate in the post-terminal period. Thus, the growth rate of investment in the terminal period is required to be equal to the growth rate of consumption in that period, as follows

$$\frac{\mathrm{I}_{\mathrm{rT}}}{\mathrm{I}_{\mathrm{rT}-1}} = \frac{\mathrm{C}_{\mathrm{rT}}}{\mathrm{C}_{\mathrm{rT}-1}} \quad (9)$$

[10] Incrementally approaching the numerical solution of a complex problem by starting from the solution of an easier or known problem is known in mathematics as 'homotopy' and is widely used in economics and other disciplines alike

[11] Active population is analogous to the level of population representing the labour force.

This condition gives us a way to determine the demand for final period investment that is consistent with the long-run equilibrium properties of the infinite horizon model.

2.4.3 Vintaging of capital stock

The occurrence of economic obsolescence indicates that production techniques change over time. Furthermore, the level of technical knowledge at some point crystallises in the capital goods produced at that time; that is, technological change becomes embodied in new machinery and equipment. Models of production which take account of the implications of the embodiment of productivity for economic behaviour are known as vintage models (Zon 1991). Vintage models agree with the observation that many innovations need to be embodied in new kinds of durable equipment before they can be made effective. Improvements in technology affect output only to the extent that they are carried into practice either by net capital formation or by the replacement of old-fashioned equipment by the latest models (Solow et al. 1966).

However, there is no representation of technology vintages in CliMAT-DGE in the form of a putty-clay formulation. This formulation implies that firms may choose a new production technique from an endless variety of new techniques, each of them characterised by its own labour and capital coefficient (Zon 1991). Though it has much merit, putty-clay is computationally intensive in the context of a large, forward-looking model. Whereas a vintage specification emphasises technology inflexibility *within* a sector, the purpose of the sector-specific capital formulation in CliMAT-DGE is to emphasise the irreversibility of the allocation of new capital *between* sectors. Thus, sector-specific capital in CliMAT-DGE precludes disinvestment in a sector beyond natural attrition due to depreciation. This assumption is plausible for energy technologies which are most affected by carbon pricing. For example, there are few other uses for much of the equipment used in coal-fired electricity generation. Hence, it is usual to assume that 100% of investment is irreversible.

2.5 Closure conditions

In any CGE model, there is the choice as to what is calculated within the model (endogenous variables) and what is considered external to the model (exogenous variables). This choice determines the model closure conditions. Closure conditions ensure there are enough independent equations to explain the endogenous variables. The choice of the closure conditions defines the direction of causality in a model, and determines how equilibrium is reached after policy shocks (Burfisher 2011).

The following sections describe the closure conditions used in CliMAT-DGE.

2.5.1 Labour, land and natural resources

The current version of CliMAT-DGE is not designed to study labour market. The supply of labour in each region is undifferentiated by skill level and exogenously specified as part of the baseline scenario. We assume a full employment model closure, where a shock to the economy causes wages and rents to adjust until the fixed supply of each factor is again fully employed. If labour is fully employed, then producers must compete for workers with other industries in order to expand production. This competition drives up wages and increases manufacturers' cost of production, which is passed on to consumers through higher prices (Burfisher 2011). An exogenous growth of labour supply is assumed to reflect increases in the population and more efficient use of labour due to improving technology.

Similarly, the supply of land and natural resources are assumed to be fixed in each period. Rents vary accordingly to keep full-employment. The stock of land does not change over time, thus changes on land resources may be addressed through changes in land productivity or factor usage in each sector or country.

2.5.2 Budget

The present value of all future changes (positive and negative) in a region's current account balance must be zero because of the forward-looking dynamics of the model. As a result, New Zealand (or any other region) may run a current account surplus or deficit in any period, subject to the constraints that (i) global savings must equal global investment and (ii) the present value of a region's current and future surpluses must equal the present value of its current and future deficits. For this, capital flows are allowed among regions in response to differences in real rate of returns. Thus, the capital flows are equal both to the current account deficit (or surplus) and to the differences between aggregate expenditures (private and public consumption plus investments) and aggregate income (returns to labour, capital, energy resources, and tax revenues). That is, if one country has a current account deficit, then there must be a compensating current account surplus in other countries. Furthermore, in every region, any excess of aggregate expenditure over aggregate income today must be paid back in the future so that there is no net change in indebtedness over the model horizon.

In common with most CGE models, international assets positions are not explicitly modelled in CliMAT-DGE. Financial stocks and flows of financial assets (debt, equity, currency) are not modelled either. Thus, while a current account deficit is financed by a capital account surplus, we cannot say anything about the composition of the capital account. Foreign trade allows countries to temporarily run foreign accounts imbalances in response to environmental policies, as long as that imbalance is made up for in later years.

2.5.3 Exchange rate

CliMAT-DGE models only relative prices, which is again a conventional approach for many CGE models. The relative prices describe the percent change in an index of a country's prices relative to the world average price. Nominal prices and therefore nominal exchange rates are not modelled. However, for example, if a unilateral emissions pricing policy that makes GHGs more expensive for production sectors affects the relative prices of goods, this effect is similar in nature to a change in the real exchange rate. Thus, an increase (decrease) in the relative prices is similar to a real exchange rate appreciation (depreciation).

To illustrate this point, consider two regions (NZL and the ROW) that both produce GHG-intensive commodities. A policy that lowers the GHG price in NZL causes its world export price of commodities to fall relative to the world export price from the ROW, which has a higher GHG price. All GHG-intensive goods produced in NZL become cheaper in the world market than similar goods from the ROW. This will stimulate NZL's consumers to shift from imports toward domestic goods, and will lead the ROW's consumers to shift toward imports from domestic goods.

2.6 Technological change

CliMAT-DGE has explicit growth rates for energy-augmenting and GHG-augmenting technological change that vary by region and sector. We relate these forms of input-augmenting technological to projections of labour-augmenting technological change. The latter are based on total factor productivity projections developed by CEPII.

We model the level of energy-augmenting and GHG-augmenting technological change, $B(t)$, as

$$\mathrm{B(t)} = 1 + \mathrm{c}\ln\big(\mathrm{A(t)}\big) \tag{10}$$

where $A(t)$ is labour productivity in year t (equal to one in the base year). While this relationship is arbitrary, it captures two important ideas. First, forms of technological change face strongly diminishing returns, for example, because of thermodynamic limits to the efficiency of energy conversion. The natural logarithmic function allows for continuing improvement, but at a slowing rate. In addition, the coefficient c accounts for the evaluation of the likely scope of such improvements over the years. For energy end-uses we choose $c = 1$ as there is considerable potential to improve energy efficiency in end-uses in the long run. By contrast, we assume there is much less potential to improve the efficiency of energy conversions (e.g. in the electricity sector) because of the nature of these processes and the large cost of energy in these sectors. Thus, we choose $c = 0.1$ in these cases. We also use this value for output-linked GHG emissions (discussed in section 2.8). Second, $A(t)$ and c will be positively correlated with $B(t)$ and the rate of more specific types of technological improvement. Note that these forms of ‘directed’ technical change are exogenous in the model, which is a typical assumption for many dynamic CGE models.

2.7 International trade

All goods in CliMAT-DGE can be traded in world markets. Imports and domestic production are aggregated into an Armington (1969) aggregate using an approach that assumes domestic and foreign goods are imperfect substitutes. The extent to which imported and domestic goods imported goods differ is determined by the elasticity of substitution between them. Thus, firms in CliMAT-DGE will produce a composite good that is an aggregate of domestic- and foreign-produced goods. The changes in the relative shares of foreign and domestic goods in the composite are determined by changes in the relative prices of these goods at home and overseas, as specified by initial shares of these goods in the benchmark GTAP data and the Armington substitution elasticity. As a result, a change in domestic prices can cause a shift in demand between domestic production and competitive imports of a given good, but only to a limited extent (Dellink, 2005).

CliMAT-DGE’s use of the Armington goods specification allows an explicit representation of bilateral trade flows. As a result, regions in the model can be both importers and exporters of a particular good. The model explicitly tracks bilateral trade flows, which include export taxes, import tariffs, and international transport margins.

2.8 GHG emissions accounting

We relate sector baseline emissions from GTAP (measured in GtCO2e) to the GHGs embodied in the value of factor inputs, intermediate inputs, and outputs to create emissions intensity factors (measured as CO2e/$). The benchmark GHG emissions are separated among intermediate use ($ghgiz_{rcd,ghg}$), final output ($ghgoz_{ra,ghg}$), and factor use ($ghgfz_{rfa,ghg}$).[12] These are aggregated into benchmark GHG emissions by demand $\left(ghgz_{r,d,ghg}\right)$. These figures serve as GHG endowments for each region in the simulation. Additionally, emissions are separated for energy uses.

Benchmark emissions intensities are calculated as follows:

$$\mathrm{ghgfi_{rfat}} = \textstyle\sum_{\mathrm{ghg}} \mathrm{ghgfz_{rfa,ghg}} / \mathrm{fusemz_{rfa}} \tag{11}$$

$$\mathrm{ghgii_{rcdt}} = \textstyle\sum_{\mathrm{ghg}} \mathrm{ghgiz_{rcd,ghg}} / \mathrm{cusemz_{rcd}} \tag{12}$$

$$\mathrm{ghgoi_{rat}} = \textstyle\sum_{\mathrm{ghg}} \mathrm{ghgoz_{ra,ghg}} / \mathrm{outputmz_{rac}} \tag{13}$$

where $fusemz_{rfa}$ is the benchmark factor uses at market prices, $cusemz_{rcd}$ is the benchmark commodity uses at market prices, and $outputmz_{rac}$ is the benchmark outputs at market prices. For policy analysis, the intensity factors (Equations 11-13) may be exogenously adjusted to simulate the improvement in GHG intensities over time due to, say, technological change (see section 2.6). The emission factors in CliMAT-DGE can vary by input, sector, and region. In this version of the model, the trajectory of the model baseline GHG emissions intensities at the regional level were closely aligned with the mean energy intensity of GDP projections published by the IPCC (Edenhofer et al. 2014) [13,14].

The initial GHG emissions are based on the GTAP CO2 and non-CO2 databases (Lee 2002), and are specified in IPCC (2007) AR4 global warming potentials (GWPs). Baseline GHG projections for New Zealand are adjusted to match those listed in the 6th National Communications projections (MfE 2013).

2.9 GHG emissions market

The model is suitable to simulate policies such as GHG emissions targets through price or quantity constraints, that is, exogenous GHG prices or emissions cap on specific sectors (e.g. electricity, manufacturing). Any region can meet a specific GHG emissions target through a combination of domestic abatement and purchasing of GHG emission reduction permits from

[12] See the appendix for the mathematical notation

[13] See Figure TS.7.C

[14] N.B. the impacts of adjusting this assumption could be tested in the future through sensitivity analysis.

abroad. In previous versions of CliMAT-DGE, the only sources of emissions reductions were: (a) an exogenously set GHG price, for which domestic abatement occurred until the marginal cost of abatement was equal to the GHG price, or (b) an exogenously set regional emissions reduction target. The updated version of the model now includes the option for regions to purchase permits in international markets at a globally uniform GHG price, until the specified emissions reduction target is reached (e.g. New Zealand target of 20% below their baseline GHGs by 2030).

In CliMAT-DGE, the production and consumption of goods are linked to the benchmark sector GHG emissions as follows:

$$(\mathrm{CPRI_{rt}})\mathrm{PC_{rt}} - \mathrm{PGHG_{rt}} = 0 \qquad (14)$$

where $CPRI_{rt}$is the carbon price target in USD per tCO_2e, PC_{rt}, is the price of consumption goods, and $PGHG_{rt}$ is the price of GHG emissions at user cost. In the context of MPSGE, Equation 14 implies that for every unit of production or consumption of a good, it is accompanied by an increase in GHG emissions.

The CliMAT-DGE model explicitly represents direct emissions of household fuel combustion (both home and vehicular). These emissions could be priced in the same way as or differently from direct agricultural, energy and industrial emissions. Note that given the assumptions of perfect competition, etc. employed in the model, it is economically equivalent imposing emissions obligations at any point in the value chain. However, it is not easy to model obligations at up-stream points because of how GHGs are allocated in the GTAP database[15].

The endogenous GHG emissions trading component is programmed as a top-down approach. Some conditions apply. First, any country or region can only import as many permits, $ghgimp_{rt}$, that are available for export from other regions, $ghgexp_{rt}$, (Equation 15). Second, any region must meet a binding cap (Equation 16) through a combination of domestic GHG abatement, $DOMghg_{rt}$ and permit imports, less permit exports (Equation 17). Third, in the case where there is the potential for an oversupply of permits available on the market, we constrain the traded permit price to be equal to the marginal cost of abatement (i.e., domestic GHG price) of the region purchasing the permits[16].

$$\mathrm{ghgimp_{rt}} \leq \mathrm{ghgexp_{rt}} \qquad (15)$$

$$\mathrm{TOTghg_{rt}} \leq \mathrm{CAP_{rt}} \qquad (16)$$

$$\mathrm{TOTghg_{rt}} \leq \mathrm{DOMghg_{rt}} + \mathrm{ghgimp_{rt}} - \mathrm{ghgexp_{rt}} \qquad (17)$$

[15] N.B. Although most of GHG emissions are initially priced at the production-level, these costs are passed through to households that consume the goods.

[16] This approach simulates an international GHG market where all regions facing a GHG price will also face a specified emissions target (e.g., 10% below 1990 levels by 2025) and hence likely have a limited number of permits to sell. If this constraint was not imposed, and supply significantly exceeds demand, then the value of the traded permits would be close to 0. In this case, the region that is allowed to purchase permits may find it more efficient to not reduce domestic emissions at all and purchase all of their reduction requirements from other regions. The latter option is not likely to be supported under an international climate change policy agreement.

To illustrate how the GHG pricing in the CliMAT-DGE works, consider the following global cap-and-trade scheme where all countries and all emission are included, there is no free allocations to firms, and there is a single global carbon market. Each representative household gets an allocation of permits for its country. The household can sell those permits to domestic firms or on the global carbon market. Globally traded permits are a single homogenous good. Thus, there is no bilateral trade and any country is either a permit importer or exporter. Hence, the model only represents net trades at the country level. The supply of permits that may be exported or imported is determined by the constraints of the policy scenarios, whether the country or sector is subject to the policy, and the level of the regional emissions reduction targets.

2.10 National accounts

The national accounts terms in CliMAT-DGE are constructed from both the benchmark projections in the baseline, and the policy scenario projections. As the model relies on the GTAP sectors, we do not construct any mapping between the sectors modelled and the New Zealand system of national accounts or the New Zealand Standard Industrial Classification.

Benchmark gross domestic product (GDP), $gdpz_r$, is constructed as follows

$$\mathrm{gdpz_r} = \mathrm{conz_r} + \mathrm{invz_r} + \mathrm{botz_r}, \tag{18}$$

where benchmark aggregate consumption is

$$\mathrm{conz_r} = \textstyle\sum_{c} \ \mathrm{cusemz_{rc,"consumption"}}. \tag{19}$$

Aggregate investment (gross capital formation) is calculated as

$$\mathrm{invz_r} = \textstyle\sum_{c} (\mathrm{cusemz_{rc,investment}})(1 + \mathrm{txiz_{rc,investment}}), \tag{20}$$

where $txiz_{rc,investment}$ represents the commodity input tax rates including final uses. The benchmark balance of trade is

$$\mathrm{botz_r} = \textstyle\sum_{c} \ \mathrm{itptz_{rc}} + \sum_{c,r} \mathrm{expwz_{rc}} + \sum_{r,c} \mathrm{impwz_{rc}}, \tag{21}$$

where $itptz_{rc}$ is the benchmark international transport services supplied, and $expwz_{rc}$ and $impwz_{rc}$ are benchmark exports and imports, respectively.

The benchmark projections and model initialization incorporate value-added tax revenues that are calculated as the difference between the value of goods at market and agent prices. These revenues are based on GTAP data and not on official tax revenues figures. The VAT taxes are applied to production, capital, labour and foreign trade.

2.11 Other parameter values and NZ specific additions

CliMAT-DGE dynamic baseline requires information and data on projected changes in regional population, GDP, technology, and consumption growth. For this purpose, the model incorporates realistic projections of key macroeconomic (e.g. labour productivity) and other (e.g. energy efficiency) variables. A summary of the key sources and assumptions for the baseline construction is given in Table 6.

The baseline relies on a growth scenario developed by CEPII projections (Fouré et al., 2010), which are built on economic forecasts of the International Monetary Fund; labour force projections of the International Labour Organisation; and demographic projections of the United Nations. CEPII presents economic growth scenarios for 128 countries to 2050, based on a three-factor production function that includes capital, labour and energy. The CEPII model is fitted with United Nations and International Labour Office labour projections, and econometric estimations of (i) capital accumulation, (ii) savings rates, (iii) relationship between savings and investment rates, and (iv) technological progress (which includes energy and total factor productivity). The CEPII projections include four novelties. First, they account for the energy constraint by including it in the production function. Second, they estimate a non-unitary relationship between savings and investment, departing from assumptions of either a closed economy or full capital mobility. Third, they account for the 2008-09 global crisis by initialising the projection model in 2013 while relying on IMF projections between 2008 and 2012. Finally, they disentangle real gross domestic product (GDP) growth rates from relative price effects through a consistent Balassa-Samuelson effect. In addition, the CEPII projections establish the difference between the long-run path of the world economy in real terms, which is relevant to future GHG emissions, and the long-run path of the world economy in current dollars, which depends on the relative valuations of incomes. In order to address this difference it is necessary to model long run real exchange rates, CEPII separates real GDP growth rates from relative price variations through a consistent Balassa-Samuelson effect (Fouré et al., 2010). For the projections of the CEPII baseline see the Appendix.

Energy supply and efficiency projections are based primarily on several 2009 through 2012 editions of the World Energy Outlook, produced by the International Energy Agency. Some of the projections used for the baseline are included in the Appendix.

Table 6: Baseline assumptions

Category	Assumption	Source/Notes
Labour productivity	Varies for each region	Exogenous - CEPII
Active population	Varies for each region	Exogenous - CEPII
Land and resource productivity	Varies for each sector and region	Exogenous - Same as labour productivity (CEPII)
Energy productivity (linked to energy emissions)	Varies for each region	Exogenous - Based on labour productivity (CEPII)
Fossil fuel resources	Varies for each region	Set to target exogenous- IEA WEO projections of fossil fuel supplies
Fossil and carbon-free electricity supply shares	Fixed for each region	Exogenous- own assumptions

CliMAT-DGE does not incorporate heterogeneous households, only a representative agent. Thus, there are no differences in prices for different household consumers. It is feasible the producers could face alternative input costs via the tax/subsidy structure.

All monetary outputs are reported in 2012 New Zealand dollars ($), which were scaled from the GTAP standard output of 2007 USD in CliMAT-DGE by using a combination of the NZ Treasury CPI and the World Bank GDP deflator.[17]

[17] This approach results in a factor of 1.62 2012 $ per 2007 USD.

3 Baseline Calibration

CliMAT-DGE is initially calibrated to a baseline or reference case for which all policy scenario analysis is referenced against or compared to. In CGE modelling it is imperative to have a baseline that the scenarios can be compared to as the outputs from the model are not just projections but relative changes from the baseline scenario. Existing carbon and water policies are implicit in the baseline calibration, and changes to these policies or the occurrence of exogenous shocks (e.g. unanticipated recessions) would change the trajectories of the BGP. All monetary figures in this section are expressed in 2012 NZL dollars.

3.1 Gross Domestic Product

Baseline estimates of RGDP, in real terms, for CliMAT-DGE and other global IAMs used in recent IPCC reports are shown in Figure 6. GDP for CliMAT-DGE in 2007 is estimated to be about $85 trillion, which is close to the average of other IAMs. We estimate that global GDP reaches about $184 trillion by 2045, although it increases at a rate of 3.6%/yr, which is less than most of other IAMs (average of 5.8%/yr). However, the global GDP for CliMAT-DGE is in the middle range of the IAMs over the period of 2021–2030, suggesting it is appropriate for policy analysis in the short and long-run.

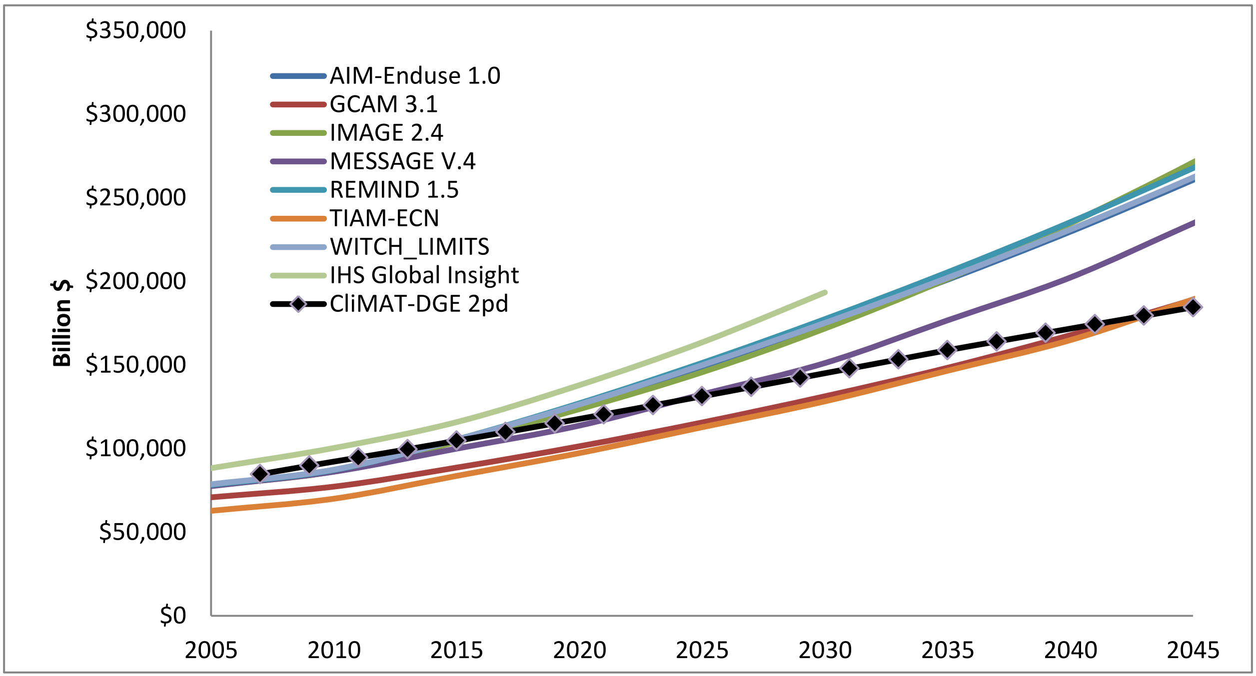

Figure 5: Baseline global real GDP projections.

Figure 6 shows a comparison of GDP projections by NZ Treasury and the CliMAT-DGE figures. CliMAT-DGE slightly overestimates GDP because the model specification is not designed to incorporate an economic recession such as the one post-2007 global financial crisis. However, the time trend in GDP is relatively similar to the NZ Treasury long-term projections. Thus, we do not see significant inaccuracy on the model's estimates. Figure 8 breaks out estimated GDP by the individual components: household and government consumption, investment, exports, and imports.

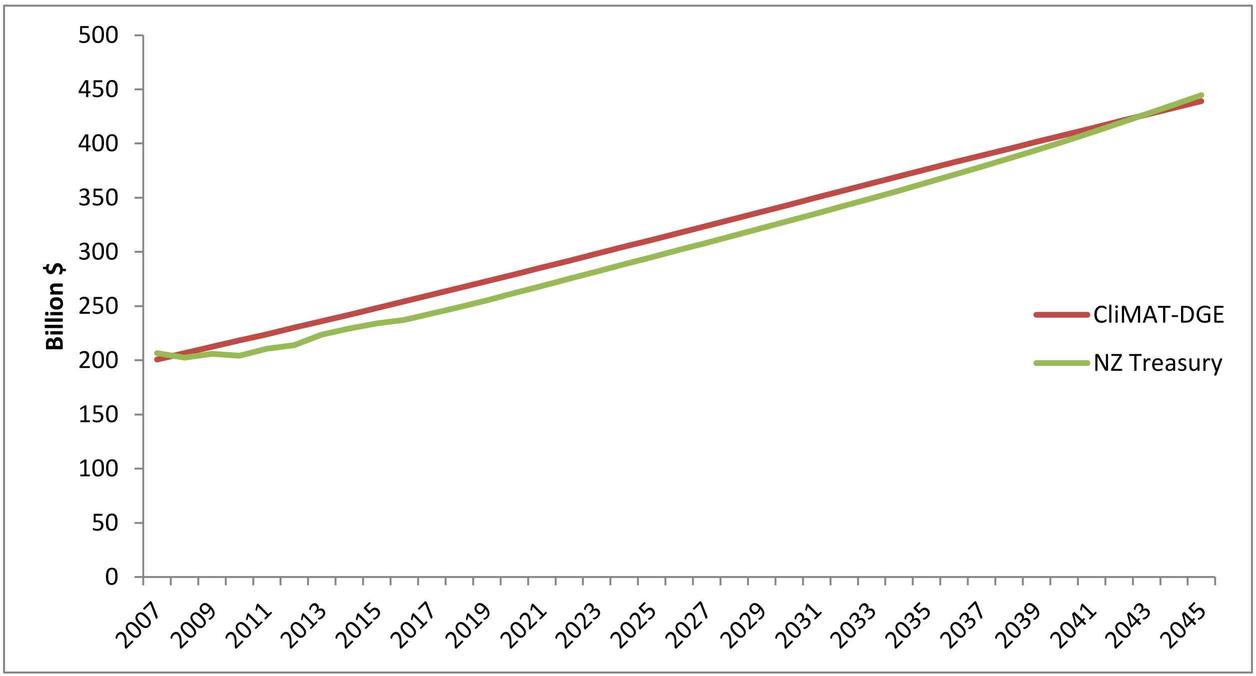

Figure 6: Baseline New Zealand real GDP projection (billion $)

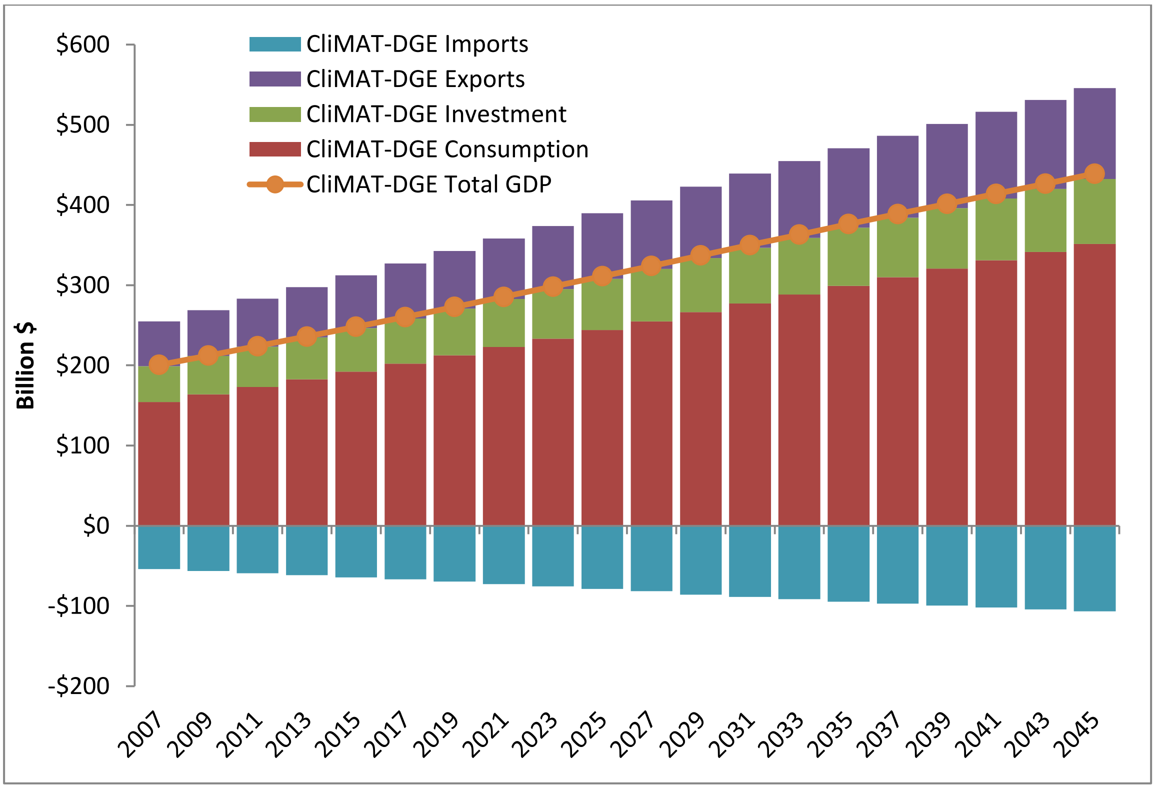

Figure 7: New Zealand's GDP, by component (billion $)

3.2 Real gross national disposable income

Real gross national disposable income (RGNDI) measures the real purchasing power of national disposable income. RGNDI includes GDP but also accounts changes in the terms of trade, and real gains from net investment and transfer income with the rest of the world. That is, RGNDI is a measure of the volume of goods and services that New Zealand residents have command over and is sometimes used to represent national welfare. RGNDI is calculated as follows:

$$\mathrm{RGNDI_{rt}} = \mathrm{GDP_{rt}} + [\mathrm{E_{rt}}((\mathrm{EPI_{rt}}/\mathrm{IPI_{rt}})] - 1)] - [\mathrm{GHGcost}/\mathrm{IPI_{rt}})], \tag{22}$$

where E_{rt} is the value of exports, EPI_{rt} is the export price index, IPI_{rt} the import price index, and $GHGcost$ is cost of GHG permits purchased from abroad to achieve a reduction target.

The model estimates that RGNDI will increase from about $200 billion in 2007 to $443 billion in 2045 (Fig. 9). There are no other known sources of New Zealand RGNDI with which to compare this figure; however, it is closely aligned with the growth in GDP published by the NZ Treasury.

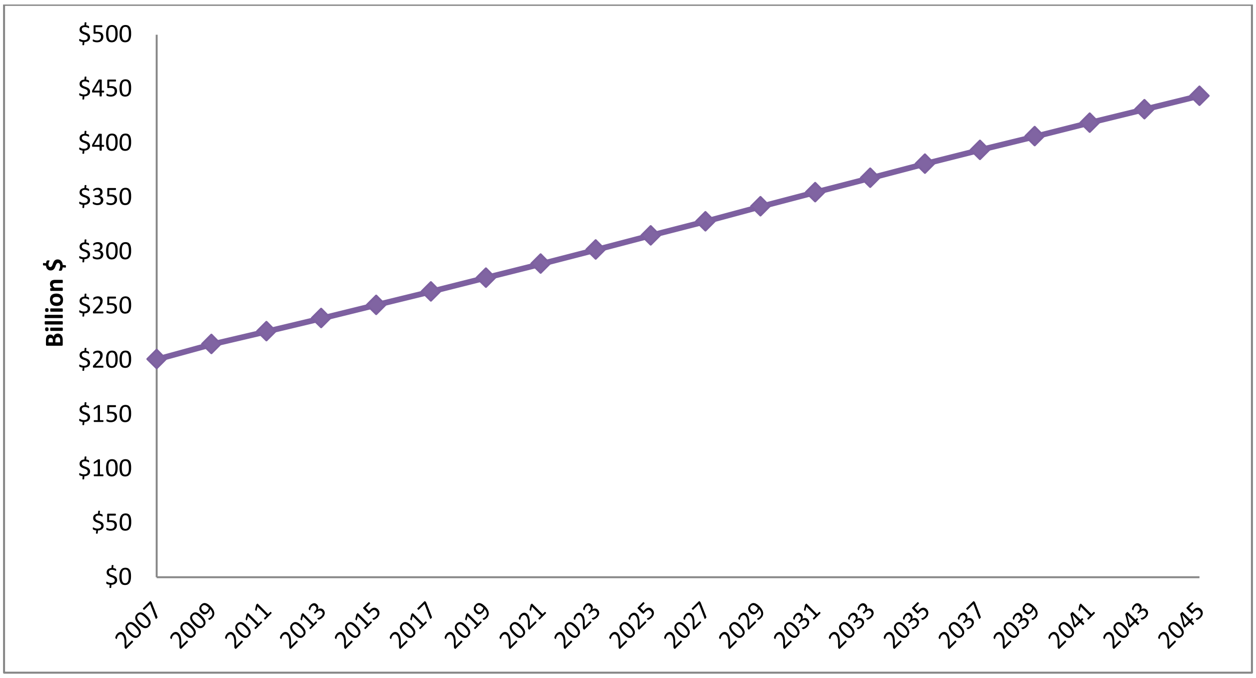

Figure 8: Baseline New Zealand RGNDI projection.

3.3 Welfare

CliMAT-DGE measures consumer welfare using a Hicksian money-metric welfare index. The index represents the utility derived from aggregate consumption through the Hicksian equivalent variation, given the policy impacts. That is, the equivalent variation (EV) is the amount of money paid to an individual with base prices and income that leads to the same satisfaction as that generated by a price and income change. EV is calculated as the net present value (starting in 2012 using a discount rate of 5%) of the aggregate expenditure of the representative agent on consumption, over the lifetime of the model run. CliMAT-DGE is setup for a representative agent per region where total baseline welfare is estimated to be $14.7 trillion for New Zealand and $6,436 trillion globally.

3.4 Greenhouse Gases

Baseline global GHG emissions for CliMAT-DGE and select IAMs are shown in Figure 10. World emissions in CliMAT-DGE are estimated to be about 44 GtCO2-e in 2007 and to reach 82 GtCO2-e by 2052, an increase of about 2% per annum. The current baseline scenario sees median temperature rise reach about 4.3 degrees Celsius above pre-industrial levels by the end of the century (Daigneault et al. 2014).

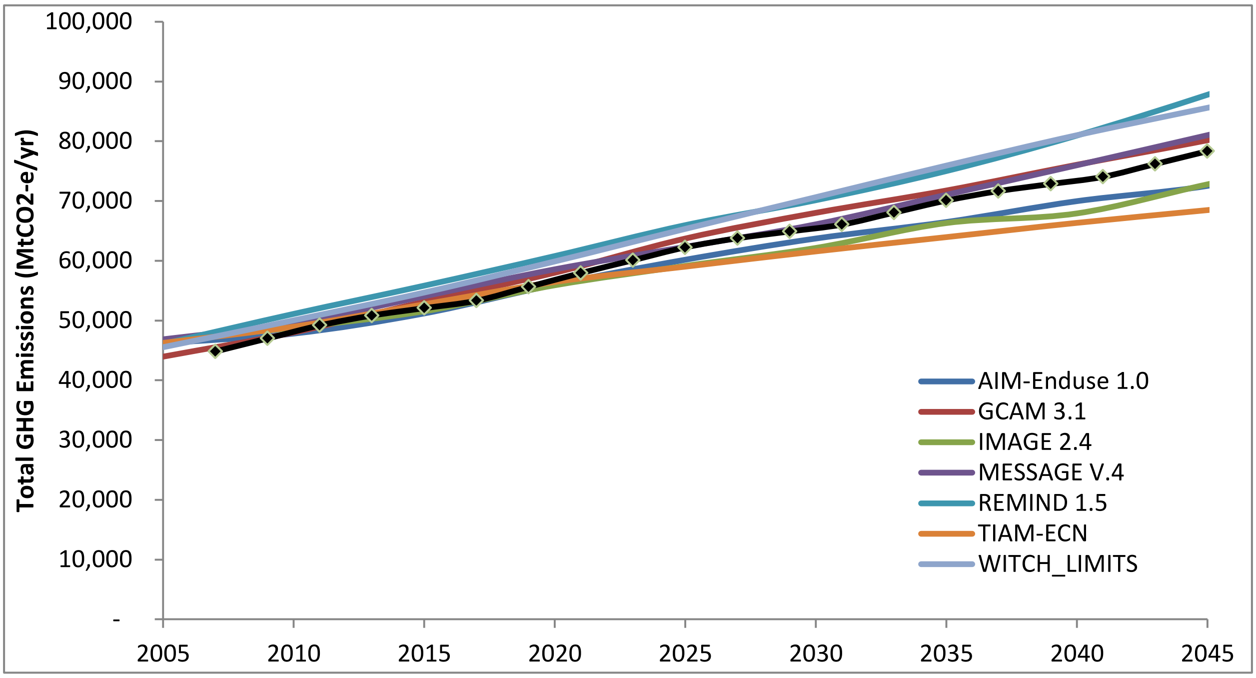

Figure 9: Baseline annual GHG emissions projections.

New Zealand's emissions were updated to be closely aligned with the MfE's projections in the 6th National Communications, as shown in Figure 11. CliMAT-DGE (and GTM for LULUCF[18]) estimates GHG emissions to increase in gross (net) emissions from about 80 (62) MtCO2-e in 2007 to 89 (77) MtCO2-e in 2030. The figure shows that gross emissions are closely aligned with MfE projections over the entire time period, but net emissions diverge over the 2020–2030 period because of the different baseline estimates for forest carbon sequestration/emissions from LULUCF.

Figures 11 and 12 show the projected baseline GHG emissions by individual sector and gas. Carbon dioxide (CO_2) is estimated to be relatively constant over time, while all three non-CO_2 gases are estimated to increase over time at a rate of about 1%/yr. Most of the aggregate increases in non-CO_2 emissions are estimated to occur in the agricultural sector, which is also consistent with MfE projections.

[18] Land use land use change and forestry

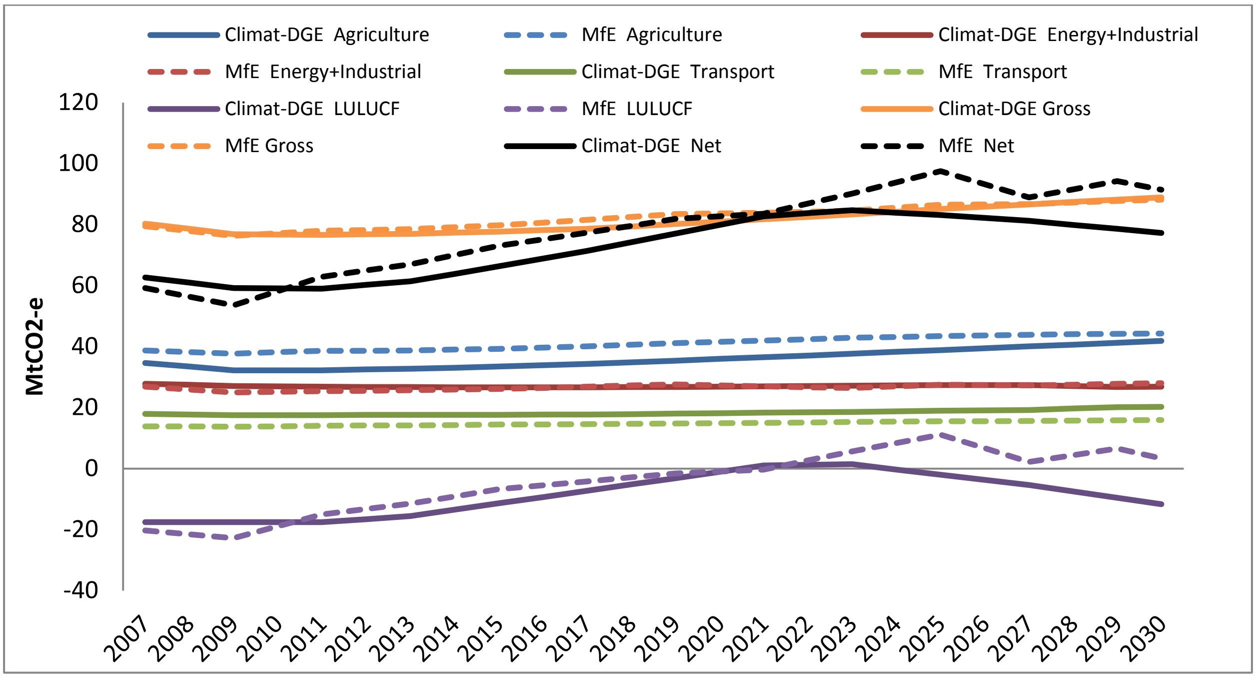

Figure 10: New Zealand GHG emissions by sector (MtCO2-e).

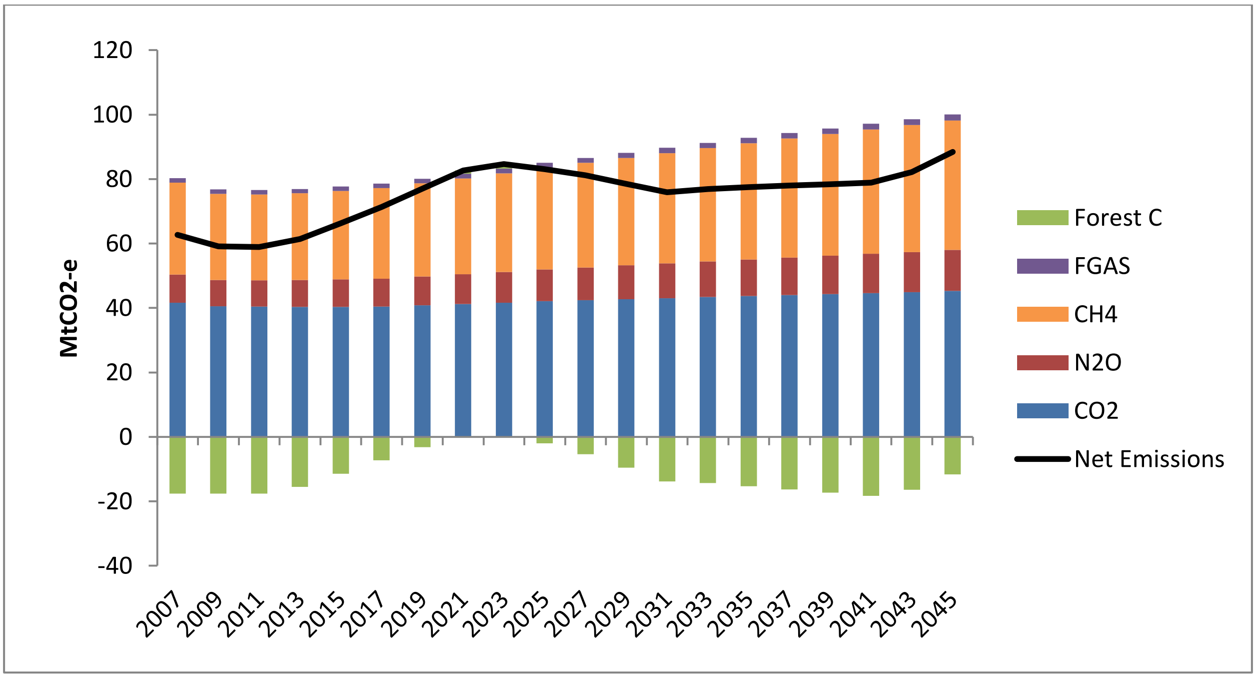

Figure 11: New Zealand GHG emissions by gas (MtCO2-e).

4 Illustrative Climate Change Policy Scenario

Basic policy scenarios are simulated by changing the value of one or more parameters from their baseline values. GHG reduction policy scenarios are defined in terms of GHG prices or quantity constraints (i.e. regional cap on emissions). For regional cap scenarios we allow emissions trading between regions, and banking and borrowing between periods. Other policy parameters that can be changed are exogenous time-dependent tax rates on inputs, outputs or international trade. For an illustrative example consider a set of scenarios where a series of exogenous GHG emissions prices are set worldwide for all sectors of the economy (e.g. energy, transport, agriculture) to estimate sector-specific contributions to regional GHG mitigation. No permit trading is allowed, nor are there regional caps on GHG emissions. In this scenario, we impose constant GHG prices ranging from $32 to $324/tCO2e ($20–200 USD) from 2022 onwards.

Figure 13 shows the marginal abatement curves (MAC) for all sectors in New Zealand in 2027. Secondary energy sectors may reach abatement of 80% when the price is greater than $300. However, substitution to carbon-free electricity comes in to play at this point. The cost structure of each sector defines the extent of emissions reductions. The EMT and NSV sectors in New Zealand may reach up to 35% and 52% reductions, respectively, at a price of $324/tCO2e ($200 USD/tCO2e). In turn, primary product (agriculture) sector reductions are about 10%, due to the lack of low-cost mitigation options.

Figure 14 shows the World MAC for each sector for 2027. The World primary production sector is more responsive to GHG pricing as reductions may be by 40% below the baseline. The EMT sector is slightly less responsive in New Zealand than in the World where reductions below the baseline are around 35% and 41%, respectively, for a GHG price of $300. In turn, the NSV and Value-Added agriculture sectors are more responsive in New Zealand. Finally, among the sectors under GHG pricing, Transport is the least responsive. For example, for a GHG price of $300, emissions decline by 20% and 19% for NZL and the World, respectively.

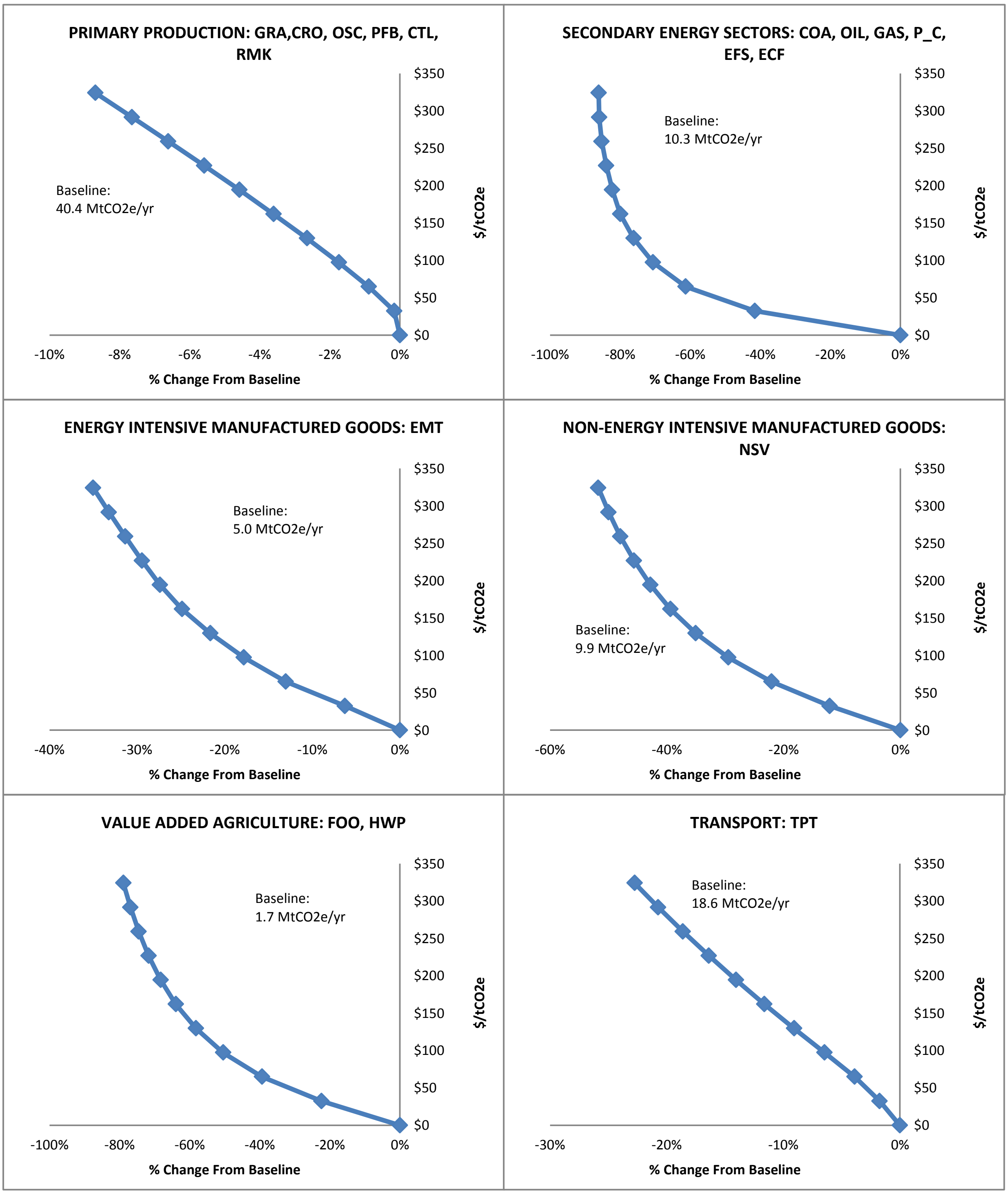

Figure 12: Sectoral Marginal Abatement Curves for New Zealand, 2027.

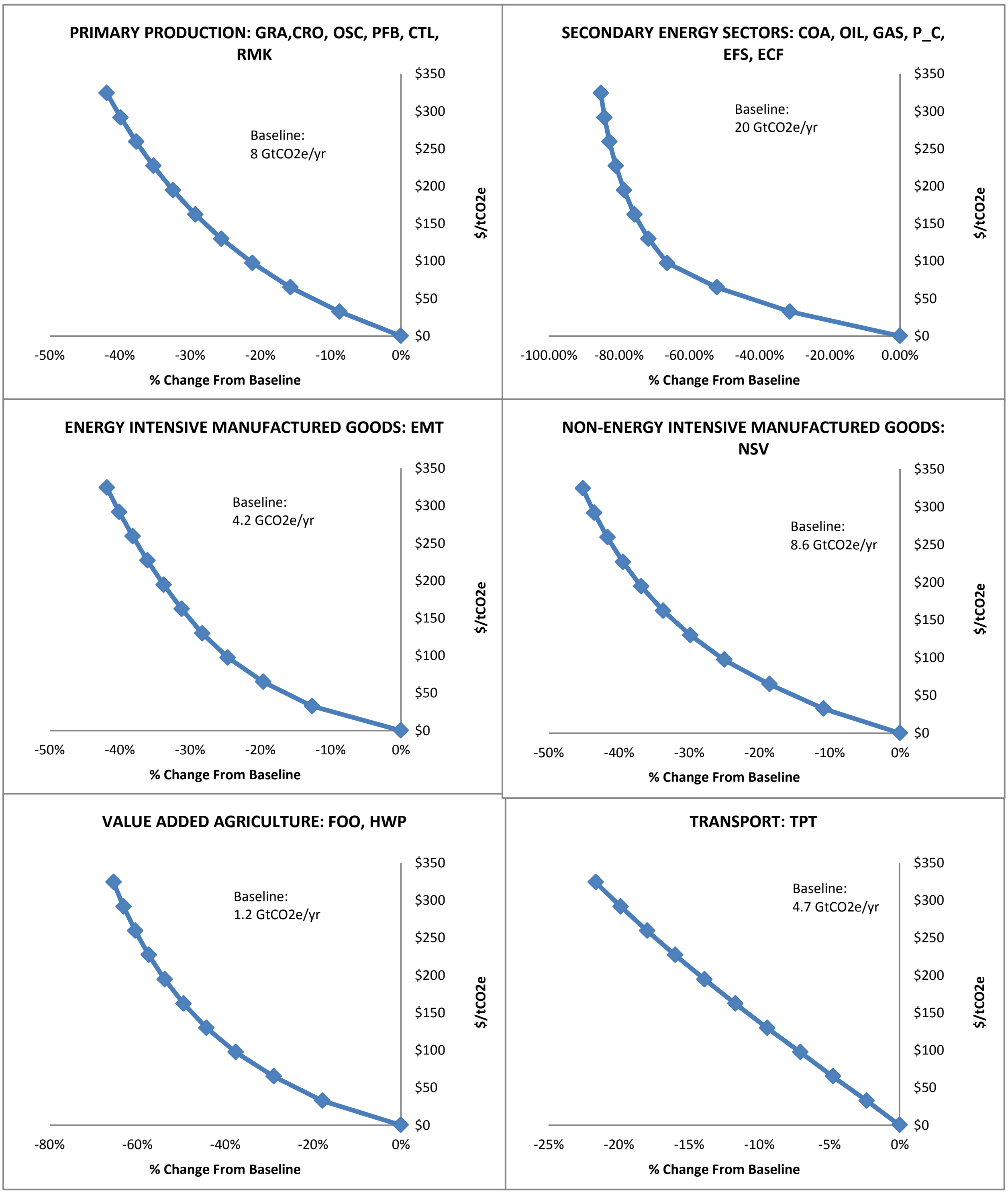

Figure 13: Sectoral Marginal Abatement Curves for the World, 2027

5 Model extensions

5.1 The New Zealand Integrated Assessment Modelling System

CliMAT-DGE can be linked to the New Zealand Integrated Assessment Modelling System (NZIAMS). NZIAMS links biophysical and economic models with a strong focus on agriculture and forestry, as these sectors make up a large share of the New Zealand economy. The component models of NZIAMS (Fig. 15) are as follows:

1. The CliMAT-DGE model, a multiregional and multi-sectoral dynamic general equilibrium model that is capable of incorporating climatic impacts on crop yields, before simulating policy scenarios. This is the core model in NZIAMS.

2. The climatic model MAGICC to translate global emissions into global atmospheric GHG concentrations and mean temperatures. MAGICC models the global atmosphere and ocean system (Wigley 2008), to emulate the responses of global climate variables in complex Atmosphere Ocean General Circulation Models (AOGCMs). While an AOGCM typically takes weeks to run on a supercomputer, MAGICC runs in seconds on a desktop computer. MAGICC is calibrated to emulate the responses of any of the AOGCMs and carbon cycle models used in the IPCC Fourth Assessment Report (Meinshausen et al. 2011).

3. The Global Yields Emulator (GYE) model emulates the responses of complex crop models using a statistical pattern scaling methodology. GYE estimates regional yield changes for wheat, maize, soya and rice, and relies on the mean climatic variables produced by MAGICC. The yield changes are fed into either the top-down or bottom-up components of CliMAT-DGE. GYE operates within the decision support system for agrotechnology transfer (DSSAT) framework (Shoals et al. 1998; Jones et al. 2003) and for forestry from the MC1 dynamic vegetation model (Bachelet 2001). The basic output of the GYE is yield changes on a 0.5 degree global grid, which can be aggregated spatially and temporally to provide inputs for CliMAT-DGE. The pattern-scaling methodology of GYE has been used to estimate regional climate changes based on changes in global variables. However, to our knowledge, this is the first application of the methodology to physical impacts of climate change

The NZIAMS links the three models through feedback loops and thereby accounts for the impacts of the climatic and biophysical changes. The NZIAMS also includes a downscaled partial equilibrium (PE) sub-model that provides further detail to the agriculture and forestry sectors and can be linked to the NZIAMS. It explores each region in more detail with regional disaggregation into agro-ecological- zones (AEZs). More details on NZIAMS are available in Lennox et al. (2013).

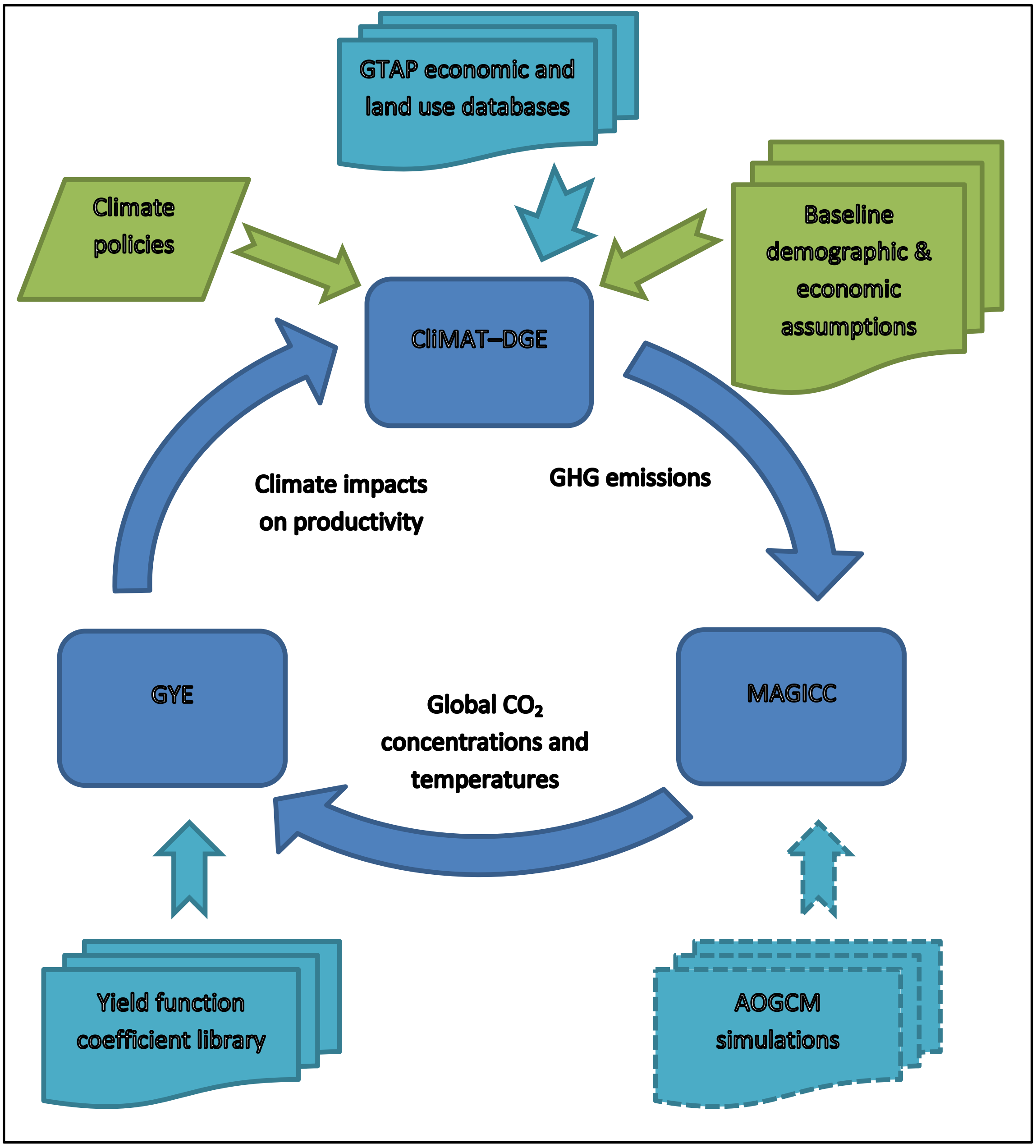

Figure 14: NZIAMS core system, comprising CliMAT-DGE economic model, MAGICC climate model and Global Yields Emulator (GYE).

5.2 The Global Timber Model and the New Zealand Forest and Agriculture Regional Model

The Global Timber Model (GTM) is an economic model capable of examining global forestry land use, management, and trade responses to policies. In responding to a policy, the model captures afforestation, forest management, and avoided deforestation behaviour. The model estimates harvests in industrial forests and inaccessible forests, timberland management intensity, and plantation establishment, all important components of both future timber supply and carbon flux. The model also captures global market interactions, global timber supply and the associated carbon accounting, including carbon stored in harvested wood products. The current version of the model tracks more than 200 forest types across 17 timber regions. The New Zealand region includes 12 regional *Pinus radiata* and other exotic forest plantations as well as native forest. It solves in 10-year increments through 2200, taking into account the long-run dynamics of forest growth and harvest schedules. The model has been used internationally in a variety of forest and climate change policy assessments, including the recent analyses carried out by the US Environmental Protection Agency.[19] More details on the GTM model can be found in Daigneault et al. (2012a) and Sohngen & Mendelsohn (2007). The regional GHG prices estimated with CliMAT-DGE may be fed into GTM. The timber model can then estimate the change in regional forest stock and carbon sequestration as a result of the proposed GHG emission reduction policy. See Figure 16 for a diagram of the key components of the modelling system.

National-level NZFARM is a recursive dynamic, partial equilibrium, nonlinear, mathematical programming model of the New Zealand forest and agriculture sector. It is designed for detailed modelling of land use at the regional scale to enable the consistent comparison of policy scenarios against a baseline by assessing relative changes in economic and environmental outputs. It accounts for production of commodities (e.g. meat, milk, timber, etc.) and GHG emissions (e.g. CH_4 from enteric fermentation, N_2O from grazing and fertiliser, etc.) from more than 20 different enterprises including dairy, sheep and beef, timber, crops, and horticulture. The national-level model is currently parameterised at the territorial authority (TA) level and solves in 5-year increments.

The NZFARM objective function estimates the level of production outputs that maximize the net revenue[20] of production across the entire territorial authority. NZFARM includes constraints about feasible land-use and management options for each soil, climate, and land-use class combination; agricultural production costs and output prices; environmental factors (e.g. soil type); water for irrigation; and regulated environmental outputs (e.g. GHG emissions price or cap). More details can be found in Daigneault et al. (2012b, 2014).

For policy analysis, we can feed the GHG prices estimated with CliMAT-DGE into NZFARM. The model then estimates the change in land use, farm production, and GHG emissions.

[19] http://www.epa.gov/climatechange/EPAactivities/economics/legislativeanalyses.html

[20] Net revenue (farm profit) is measured as annual earnings before interest and taxes, or the net revenue earned from output sales less fixed and variable farm expenses.

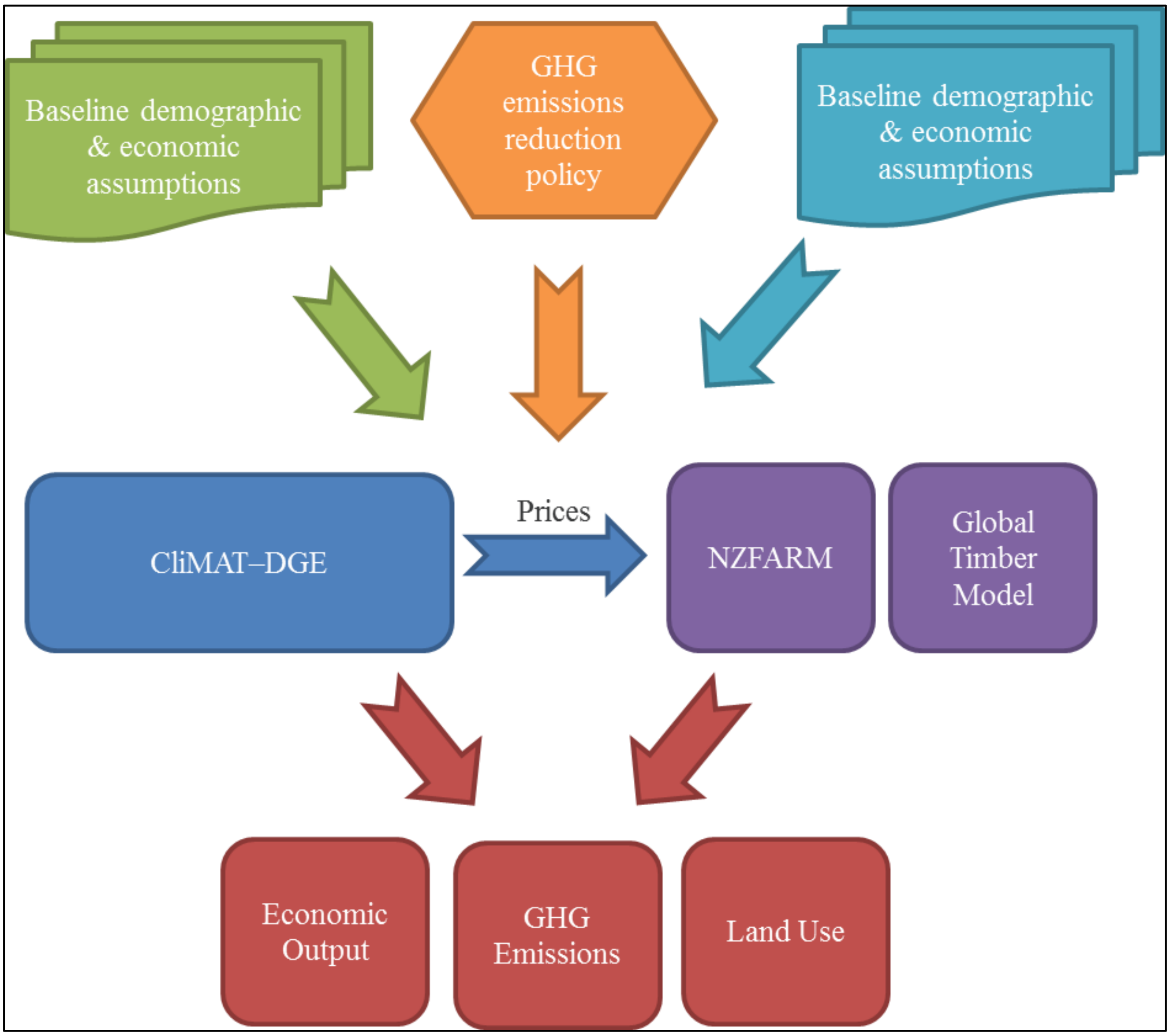

Figure 15: Economic modelling system linkages.

6 Future research

Due to the reliance on exogenous elasticity values and a single base-year observation, comprehensive sensitivity analysis on key elasticities should be performed. In addition to scenarios, the GAMS code of CliMAT-DGE allows the definition of multiple sets of behavioural parameters and sensitivity cases. For example, different elasticity values can be used in different sensitivity cases. Certain elements of the model structure may also be switched on or off in sensitivity analysis, e.g. sector-specific versus generic capital stocks. In principle, sensitivity could also use different baseline specifications, although this has not been implemented to date. However, to some extent changing behavioural or structural parameters will in themselves alter the baseline.

Future work may include constructing projections consistent with CEPII for specific countries for which we may need model simulations. In addition, effort should be invested in resolving outstanding issues with aggregating sectoral GTAP data such that a greater set of aggregations can be represented and adequately modelled in CliMAT-DGE.

It is widely recognised that backstop technologies having zero or even negative emissions are necessary to achieve ambitious emissions reductions targets (van Vuuren et al., 2011). For this CliMAT-DGE includes backstop technologies, however, we found that the model became much more difficult to solve at a large scale if backstops were included. This has been partially resolved compared with previous versions of the models. Still, the remaining numerical difficulties may be resolved through further research as a larger set of backstop technologies may be necessary to widen the scope of analysis.

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Appendix 1 – Mathematical Notation

Table 7: Mathematical Notation in CliMAT-DGE

r	Region
f	Factors of production
a	Activities
ghg	Greenhouse gas (CO2, NH4, NO2, fluorinated gases)
d	Demand
c	Commodities

Appendix 2 – GTAP and CliMAT-DGE Sector Aggregation

Table 8: Mapping between GTAP and CliMAT-DGE Sectors

CliMAT-DGE Primary Production Sectors	GTAP Sector	Notes
GRA	PDR, WHT, GRO	Grains including rice
CRO	V_F, OCR	Other crops
OSC	OSD, C_B	Oil seeds and sugar cane
PFB	PFB	Plant based fibres
CTL	CTL, WOL	Bovine cattle, sheep and goats, horses
RMK	RMK	Raw milk
FRD	FRD	Deforestation
FST	FRP	Forests
CliMAT-DGE Manufacturing and Value Added Sectors	**GTAP Sector**	**Notes**
FOO	CMT, OMT, VOL, MIL, PCR, SGR, OFD, B_T	Food products
HWP	LUM, PPP,	Harvested wood products
EMT	OMN, CRP, NMM, I_S, NFM, OTP, WTP, ATP	Energy-intensive manufacturing
NSV	OAP, FSH, TEX, WAP, LEA, FMP, MVH, OTN, ELE, OME, OMF, WTR, CNS, TRD, CMN, OFI, ISR, OBS, ROS, OSG, DWE	Non-energy-intensive manufacturing
CliMAT-DGE Energy	**GTAP Sector**	**Notes**
COA	COA	Coal
OIL	OIL	Oil
GAS	GAS, GDT	Gas
P_C	P_C	Petroleum-commodities
ELY	ELY	Electricity
EFS	n/a	Constructed from shares of electricity generated from fossil fuel sources
ECF	n/a	Constructed from shares of electricity generated from carbon-free sources

Table 9: Definition of GTAP sectors

pdr	Rice, not husked
	Husked rice
wht	Wheat and meslin
gro	Maize (corn)
	Barley
	Rye, oats
	Other cereals
v_f	Vegetables
	Fruit and nuts
osd	Oil seeds and oleaginous fruit
c_b	Plants used for sugar manufacturing
pfb	Raw vegetable materials used in textiles
ocr	Live plants; cut flowers and flower buds; flower seeds and fruit seeds; vegetable seeds
	Beverage and spice crops
	Unmanufactured tobacco
	Cereal straw and husks, unprepared, whether or not chopped, ground, pressed or in the form of pellets; swedes, mangolds, fodder roots, hay, lucerne (alfalfa), clover, sainfoin, forage kale, lupines, vetches and similar forage products, whether or not in the form of pellets
	Plants and parts of plants used primarily in perfumery, in pharmacy, or for insecticidal, fungicidal or similar purposes
	Sugar beet seed and seeds of forage plants
	Other raw vegetable materials
ctl	Bovine cattle, sheep and goats, horses, asses, mules, and hinnies, live
	Bovine semen
oap	Swine, poultry and other animals, live
	Eggs, in shell, fresh, preserved or cooked
	Natural honey
	Snails, live, fresh, chilled, frozen, dried, salted or in brine, except sea snails; frogs' legs, fresh, chilled or frozen
	Edible products of animal origin n.e.c.
	Hides, skins and furskins, raw
	Insect waxes and spermaceti, whether or not refined or coloured
rmk	Raw milk
wol	Raw animal materials used in textile
for	Forestry, logging and related service activities
cmt	Meat of bovine animals, fresh or chilled
	Meat of bovine animals, frozen

	Meat of sheep, fresh or chilled
	Meat of sheep, frozen
	Meat of goats, fresh, chilled or frozen
	Meat of horses, asses, mules or hinnies, fresh, chilled or frozen
	Edible offal of bovine animals, swine, sheep, goats, horses, asses, mules or hinnies, fresh, chilled or frozen
	Fats of bovine animals, sheep, goats, pigs and poultry, raw or rendered; wool grease
omt	Meat of swine, fresh or chilled
	Meat of swine, frozen
	Meat and edible offal, fresh, chilled or frozen, n.e.c.
	Preserves and preparations of meat, meat offal or blood
	Flours, meals and pellets of meat or meat offal, inedible; greaves
	Animal oils and fats, crude and refined, except fats of bovine animals, sheep, goats, pigs and poultry
vol	Soya-bean, ground-nut, olive, sunflower-seed, safflower, cotton-seed rape, colza and mustard oil, crude
	Palm, coconut, palm kernel, babassu and linseed oil, crude
	Soya-bean, ground-nut, olive, sunflower-seed, safflower, cotton-seed, rape, colza and mustard oil and their fractions, refined but not chemically modified; other oils obtained solely from olives and sesame oil, and their fractions, whether or not refined, but not chemically modified
	Maize (corn) oil and its fractions, not chemically modified
	Palm, coconut, palm kernel, babassu and linseed oil and their fractions, refined but not chemically modified; castor, tung and jojoba oil and fixed vegetable fats and oils (except maize oil) and their fractions n.e.c., whether or not refined, but not chemically modified
	Margarine and similar preparations
	Animal or vegetable fats and oils and their fractions, partly or wholly hydrogenated, inter-esterified, re-esterified or elaidinised, whether or not refined, but not further prepared
	Cotton linters
	Oil-cake and other solid residues resulting from the extraction of vegetable fats or oils; flours and meals of oil seeds or oleaginous fruits, except those of mustard; vegetable waxes, except triglycerides; degras; residues resulting from the treatment of fatty substances or animal or vegetable waxes
mil	Dairy products
pcr	Rice, semi- or wholly milled
sgr	Sugar
ofd	Prepared and preserved fish
	Prepared and preserved vegetables
	Fruit juices and vegetable juices
	Prepared and preserved fruit and nuts
	Wheat or meslin flour
	Cereal flours other than of wheat or meslin

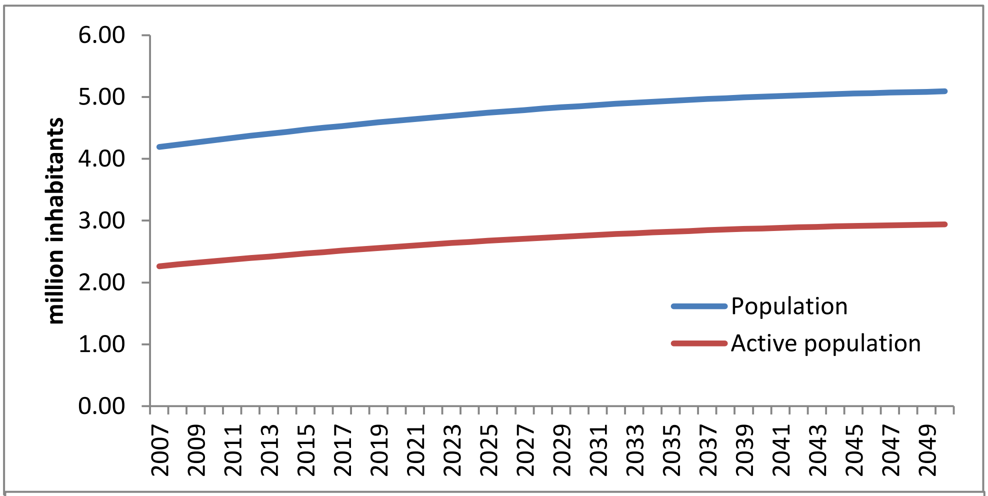
	Groats, meal and pellets of wheat
	Cereal groats, meal and pellets n.e.c.
	Other cereal grain products (including corn flakes)
	Other vegetable flours and meals
	Mixes and doughs for the preparation of bakers' wares
	Starches and starch products; sugars and sugar syrups n.e.c.
	Preparations used in animal feeding
	Bakery products
	Cocoa, chocolate and sugar confectionery
	Macaroni, noodles, couscous and similar farinaceous products
	Food products n.e.c.
b_t	Beverages
	Tobacco products
fsh	Hunting, trapping and game propagation including related service activities
	Fishing, operation of fish hatcheries and fish farms; service activities incidental to fishing
col	Mining and agglomeration of hard coal
	Mining and agglomeration of lignite
	Mining and agglomeration of peat
oil	Extraction of crude petroleum and natural gas (part)
	Service activities incidental to oil and gas extraction excluding surveying (part)
gas	Extraction of crude petroleum and natural gas (part)
	Service activities incidental to oil and gas extraction excluding surveying (part)
omn	Mining of uranium and thorium ores
	Mining of metal ores
	Other mining and quarrying
tex	Manufacture of textiles
	Manufacture of man-made fibres
wap	Manufacture of wearing apparel; dressing and dyeing of fur
lea	Tan and dressing of leather; manufacture of luggage, handbags, saddlery, harness and footwear
lum	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials
ppp	Manufacture of paper and paper products
	Publishing, printing and reproduction of record media
p_c	Manufacture of coke oven products
	Manufacture of refined petroleum products
	Processing of nuclear fuel
crp	Manufacture of basic chemicals

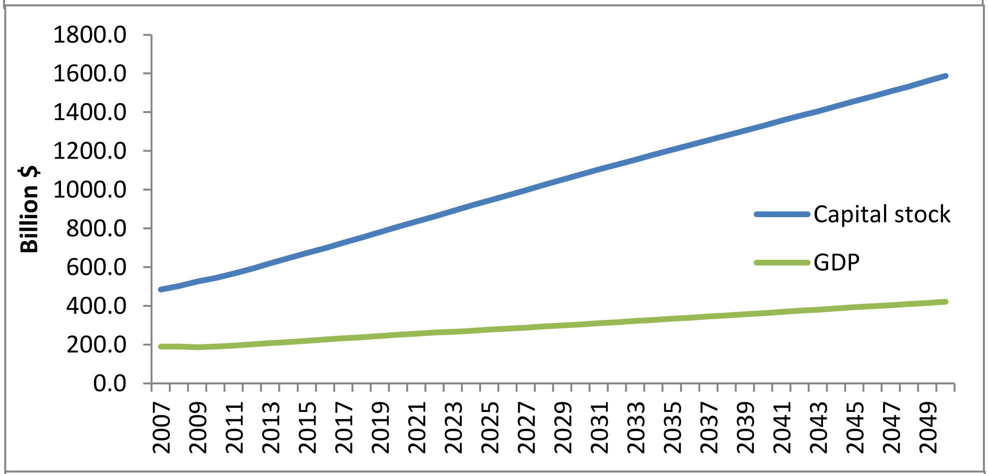
	Manufacture of other chemical products
	Manufacture of rubber and plastics products
nmm	Manufacture of other non-metallic mineral products
i_s	Manufacture of basic iron and steel
	Casting of iron and steel
nfm	Manufacture of basic precious and non-ferrous metals
	Casting of non-ferrous metals
fmp	Manufacture of fabricated metal products, except machinery and equipment
mvh	Manufacture of motor vehicles, trailers and semi-trailers
otn	Manufacture of other transport equipment
ele	Manufacture of office, accounting and computing machinery
	Manufacture of radio, television and communication equipment and apparatus
ome	Manufacture of machinery and equipment n.e.c.
	Manufacture of electrical machinery and apparatus n.e.c.
	Manufacture of medical, precision and optical instruments, watches and clocks
omf	Manufacturing n.e.c.
	Recycling
ely	Production, collection and distribution of electricity
gdt	Manufacture of gas; distribution of gaseous fuels through mains
	Steam and hot water supply
wtr	Collection, purification and distribution of water
cns	Construction
trd	Sales, maintenance and repair of motor vehicles and motorcycles; retail sale of automotive fuel
	Wholesale trade and commission trade, except of motor vehicles and motorcycles
	Non-specialized retail trade in stores
	Retail sale of food, beverages and tobacco in specialized stores
	Other retail trade of new goods in specialized stores
	Retail sale of second-hand goods in stores
	Retail trade not in stores
	Repair of personal and household goods
	Hotels and restaurants
otp	Land transport; transport via pipelines
	Supporting and auxiliary transport activities; activities of travel agencies
wtp	Water transport
atp	Air transport
cmn	Post and telecommunications
ofi	Financial intermediation, except insurance and pension funding

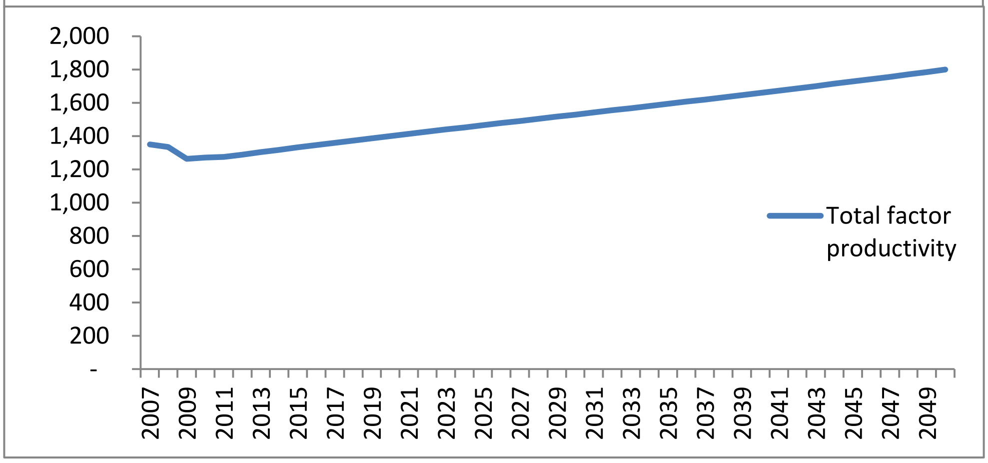
	Activities auxiliary to financial intermediation
isr	Insurance and pension funding, except compulsory social security
obs	Real estate, renting and business activities
ros	Recreational, cultural and sporting activities
	Other service activities
	Private households with employed persons
osg	Public administration and defense; compulsory social security
	Education
	Health and social work
	Sewage and refuse disposal, sanitation and similar activities
	Activities of membership organizations n.e.c.
	Extra-territorial organizations and bodies

Appendix 3 – CEPII baseline projections

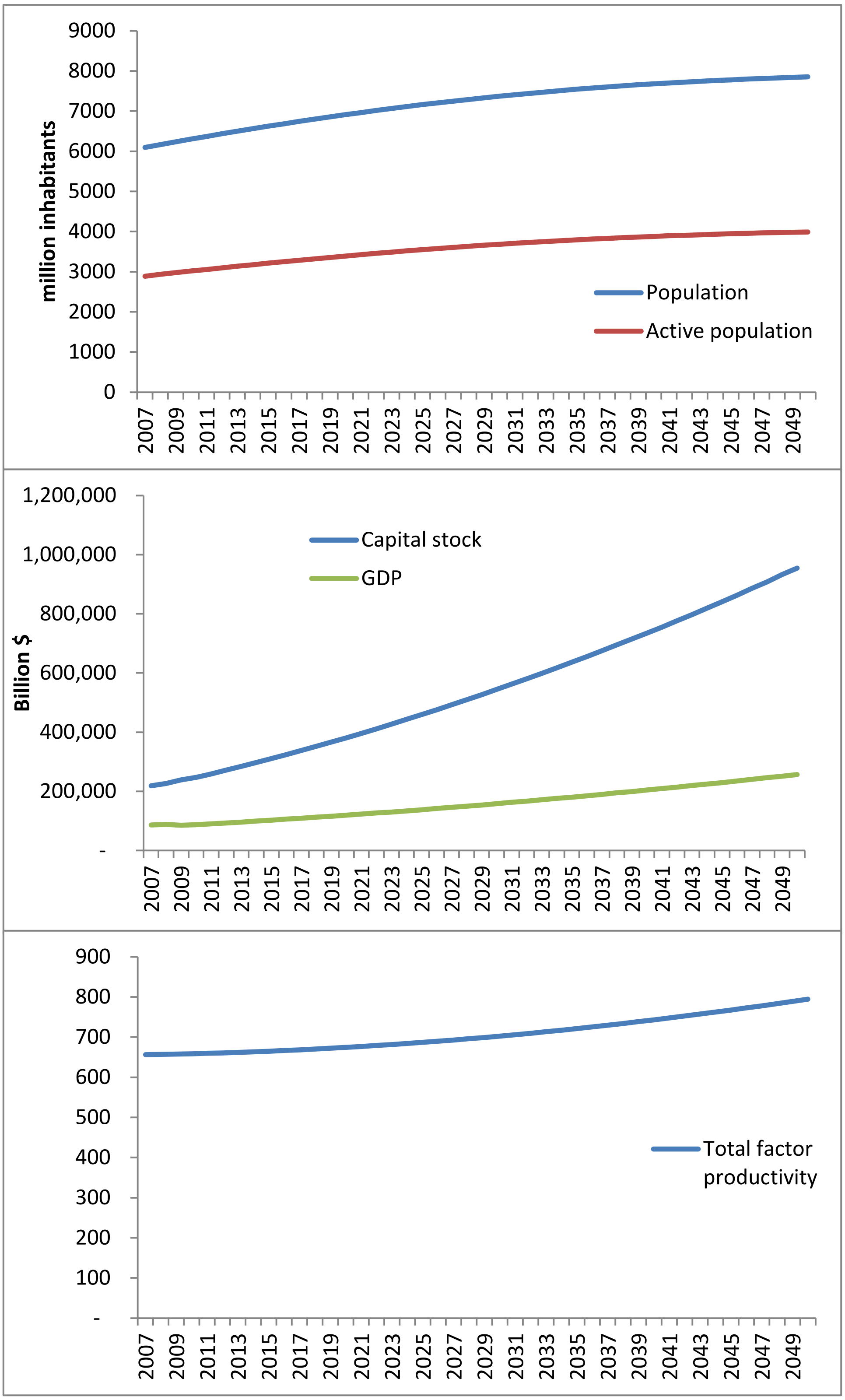
New Zealand







Entire World



Appendix 4 – Disaggregation of GTAP electricity sector into carbon-free and fossil electricity shares and baseline forecasts

Coal, oil, gas, petroleum refining, carbon-free electricity, and fossil electricity are defined as separate sectors. Carbon-free and fossil electricity generation sectors are disaggregated from the single electricity GTAP sector. We allocate fossil fuel inputs to the fossil electricity sector and distribute the outputs following the market shares derived from IEA generation data.

The baseline forecasts of the carbon-free and fossil electricity shares were estimated at country-level using regional forecasts from 2000 to 2035. Baseline data at country-level allows flexibility in the regional aggregations used in CliMAT-DGE. To develop the baseline we used existing regional level forecasts of electricity generation using alternative energy sources and fossil fuel supply from the International Energy Agency World Energy Outlooks (2004 to 2009) (Mandil 2004; OECD 2009). To develop country level forecasts, from 2000 to 2035, of electricity generation using renewable, nuclear, hydro, fossil and other energy sources (Table A3) the following steps were undertaken:

1. At the base year ($t_0 = 2010$) the country level, i, electricity generation by source, k, (renewable, hydro, nuclear, fossil and other), E_{it_0}, were estimated from International Atomic Energy Agency (2011), International Energy Agency (2010), along with the total country level electricity generation, $Eit0$.

2. The country level total electricity generation, Eit, in the forecast year, t, is estimated from

    a. Country level GDP indices (Fouré et al., 2010) from the base-year Y_{it_0} to the forecast year Y_{it},

    b. Base year total country-level electricity generation, E_{it_0}

    c. Forecast total regional electricity generation, Et

    We solve the following optimisation problem for forecast year t:

$$\min_{\theta} \theta \left[\sum_i E_{it_0} \left(Y_{it} - Y_{it_0} \right) \right]$$

$$\text{subject to} \qquad \theta \sum_i E_{it_0} \left(Y_{it} - Y_{it_0} \right) = E_t$$

    The country-level total electricity generation was then calculated as:

$$E_{it} = \theta E_{it_0} \left(Y_{it} - Y_{it_0} \right)$$

3. The estimated country level electricity generation by source, Eikt, in the forecast year, t, is estimated from

    a. Country-level total electricity generation, Eit, in the forecast year

b. Regional-level electricity generation, Ekt, by energy source in the forecast year

by solving the following optimisation problem for forecast year *t*:

$$\min_{E_{ikt}} \left[\sum_{ik} \left(\frac{E_t}{E_{t_0}} (E_{ikt} - E_{ikt_0}) \right)^2 + \left(E_{kt} - \sum_i E_{ikt} \right) + \left(E_{it} - \sum_k E_{ikt} \right) \right]$$

$$\text{subject to} \qquad E_{ikt} \geq 0$$

Additional constraints were added to this optimisation to set country-level electricity generation from nuclear to zero if there was no nuclear energy in the base year (2010).

An example of the New Zealand forecast electricity generation, by energy source is shown in Figure 17.

Table 10: World Energy Outlook energy sources and aggregates of sources

Energy	Sources
Renewable	Solar Photovoltaic, wind
Hydro	Hydro, geothermal
Nuclear	Nuclear
Fossil	Coal, oil, gas
Other	Biomass, waste

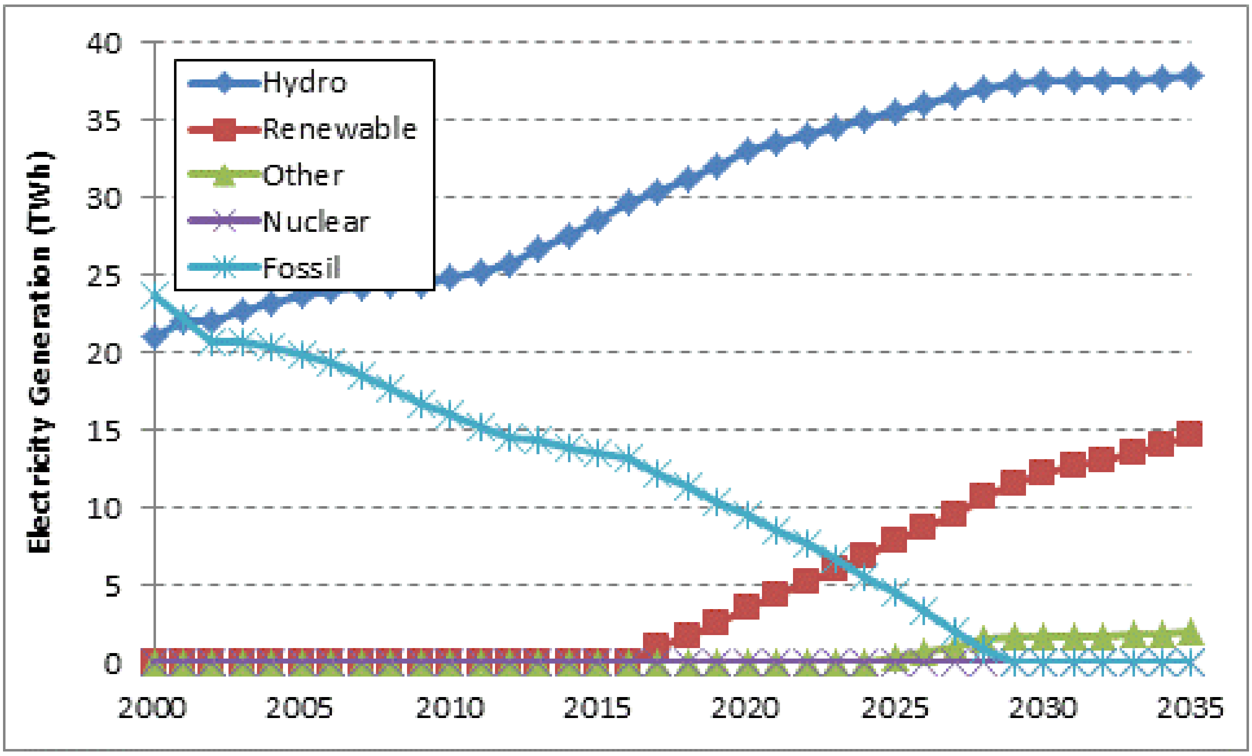


Figure 16: Forecast electricity generation, by source, for New Zealand from 2000 to 2035.