

A Hybrid Energy-Economy Model for Global Integrated Assessment of Climate Change, Carbon Mitigation and Energy Transformation

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Abstract

This paper introduces the design of the CSIRO variant of the Global Trade and Environment model (GTEM-C). GTEM-C is a hybrid model that combines the top-down macroeconomic representation of a computable general equilibrium model with the bottom-up engineering details of energy production. The model features detailed accounting for global energy flows that are embedded in traded energy goods, and it offers a unified framework to analyse the energy-carbon-environment nexus. As an illustrative example, we present simulation results on global energy transformation under the Intergovernmental Panel on Climate Change's representative carbon pathways 4.5 and 8.5. By testing the model's sensitivity to the relevant parameter, we find that the pace of electrification will significantly contain the spiking of carbon prices because electricity can be produced from carbon-free or less carbon-intensive technologies. The decoupling of energy use and carbon footprint, due to the uptake of clean electricity technologies, such as nuclear, wind, solar, and carbon capture and storage, allows the world to maintain high level of energy consumption, which is essential to economic growth.

Keywords: Computable General Equilibrium, Hybrid Model, Integrated Assessment, Carbon Mitigation Policy

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1 Introduction

Climate change poses a significant threat to our societies. Avoiding dangerous anthropogenic climate change requires reductions in greenhouse gas (GHG) emissions. The imposition of a carbon price, either through tax or emission permits, is believed to be an effective approach to reducing GHG emissions. However, a carbon price will increase the cost of goods and services. This places burden on national economies, changing the landscape of competitiveness in the global economy. Therefore, the cost of decarbonisation needs to be weighed against the potential benefit of avoiding dangerous anthropogenic climate change. The policy problem presented by climate change requires an integrated analysis of the tradeoffs between economic growth and environmental degradation.

Integrated modelling provides a unified framework to integrate transdisciplinary knowledge about human societies and the biophysical world. This approach offers a holistic understanding of the energy-carbon-environment nexus [1], and has been intensively used for scenario analysis of possible climate futures [2-5]. The CSIRO's Global Integrated Assessment Modelling framework (GIAM) [6-7] was developed to study alternative GHG emissions pathways for the Garnaut Review [8]. The GIAM framework started with the original Global Trade and Environment Model (GTEM) [9] as its economic core [7]. However, the original GTEM model is based on the Global Trade Analysis Project (GTAP) model versions 4.1, which suffers from defects in the regional household demand system [10-11]. Additionally, the "technology bundle" approach that GTEM uses to model the energy-intensive sectors is based on outdated data source and ad hoc selection of parameters [7,12]. Most importantly, although the original GTEM model features disaggregated modelling of the electricity sector, it does not account for global energy flows embedded in fossil fuels such as coal, oil and gas. These drawbacks of the model make GTEM less capable of meeting the emerging needs of global energy and environmental research, particularly around the needs of the new generation of Climate and Earth System Models [13].

Over the last few years, an interdisciplinary team of CSIRO climate scientists and economists have developed a hybrid model that combines the top-down macroeconomic representation of a computable general equilibrium (CGE) model with the bottom-up engineering details of energy production and consumption [14-17]. This model builds upon the global trade and economic core

of GTAP [10], and has inherited the “technology bundle” approach of GTEM for modelling heterogeneous electricity technologies [9]. To explicitly recognise its connection with the original GTEM, this hybrid model is named as the CSIRO variant of the Global Trade and Environment model (GTEM-C).

Compared to GTAP and the original GTEM, several modelling innovations have been made in GTEM-C in relation to: (1) regional household demand system using the theoretical framework presented in McDougall [11]; (2) electricity generation using the US Energy Information Administration (EIA)’s latest estimates for cost structures of different types of power plant [18], and for partial elasticities of substitution among fossil fuel power technologies [19]; (3) accounting of non-combustion carbon emissions using the GTAP non-CO₂ emissions database [20-21]; (4) price-induced endogenous carbon technological progress according to the empirical finding of Popp [22]; (5) accounting of global flow of commodity-embedded energies using the GTAP energy database [23]; and (6) linkage with the global climate and earth system models for integrated assessment following the work of Nordhaus [24], Bosello and Roson [25], Bandara et al. [26], and Dunne et al. [27].

This paper is to document main features of the GTEM-C model, and illustrate its application in the GIAM framework. The rest of the paper is organized as follows. Section 2 offers a brief review of the literature, and highlights the difference and novelty of the GTEM-C model from the existing ones. Section 3 presents the structure of GTEM-C. Section 4 demonstrates the application of GTEM-C in studying the role of electrification in neutralizing the economic impacts of a global carbon price. Section 5 concludes by discussing advantages and disadvantages of the GTEM-C model, and pointing out directions for future research.

2 Literature Review

CGE modelling is a widely-used tool for analysing energy and environmental policies. This approach provides a coherent and systematic evaluation framework that places government policies in the socioeconomic context of resource allocation, commodity circulation, price

formation, and wealth generation [28]. Examples of their use may be found in recent publications [29-37].

However, CGE models typically assume that each economic sector is represented by a price-taking firm producing a homogenous good. In other words, the production technologies in each sector are the same in such models, and differences are in the relative use of factor and intermediate inputs. Such technological generality is problematic when considering energy policies, as specific aspects of energy production technologies have important differences. These differences can have important implications for energy prices and economy-wide output [38-39]. The inability to support disaggregated analysis is therefore a short-coming for traditional CGE models.

This has led to the development of hybrid models that incorporate bottom-up technology details of energy within a top-down CGE framework. A great amount of effort has been devoted to the modelling of the electricity sector. For example, Sue Wing [40-41] proposes a structure and numerical algorithm to model electricity generation as a constant elasticity of substitution (CES) aggregate of multiple technologies. In the more recent Phoenix model [42], the authors further place generation into three nests: base load, intermediate load, and peak load. This approach preserves the general equilibrium of the models, while allows different electricity generation technologies to be modelled as competing substitutes. However, it assumes constant elasticity substitution between any two technologies (such as coal, oil and gas power generators), which contradicts the empirical findings of Dahl and Ko [43], Ko and Dahl [44], and EIA [19].

In contrast, some “bottom-up” energy models move away from the restrictive assumptions common to CGE models. Sands [45], Schumacher and Sands [46-47], and Fujimori et al. [32] use the Logit functions to determine the share of electricity production from a particular generation technology. Similarly, the Cambridge Econometrics Model (E3ME) relies on econometrically estimated equations to capture two-way linkages and feedbacks between the world’s economies and energy systems [48]. However, the difficulty with using these approaches in CGE models is that they are difficult to relate to the models’ economy-wide general equilibrium.

The original GTEM model [9] takes a different approach, and uses the CRESH (Constant Ratios of Elasticities of Substitution, Homothetic) function to disaggregate the electricity sector in GTAP into a bundle of heterogeneous technologies. The CRESH function, which is due to Hanoch [49], allows for different degrees of substitution between any two technologies. This technology bundle approach follows from the standard economic theory of general equilibrium, and allows for different assumptions about substitutability between technologies. However, previous implementations of the approach in the GTEM model are based on outdated data source and ad hoc selection of parameters for the elasticities of substitution. Moreover, there has been little written about the approach's mathematical properties and the link between its parameters and various econometric estimates of substitution between fuels and technologies in electricity generation.

The development of the GTEM-C model is to further this line of inquiry. It extends the widely-used GTAP CGE model [10-11], and uses a revised technology bundle approach of Arora and Cai [12] to disaggregate the electricity sector in GTAP into 13 heterogeneous technologies. GTEM-C also makes use of the CRESH function to model the competition between energy services (namely, coal, petroleum products, gas and electricity) in industrial process and household consumption. This enables the model to simulate alternative scenarios of technology development and to investigate of role of electrification in energy-related environmental policies as we will demonstrate in Section 4. We have explored the mathematical structure of the CRESH function, and established the link between its parameters and econometric estimates in the existing literature [19, 50]. This is the first novelty of GTEM-C.

Another novelty of GTEM-C is to entail detailed accounting for global energy flows that are embedded in traded energy goods, as well as for four GHG emissions (CO_2 , N_2O , CH_4 and the F-gases) that are emitted from fossil fuel combustion, industrial process and agricultural production. This is done by linking the GTAP input/output dynamics to energy and emissions databases that are recently developed by McDougall and Aguiar [23], Rose and Lee [20], and Rose et al. [21]. Additionally, GTEM-C models price-induced endogenous carbon technological progress that is based on the empirical findings of Popp [22].

The GTEM-C model also makes a contribution to the literature by extending the static GTAP model to include international capital dynamics. We introduce a simple mechanism of international finance that is based on the theory of “equity home bias” [51]. Needless to say, international capital mobility and capital accumulation are important consequences of some of the international energy and environmental policies that deserve investigation. For instance, the differences in carbon taxes (or the market price of emission permits) can change the landscape of trading advantage across regions. This will lead to changes in regional energy consumption, economic growth, and subsequently international movement of energy-intensive industries.

In the following section, we will discuss main features of the GTEM-C. We focus on the model aspects that are distinct from GTAP [10] and the original GTEM [9]. In particular we will explore the energy-related economic activities, such as: (1) energy consumption; (2) electricity generation; and (3) commodity-embedded energy flows and GHG emissions.

3 The Design of GTEM-C

3.1 Overview

GTEM-C disaggregates the world economy into a set of autonomous regions. Countries of large economic size and distinct institution are modelled separately, and the rest of the world is disaggregated into regions according to geographical proximity and climate similarity. Each region has a representative household. The representative households play three important roles in the model: (1) they own and supply factor inputs of production, (2) they own the regional income including payments to all factor inputs; tax revenues and international transfers and determine regional savings; and (3) they consume goods and services.

In each of the autonomous region, local production is divided into multiple commodity sectors/industries. The regions interact with each other through trade and capital flows, and regional households consume both domestic and imported goods. Capital investment takes place across regions, so households can allocate their savings either domestically or internationally. In

contrast, other factors of production (land, labor, natural resources) are available only domestically. The GTAP 8.1 [52] database consists of 131 regions and 57 sectors. We aggregate this database into 18 regions and 19 sectors (see Tab. 1 and Tab. 2) based on their significance to the global economy, as well as, their vulnerability to climate change. We note that alternative aggregations are possible, and aggregations should be determined by the question under investigation.

[Table 1 about here.]

[Table 2 about here.]

Humans produce greenhouse gases by burning fossil fuels to generate energy for industrial and residential use. Agricultural activity and industrial processes also yield GHG emissions. This determines the environmental footprint of human activities, and the consequential (negative) environmental feedbacks. Governments, thus have a role in neutralizing the feedbacks through policy intervention, such as the imposition of Pigovian taxes and emission permits. A schematic diagram of GTEM-C is provided in Fig. 1.

[Figure 1 about here.]

As a matter of notation, throughout this paper the subscripts r, i will be used to denote the regions and sectors. Unless otherwise specified, variables starting with an upper case letter represent the levels and those starting with a lower case letter represent the percentage changes. A nomenclature is provided as an appendix to this paper. In the following sub-sections we work through: (1) households and consumption; (2) firms and production; (3) factor supplies; (4) international finance; (5) global transportation; (6) energy use and GHG emissions; and (7) equilibrium.

3.2 Households and Consumption

Each region has one household that represents final consumption (private consumption, as well as the government's procurement, i.e., public consumption), and all regional households' savings. The household's preferences are nested in a hierarchy of consumption, building from details on goods and services consumed up to measures of composite utility defined on a per capita basis (see Fig. 2).

[Figure 2 about here.]

Following McDougall [11], we adopt the new GTAP demand system and assume that the regional representative household maximizes per capita aggregate utility

$$U = (Up)^\alpha (Ug)^\beta (Us)^\gamma \quad (1),$$

subject to the income constraint:

$$Ep(Up, Pp) + Eg(Ug, Pg) + Es(Us, Ps) = Y/POP \quad (2).$$

Here, α , β and γ are positive parameters; Y denotes regional income and POP denotes regional population; $Ep(\cdot)$ is the per capita private expenditure that is a function of per capita utility from private consumption Up and the price of private consumption Pp ; and $Eg(Ug, Pg)$ and $Es(Us, Ps)$ are defined in a similar way. Although the structures of $Ep(\cdot)$, $Eg(\cdot)$ and $Es(\cdot)$ as well as the values of Up , Ug and Us are implicitly implied in the GTAP database, the percentage changes of them after a policy shock can be calculated by solving the new equilibrium as per McDougall [11].

In the private consumption component, the household's preference over the energy composite and other final goods is represented by the Constant Difference in Elasticity (CDE) function which is due to Hanoch [53]. Specifically, following Hertel [10, p49], we let the household's indirect utility function be:

$$1 = \sum_i B_i (Up/POP)^{\varepsilon_i \varphi_i} (P_i/Ep(Up, Pp))^{\varepsilon_i} \quad (3),$$

where, for each good, B_i , ε_i , φ_i are the distribution, substitution and expansion parameters. The indirect utility function gives the household's maximal utility from private consumption when faced with a vector of prices $[P_i]$ and per capita private expenditure $Ep(Up, Pp)$. Consequently the optimal demand can be recovered by Roy's identity [53-54], which yields the linearized equality:

$$q_i = \sum_k EP_{i,k} \cdot p_i + EY_i \cdot (e_p - pop) \quad (4).$$

Here, for each good i , q_i is the percentage change of demand, p_i is the percentage change of price, and $e_p - pop$ is the percentage change of per capita private expenditure. Moreover, $EP_{i,k}$ is the cross price elasticity of substitution between goods i and k , that is mainly controlled by the substitution parameters ε_i , ε_k , and EY_i is the income elasticity that is mainly controlled by the

expansion parameter φ_i . Both elasticities also vary with the budget share of each good. The CDE preference is non-homothetic in the sense that the ratios of goods demanded by consumers will depend not only on relative prices but also on income. Down to this level, the consumption structure of GTEM-C is the same as that of the GTAP model except for that coal, petroleum products, gas, and electricity are aggregated into the energy composite.

The current version of our model has an “Oil” sector that produces crude oil and a “P_C” sector that produces refined petroleum products. According to the GTAP database, crude oil is rarely used in final consumption and industrial production other than gas and oil extraction, refining, chemicals, and electricity generation. Therefore, we have excluded crude oil from the energy composite. For this energy composite, we borrow from GTAP the substitution and expansion parameters (in Eq. 3 and 4) for electricity. The parameters for other sectors are directly taken from the GTAP database. The demand system is calibrated to follow Engel’s law such that private demand for subsistence goods, such as crops, livestock and processed food, will drop as regional income increases, whereas private demand for luxury goods, such as manufacturing, energy and services, will rise as regional income increases.

As for the energy composite, GTEM-C uses the CRESH function to represent the household’s aggregate preference over coal, petroleum products, gas, and electricity. Specifically, for X units of demand for the energy composite, it implies the following identity:

$$\sum_i (Q_i/X)^{d_i} \cdot D_i/d_i = \kappa \quad (5),$$

where each d_i is less than 1 but not equal to zero, each D_i is positive and the D_i ’s and κ are normalized such that $\sum_i D_i = 1$. The CRESH function is due to Hanoch [49], and the mathematical derivation is available from Dixon et al. [55, p64-76]¹.

With the CRESH function, percentage change of demand for each good q_i is determined by:

$$q_i = q_X + a_i \cdot (p_i - p_X^*) \quad (6).$$

Here, q_X is the percentage change of the household’s aggregate energy demand; p_i is the percentage change of fuel i ’s price; and $p_X^* = \sum_i a_i \cdot s_i \cdot p_i$ is the percentage change of the

¹ It is important to note that when $d_i = d$ for all i , the CRESH function collapses to the CES function, $1/d \cdot \kappa \cdot \sum_i Q_i^d \cdot D_i = X$.

aggregate energy price weighted by the a_i 's and the fuel cost shares $s_i = Q_i \cdot P_i / \sum_j Q_j \cdot P_j$. The coefficient a_i is linked to d_i such that $a_i = -1/(1 - d_i)$, and it can be roughly interpreted as the energy commodity i 's price elasticity of substitution. Because each a_i can correspond to a different value of d_i , the CRESH function allows different elasticities of substitution among the primary and secondary energies.

Currently, all the a_i 's are set to a benchmark of 0.5, such that the inter-fuel elasticities of substitution², $\delta_{i,j} = \partial \left(\ln \frac{Q_j}{Q_i} \right) / \partial \left(\ln \frac{P_i}{P_j} \right)$, are all 0.5 (see Hanoch [49] and Chambers [57, p93-97]). This means, for example, if the relative price of coal to gas increases by 1% due to a carbon price for instance, the demand for gas relative to coal will increase by 0.5%; similarly, if the relative price of coal to electricity increases by 1%, the demand for electricity relative to coal will increase by 0.5%. While our choice of the a_i values is consistent with the literature that is surveyed in Stern [50], it is important to note that the model's behaviour can be very sensitive to the a_i values. For instance, assigning higher value of a_i to electricity, the model can simulate fast-track electrification of energy that is required by the transition to a low-carbon economy with the imposition of carbon prices.

In the sectoral composition, each commodity is an aggregate of imported and domestic goods. The preference is represented by the Constant Elasticity of Substitution (CES) function, which allows imperfect substitution between imported and domestic goods, Q_i^{Imp} and Q_i^{Dom} :

$$Q_i = \left[\rho_{Dom} (Q_i^{Dom})^{\frac{\sigma-1}{\sigma}} + \rho_{Imp} (Q_i^{Imp})^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}} \quad (7).$$

Here, σ is commonly known as the Armington elasticity of substitution between imported and domestic goods, and ρ_{Dom} and ρ_{Imp} are the budget share parameters. For more details, please see, for example, Burfisher [57, p75]. Finally the imported good Q_i^{Imp} is, in turn, a CES composite of shipments from various sources $Q_{r,i}^{Imp}$, i.e.,

² The inter-fuel elasticities of substitution, i.e., $\delta_{i,j} = \partial \left(\ln \frac{Q_j}{Q_i} \right) / \partial \left(\ln \frac{P_i}{P_j} \right)$, is a function of all $s_i = Q_i^d / X$ and a_i . Specifically, the cross price elasticities are $\varepsilon_{i,j} = \partial (\ln Q_j^d) / \partial (\ln P_i) = \frac{s_j a_j a_i}{\sum_k s_k a_k}$ and $\varepsilon_{i,i} = \partial (\ln Q_i^d) / \partial (\ln P_i) = \frac{s_i a_i a_i}{\sum_k s_k a_k} - a_i$. Consequently, the Morishima elasticities of substitution are $M_{i,j} = \varepsilon_{j,i} - \varepsilon_{i,i}$, and $\delta_{i,j} = \frac{s_i}{s_i + s_k} M_{i,j} + \frac{s_j}{s_i + s_k} M_{j,i}$.

$$Q_i^{Imp} = \left[\sum_r \rho_r (Q_{r,i}^{Imp})^{\frac{\eta-1}{\eta}} \right]^{\frac{\eta}{\eta-1}} \quad (8),$$

where ρ_r is budget share parameter, and η is the elasticity of substitution among imports from different sources.

In contrast, public consumption of final goods in GTEM-C is simply modelled by the Cobb-Douglas function, which assigns fixed nominal shares to each sector. In other words, government procurement will shift weight towards goods that are of lower prices given the same public budget. Similarly, sectoral commodities are nested CES aggregates of imported and domestic goods. This follows Hertel [10].

The above formulation of household preferences possesses several features that fit observed consumption patterns [11]. First, as regional income rises, budget shares of luxury goods rise while those of subsistence goods decline; budget shares of public consumption and saving increase while that of private consumption falls. Second, regional income being the same, a more populated economy will demand more subsistence goods and less luxury goods than a less populated economy.

3.3 Firms and Production

3.3.1 Electricity: A Technology Bundle (TB) Industry

The GTEM-C model follows Pant [9] to distinguish the technology bundle industry from a general industry. A technology bundle industry consists of a bundle of heterogeneous and competing technologies, and an assembling service that unifies products of all technologies into a homogeneous industrial output. Fig. 3 outlines the production structure of a typical TB industry. At the top level, the industrial output Q_i is a Leontief function of the assembling service³ Q_i^A and the technology bundle Q_i^B , i.e.,

$$Q_i = \text{Min}\{A_i Q_i^A, B_i Q_i^B\} \quad (9),$$

³ In the context of electricity, this assembling service can be understood as operation and maintenance, transmission and distribution.

where A_i and B_i are scale factors, and Min is the minimum operator. The Leontief function is non-smooth, which captures the rigidity of production in the presence of fixed sunk cost or resource immobility. At the lower nest, the assembling service is also a Leontief function of non-technology-specific intermediate inputs. The technology bundle is a CRESH function of different technologies. Each technology is, in turn, a Leontief function of technology-specific factors, and imported and domestic intermediate inputs. Finally, intermediate inputs used by the assembling service and each technology are CES aggregates of domestic and imported goods.

[Figure 3 about here.]

Currently, electricity is the only one TB industry in GTEM-C. Electricity generation accounts for a large fraction of GHG emissions, and plays an important role in carbon mitigation. The electricity industry has three emission-intensive technologies: coal, oil and gas, as well as seven emission-free technologies: nuclear, hydro, wind, solar, biomass, waste, and other renewables⁴. Coal, oil and gas are further divided into conventional coal, oil and gas, and their counterparts with carbon capture and storage (CCS). Arora and Cai [12] has provided an intuitive description and outline of the electricity technology bundle.

We follow the approach of Arora and Cai [12] to build the electricity-technology-bundle database. In terms of output, the electricity sector is disaggregated into the 13 technologies (as aforementioned) using the IEA world energy balance table⁵. In terms of input, we rely on the latest EIA estimate of cost structure for various electricity generating technologies [18], and use them as auxiliary weights to split capital and labor into the 13 technologies. As for technology-specific intermediates, non-ferrous metal and mineral products are associated with nuclear, agricultural goods are assigned to biomass and all fuels are allocated to coal, oil and gas accordingly. To further divide coal, oil and gas into conventional and CCS sub-technologies, we apply the heuristic that CCS uses 20% more fuel, but only emits 10% of emissions [58]. With regard to the inter-fuel elasticities of substitution in electricity generation, those among coal, oil and gas are taken from the estimate of EIA [19]; while those for non-fossil fuels are calibrated

⁴ This includes geothermal, wave and others that are not specified.

⁵ Source: <http://data.iea.org/ieastore/statslisting.asp>.

such that the model's projected pattern of energy transformation is consistent with those in the literature, such as Riahi et al. [2] and Thomson et al. [4].

3.3.2 Non-TB Industries

The production within a non-TB industry also has a tiered structure (Fig. 4). At the top tier, industrial output is a Leontief function of a fuel-factor composite, and other intermediate inputs. The fuel-factor composite is either a Leontief or CES function of the fuel composite and the factor composite, allowing different levels of substitutability between fuel and other inputs. The fuel composite is a CRESH function of coal, petroleum products, gas, and electricity, while the factor composite is a CES function of natural resources, land, labour and capital. Coal, gas, petroleum products, electricity and other intermediate inputs are, again, CES aggregates of imported and domestic goods.

[Figure 4 about here.]

With respect to the parameters, we follow Hertel et al. [59] to set the inter-factor elasticities of substitution such that the long-term supply elasticities of coal, oil and gas are consistent with the estimates of Beckman et al. [60] and EIA [61]. A sensitivity analysis on the long-term supply elasticity of gas has been conducted in Arora and Cai [17]. Again, all the a_i 's in the CRESH function of industrial energy use are set to 0.5 as we have done for private energy use in Sub-Section 3.2. In section 4, we will test the model's sensitivity to these a_i values, and explore how electrification can help to neutralise the economic impacts of imposing a global carbon price.

3.4 Factor Supplies

Natural resources, land and labor are only supplied locally. Specifically, natural resources and land can be sluggishly reallocated across different sectors. Aggregate supplies of natural resources and land are assumed to be constant or decreasing in GTEM-C. Labor moves freely across all domestic sectors, but the aggregate supply grows according to demographic and labour force participation assumptions and is constrained by the available working population, which is supplied exogenously to the model as part of the population growth trajectories.

The growth over time of a region's capital stock is modelled differently to the other input factors. The capital stock K of region r changes over time according to the level of investment I_r and the level of depreciation of existing capital δK , i.e.,

$$\dot{K}_r = I_r - \delta K_r \quad (10).$$

Following the GTAP convention, we set the depreciation rate δ to 0.04 for all regions.

3.5 International Finance

While saving is the local decision of households, capital investment takes place across regions. This is managed by a “global fund” according to the following rule:

$$Qinv_r = \left(S_r / Pinv_r \right)^\theta \cdot e^{\tau \cdot (R_r - \bar{R})} \cdot \aleph^{\varphi_r} \quad (11).$$

Here $Qinv_r$ and $Pinv_r$ are the quantity and price of regional investment, and $I_r = Qinv_r \cdot Pinv_r$; and S_r is the gross regional saving, that is, net regional saving plus 4% depreciation of regional capital stock). In the first term on the right-hand-side, θ is a time-variant parameter that is negatively linked to the ratio of region r 's foreign debt DB_r to gross domestic product GDP_r ,

$$\theta = e^{-\chi \left(\frac{DB_r}{GDP_r} \right)} \quad (12),$$

where χ is positive when $DB_r > 0$, and zero otherwise. The intuition behind the algebra is that economies with abundance of savings will have more local investment. In fact, individuals and institutions in most countries hold only modest amounts of foreign equity, and this is the “equity home bias” as quoted in the literature (see Obstfeld and Rogoff [51]). However, sovereign risks as reflected by the debt-to-GDP ratio will be a counter-balancing factor, because foreign creditors are concerned about possible default and thus capital account deficit cannot be sustained unlimitedly. In the second term of Eq. 11, R_r is the regional rate of return on capital, and $\bar{R}$ is global average rate of return on capital (i.e., the weighted average of all R_r 's). Both R_r and $\bar{R}$ are endogenously determined by the model, and generally there exists a differential between the two. Our investment rule thus allows the savings of a country to flow to other countries with more productive investment opportunities. Moreover, $\aleph$ is a global uniform adjustment factor that is endogenously determined to ensure the Walras' law:

$$\sum_r I_r = \sum_r S_r \quad (13),$$

and φ_r is each region's responsiveness to this adjustment. Consequently the debt of a region accumulates as

$$\dot{DB}_r = DB_r \cdot \bar{R} + (I_r - S_r) \quad (14).$$

Here, $DB_r \cdot \bar{R}$ is the compulsory interest payment made by each region, and is subtracted from regional income. Parameters of the equations above are calibrated so that $\bar{R}$ converges to a long term steady rate that is consistent with the world economic growth. In the current version of GTEM-C, τ is set to 5, χ is set to 0.5, θ is set to 0.8 and φ_r is set to 1 for all regions.

3.6 Global Transportation

As has been noted above, both imported and domestic goods are needed for consumption and industrial use, which require international shipping services. Due to the lack of data, GTEM-C follows Hertel [10] to assume that the demand for services of each specific route is proportional to the trade flows among regions, adjusted by exogenous technological advancement. A “global transport corporate”, which exists in the international water, then intermediates and outsources the fulfilment of aggregate demand to water, air and land transportation sectors of each region, by a Cobb-Douglas technology.

3.7 Energy Use and GHG Emissions

3.7.1 Energy Accounting

Energy is embedded in energy goods. Therefore the input-output flows of energy mirror those of coal, oil, petroleum products, gas, and electricity as in GTEM-C's social accounting matrix (SAM). For instance, energy use through private consumptions of domestic gas is

$$N_{P_{GAS}}^{Dom} = Q_{P_{GAS}}^{Dom} \cdot \xi_{P_{GAS}}^{Dom} \quad (15),$$

and energy use through input of domestic coal by the electricity sector is

$$N_{F_{COL,ELY}}^{Dom} = Q_{F_{COL,ELY}}^{Dom} \cdot \xi_{F_{COL,ELY}}^{Dom} \quad (16).$$

The quantities of fossil fuel use, such as $Q_{P_{GAS}}^{Dom}$ and $Q_{F_{COL,ELY}}^{Dom}$, are tracked by the SAM, which is driven by market supplies and demands; and the energy coefficients $\xi_{P_{GAS}}^{Dom}$ and $\xi_{F_{COL,ELY}}^{Dom}$ are assumed to remain constant. There is a similar relationship between government consumption

and the energy use. The current energy data structure allows GTEM-C to capture the circulation of energy flows in the global economy. However, this approach poses a potential problem of double counting, as commodity-embedded energy is sequentially transferred to other sectors through the use of intermediate inputs. To avoid this problem, we exclude (crude) oil and calculate regional total primary energy output as the sum of domestically produced coal, petroleum products, and gas that are either locally consumed or exported, plus nuclear and renewable electricity generated. This removes the potential for double counting in the transformation of crude oil to petroleum products; and fossil fuel to electricity. Similarly, regional total final energy use is calculated as the sum of imported and domestic coal, petroleum products, and gas that are directly consumed by the household and all non-electricity sectors, plus the electricity that is locally used.

3.7.2 Emissions Accounting

Combustion-based GHG emissions, i.e., CO₂, CH₄, N₂O and the F-gases, are directly linked to fossil fuel use of the household and each industrial sector and their emission intensities. For instance, emissions from private consumptions of domestic petroleum products are:

$$M_{P_{P-C}}^{Dom} = Q_{P_{P-C}}^{Dom} \cdot \epsilon_{P_{P-C}}^{Dom} \quad (17).$$

Similarly, emissions from industrial use of domestic petroleum products by the air transport sector are:

$$M_{F_{P-C,AIR}}^{Dom} = Q_{F_{P-C,AIR}}^{Dom} \cdot \epsilon_{F_{P-C,AIR}}^{Dom} \quad (18).$$

Again, the quantity of fossil fuel use, such as $Q_{P_{P-C}}^{Dom}$ and $Q_{F_{p-c,air}}^{Dom}$, are recorded by the SAM, which is driven by market supplies and demands. For household consumption, the emission intensities are exogenously given to the model. For industrial use, however, carbon price induced technological change is allowed to reduce emissions, such that

$$\epsilon_{F_{P-C,AIR}}^{Dom} \propto (C_{P-C,AIR}/P_{AIR})^{-\eta} \quad (19).$$

Here $C_{P-C,AIR}/P_{AIR}$ is the share of the input-based carbon price mark-up in the price of air transport, and the positive parameter η measures the economy's elasticity of price induced carbon technological advancement. Our specification of carbon price induced technological change is enlightened by the empirical finding of Popp [22] that energy efficient innovations are

positively correlated to energy prices. The calibration of η is chosen such that the model's simulated pace of carbon intensity reduction is consistent with Figure 11 of Riahi [2].

Process-based GHG emissions are determined by sectoral outputs and emission intensities as well. For instance, emissions from petroleum production are:

$$M_{O_{P_C}} = Q_{P_C} \cdot \epsilon_{O_{P_C}} \quad (20).$$

Likewise, carbon price induced technological progress is assumed to be:

$$\epsilon_{O_{P_C}} \propto (C_{P_C}/P_{P_C})^{-\eta} \quad (21),$$

where C_{P_C}/P_{P_C} is the share of output-based carbon price mark-up in the price level of petroleum products.

Finally, non-combustion GHG emissions from agricultural sectors are based on the use of factor inputs. For instance, emissions from livestock are proportional to the sectoral use of capital (as a proxy for scale of farming), and emissions from paddy rice are proportional to the sectoral use of land (as a proxy for area of planting). No endogenous technological change is assumed.

3.8 Linking with Global Climate Models

As has been discussed above, GTEM-C is capable of projecting future GHG emissions. The carbon pathway can be analysed by global climate models, such as the Simple Carbon Climate Model [62] or the Australian Community Climate and Earth System Simulator Coupled Model (ACCESS) version 1.0 [63]. The simulation results of global climate models are used to quantify the climate-economy interactions through a set of empirical and econometric sub-models. These climate feedbacks are taken to GTEM-C as exogenous shocks to the socioeconomic system, and GTEM-C solves for the set of policy constraints so that its projected carbon pathway is consistent with the one that is analysed by the global climate models. This forms the circle of a GIAM exercise. A schematic diagram of GIAM is provided in Fig. 5.

[Figure 5 about here.]

Three channels of climate-economy interactions are currently considered in the GIAM framework. First, the degree of climate change represented by the surface air temperature affects

regional total factor input productivities. We currently use the quadratic damage function as per Nordhaus [24], such that

$$\Lambda_r = 1 - \frac{1}{1 + \phi_r \cdot \Delta T + \varphi_r \cdot \Delta T^2} \quad (22).$$

Here ΔT is the change of global average temperature from its 2007 level, and the damage Λ_r then enters GTEM-C as a (negative) input-augmenting productivity shock to the factor-composite in industrial production. The ϕ, φ parameters for each region are borrowed from Bosello and Roson [25]. By default, both ϕ, φ are set to be 0.005, such that global warming of 2 °C will result in roughly 3% loss of total factor input productivity. This mechanism is incorporated in GTEM-C, and the change of global average temperature ΔT is taken as an exogenous variable.

Second, changes of regional temperature and precipitation affects land productivity of various crops. A high-level programming framework within Python has been developed, which: (1) collects historical data for crop production from the Food and Agriculture Organization (FAO)⁶ and historical reanalysis of temperature and rainfall from the University of East Anglia Climate Research Unit (CRU) 3.1 database (CRU 3.1; <http://www.cru.uea.ac.uk>); (2) uses the global crop planting date database developed by Sacks et al. [64] to average monthly values of temperature and precipitation in the CRU 3.1 dataset for the growing season months and for the crop that is grown; (3) uses the constructed data to estimate the effects of historical climate change on regional crop production (see Bandara et al. [26]); and (4) combines the econometric model for crop production with the simulation results of climate models to forecast regional crop land productivities. These results are then taken to GTEM-C as exogenous shocks to land productivities of different crops.

Third, heat stress due to change of temperature and humidity affects labor productivity. The study of Dunne et al. [27] suggests that increased heat stress, as measured by the Wet Bulb Global Temperature (WBGT), will reduce labor capacity, and the authors have provided a set of formulas to quantify this negative impact of climate change. A high-level programming framework within Python has been developed, which: (1) bias-corrects and variance-corrects the simulation results of a selected climate model; and (2) applies Dunne et al. [27]’s formulas to

⁶ Source: <http://faostat.fao.org>.

forecast changes in regional labor capacity due to climate change impacts. These results are then taken to GTEM-C as exogenous shocks to labor productivity of all economic sectors.

[Figure 6 about here.]

[Figure 7 about here.]

3.9 Solution and Software

By construction, GTEM-C is a dynamic general equilibrium model. In each period, the global economy is in “equilibrium” between the producers’ and consumers’ profit/utility maximizing behaviors across all regions such that markets of commodities and factors all clear given the current constraints of capital endowment, labour supply, productivity level and policy. The equilibrium is supported by a vector of commodity and factor prices (see Arrow and Debreu [65]). From period to period, the global economy evolves “dynamically”. First, capital is accumulating despite depreciation and this enlarges the foundation for future economic growth. Second, population and climate feedbacks are also changing and these impose new constraints of labour supply and productivity. Finally, policy instruments and other exogenous forces affect the motion of the economy.

GTEM-C is built on GEMPack (General Equilibrium Modelling PACKage) (see Harrison and Pearson [66]), a suite of numerical software that solves nonlinear economic models through successive linear approximation. The set of equilibrium conditions and transition laws are linearized and written in GEMPack’s Tablo programming language. Tablo translates the algebraic specification of the model into a form which is suitable for carrying out simulations in the computer. GEMPack offers a graphical user interface, RunDynam⁷, which carries out simulations on a year-to-year basis (recursively).

In a standard implementation, GTEM-C is simulated on a year-to-year basis from 2007 through to a future year. The 2007 initial conditions are built upon the GTAP databases⁸ and the electricity-technology-bundle database that has been discussed in 3.3.1. All parameters are taken

⁷ See <http://www.copsmodels.com/gprdyn.htm>.

⁸ The GTAP GHG emission database does not match RCP8.5. We therefore have applied a global uniform scaling factor to each greenhouse gas and reconcile with RCP8.5.

from the GTAP database, except those with regard to energy consumption, electricity generation, and global financial flows, which have already been discussed above. In the following section, we demonstrate how GTEM-C can be used for integrated assessment of global environment and energy issues.

4. Application: The Role of Electrification in Mitigating Carbon

4.1 Background

The Intergovernmental Panel on Climate Change (IPCC) has selected four “Representative Concentration Pathways” (RCPs) [13] to extend the analysis of climate change mitigation scenarios. Each RCP differs greatly in the rate of annual emissions, and is named according to the long-term radiative forcing in 2100. RCP8.5 is commonly understood as the ‘business-as-usual’ scenario with no mitigation, resulting in an increase in radiative forcing of 8.5 W/m^2 [2], while RCP4.5 is the moderate mitigation scenario which caps global carbon concentration below 650 ppm CO_2 -equivalent and an increase in radiative forcing of 4.5 W/m^2 [4]. Within this context GTEM-C can be used for comparative analysis of the socioeconomic implications of different mitigation scenarios under a common set of technology and biophysical assumptions. In this section, we investigate the socioeconomic impacts of carbon mitigation from RCP8.5 to RCP4.5, focusing on the role of electrification.

4.2 Baseline Scenario

Our baseline is calibrated to align closely with RCP8.5 (Riahi et al., 2011). The population estimates are taken from the medium variant of the United Nations’ World Population Prospects⁹, with a global population of 10.6 billion people in 2100. The supply of fossil fuels is assumed to continue the trend of growth through more capital and labor inputs. No extra assumption is made regarding the exhaustion or expansion of current fossil fuel reserves; and no carbon mitigation policies are assumed. For electricity generation, the annual energy efficiency improvement is set to 0.25% for conventional fossil fuels, 0.5% for CCS fossil fuels, and 0.75%

⁹ Source: <http://esa.un.org/wpp/>.

for all other clean technologies. For other industries and private consumption, the annual efficiency improvement is assumed to be 0.15% for fossil fuels, and 0.75% for electricity. Based on the above assumptions, regional total factor productivities are iteratively derived such that regional Gross Domestic Products (GDP) will continue the momentum of growth, with world GDP reaching 450 trillion in constant 2007 dollars (2007 US\$) (see Fig. 6). We have also fine-tuned the model's assumption about carbon intensity, so that global GHG emissions follow RCP8.5, reaching 130 gigatonnes (GT) of CO₂ in 2100 (see Fig. 7).

[Figure 6 about here.]

[Figure 7 about here.]

Under the baseline scenario, GTEM-C predicts that a growing population and economy combined with our conservative assumption about future energy efficiency improvement and carbon policy lead to a large global demand for final energy, which increases from around 12700 million tonnes of oil equivalent (Mtoe) at present to 67000 Mtoe as of 2100 (see Fig. 8). Since we have not assumed the exhaustion or expansion of fossil fuel reserves, the current trends of growth in coal, gas and petroleum production will continue, leaving the structure of energy use largely unchanged, which is similar to the projection of Masui et al. [3].

[Figure 8 about here.]

As has been discussed in Sub-Section 3.9, GTEM-C is simulated from 2007. This allows us to post-validate some key variables that the model predicts against available historic records, and to enhance our confidence in the modelling. We have collected the relevant data for global GDP, GHG emissions, energy consumption, and power generation from the International Monetary Fund (IMF)¹⁰, Global Carbon Project (GCP)¹¹ and the International Energy Agency (IEA)¹², and compared them with the GTEM-C predictions over the period 2007-2013. The results are summarized in Tab. 3. Overall, it proves the creditability of GTEM-C projections.

[Table 3 about here]

¹⁰ Source: <http://www.imf.org/external/pubs/ft/weo/2014/02/weodata/index.aspx>.

¹¹ Source: <http://www.globalcarbonproject.org/carbonbudget/index.htm>.

¹² Source: <http://data.iea.org/ieastore/statslisting.asp>.

4.3 Counterfactual Experiment and Sensitivity Analysis

In the counterfactual experiment, we hold all assumptions constant as in the baseline scenario, but force the model to follow the RCP4.5 emissions trajectory (see Fig. 7). Under these constraints, we let the model solve for the trajectory for a (uniform) global carbon price that is required for carbon reduction. It is assumed that all nations of the world start mitigating their emissions simultaneously from 2010, and all GHG emissions are priced according to their global warming potentials.

As we have noted in Section 3, the model's behaviour can be very sensitive to the choice of a_i values in the CRESH functions for private and industrial energy use. The a_i values are closely related to the price elasticity of substitution among energy commodities, such as coal, petroleum products, gas, and electricity. Intuitively, higher value of a_i 's means it is easier for industries and households to substitute from fossil fuels to electricity (i.e., electrification). Because electricity can be produced from nuclear and renewable sources that are emission-free, the pace of electrification is expected to play an important role in neutralizing the economic impacts of imposing a global carbon price.

To test the model's sensitivity, we vary the a_i values for electricity in both private and industrial energy consumption in the counterfactual experiment. This generates a set of four counterfactual scenarios. In the first counterfactual scenario, the a_i values are kept the same as in the baseline scenario at 0.5. In the other three counterfactual scenarios, the a_i values for electricity are increased to 1, 2 and 5. These values roughly correspond to the fossil-electricity elasticities of substitution of 0.5, 0.8, 1.2 and 1.8, respectively. We will name each of the four counterfactual scenarios according to the a_i values.

4.4 Results

4.4.1 Caveat

The following caveat must be noted before we present the GTEM-C results. In this illustrative modelling exercise our focus is on the role of electrification in mitigating carbon emissions from RCP8.5 down to RCP4.5. We abstract in the first place from directly accounting for the

difference in climate feedbacks that are implied by the two RCPs. By not explicitly considering the potential benefits due to avoidance of future climate damages, carbon mitigation will most likely reduce economic output because the imposition of carbon prices increases the cost of industrial production and household consumption. This abstraction allows us to investigate the importance of electrification in reducing the economic cost of carbon mitigation. We will account for the benefits of mitigation at the end of this section in 4.4.5.

4.4.2 Carbon Prices

The high energy demand and fossil fuel intensity in our baseline implies that achieving carbon mitigation will require drastic transformations in the energy system. The imposition of carbon prices is commonly regarded to be an effective approach. Our estimates indicate that the global carbon price will start low and remain below \$20 per ton of CO₂-equivalent prior to 2050 (Fig. 9). This is mainly because global carbon emissions are allowed to maintain the momentum of growth under RCP4.5. Additionally as is mimicked by the GTEM-C mechanism of carbon price induced technological growth, the uptake of low-hanging-fruit mitigation technologies also helps to effectively reduce emissions.

[Figure 9 about here.]

Global carbon prices rise sharply between 2050 and 2080 due to the tightening of mitigation targets, reaching above \$500 per ton of CO₂-equivalent. However, the pace of electrification will significantly contain the spiking of carbon prices because electricity is less carbon intensive or even carbon free. Our results suggest that doubling the α_i values for electricity use in private and industrial consumption will lead to almost a \$100 difference in global carbon prices as of 2080. The price wedge remains beyond 2080, when global emissions level out.

Thomson et al. [4, Fig. 10d] has compared the carbon price needed to reach 4.5 W/m² in the 28 scenarios conducted under the U.S. Climate Change Science Program [67], the Energy Modelling Forum [68], and their own work. This forms a spread of estimates, ranging from \$55 to \$2141 per ton of CO₂-equivalent in 2100. Overall, the GTEM-C estimates for global carbon price are within but fall in the higher part of the range. This is because we have not allowed for the banking and borrowing of emission rights, but forced the model to follow the RCP4.5

emissions trajectory year-on-year. The carbon price stays low in the short and medium term, but increases exponentially between 2050 and 2080. This price trajectory does not follow the Hotelling rule [4], which states that the optimal mitigation path should be such that the carbon price rises over time at the interest rate, adjusted by the rate of ocean carbon uptake [69-70]. As a result, GTEM-C tends to predict higher carbon prices.

4.4.3 Final Energy Use

Carbon price raises the cost of fossil fuels which are the dominant source of energy use in the baseline, so the industries and households will reduce their total final energy use by 18 to 27% (see top panel of Fig. 10), and minimize their cost by switching towards electricity that can be produced from carbon-free or less carbon-intensive technologies. This is crucial in decarbonising the global economy. It is made possible by increased reliance on clean electricity technologies, such as nuclear, wind, solar, and carbon capture and storage. As a result, electricity will see its share almost doubled in global final energy use in all the four counter-factual scenarios (middle panel of Fig. 10). In terms of electricity generation, conventional fossil fuels will be eventually phased out, replaced by the clean energies (bottom panel of Fig. 10). Such trends are even more significant when the elasticity of substitution between fossil fuels and electricity is higher. The decoupling of energy use and carbon footprint allows the world to maintain high level of energy consumption, which is essential to economic growth.

[Figure 10 about here.]

4.4.4 Economic Cost of Mitigation

In the short-term, our simulation results indicate that the imposition of a carbon price will boost the growth of the electricity sector and other downstream sectors if the α_i 's for electricity is sufficiently high, leading to increases in world GDP before 2050. This "double dividend" has important economic implications especially for the developing countries, as carbon mitigation can potentially stimulate growth. In the long-term, the potential for industries and households to substitute away from fossil fuels to electricity that is generated from clean sources and to avoid the burden of carbon prices will drastically reduce the economic cost of de-carbonization when

mitigation is most stringent beyond 2050 (Fig. 11), leading to annual estimated savings of around 2.5 trillion dollars (2007 US\$) at the end of the century.

[Figure 11 about here.]

Summing up the short-term gains with the long-term costs of mitigation with a discount factor, (ρ), our results suggest that faster pace of electrification can make mitigation less of a burden to the economy (Tab. 4A). This result is robust under different choices of the discount factor.

4.4.5 Accounting for Mitigation Benefits

The readers should also note that we have not yet considered the potential benefits of mitigation due to avoidance of future climate damages. In one aspect, as per Dunne et al. [27], carbon mitigation from RCP8.5 to RCP4.5 will significantly reduce the negative impacts of increase heat stress on labor capacity, as measured by the Wet Bulb Global Temperature (WBGT). Using the ACCESS [63] version 1.0 simulations of future climates under RCP scenarios 4.5 and 8.5, and the formula of Dunne et al. [27], our estimate suggests that the potential mitigation benefit from reduced heat stress on labor capacity could be above 5 trillion 2007 US\$ per annum (see Fig. 11) when the negative impacts of climate change become significant from the 2040's. Singly accounting for this benefit, we find that mitigation is unambiguously a profitable action (Tab. 4, Panel B), letting alone other potential benefits such as preventing climate catastrophes and sea level rise.

[Table 4 about here.]

5 Concluding Remarks

In this paper we have introduced the design of GTEM-C, a hybrid model that combines the top-down macroeconomic representation of a computable general equilibrium (CGE) model with the bottom-up engineering details of energy production and consumption. The model has two main advantages. First, it includes detailed representation of major geographic regions and economic activities that are most relevant to global environmental and energy issues such as climate change, carbon mitigation and energy transformation. This provides a unified framework to analyse economic trade-offs associated with the production and use of fossil fuels, greenhouse

gas emissions, and environmental issues. Second, it adopts the general equilibrium approach which reproduces the structure of the global economy and records the economic transactions among regional producers and households. This is important for modelling global policy changes whose impacts are expected to be complex, and transmitted by different channels, and materialize not only in one but various rounds.

GTEM-C, however, is also subject to limitations. First, like other CGE models, GTEM-C is based upon the economic theory of market equilibrium and rationality. That is, dynamics simulated by the system of equations only describe average human behaviours over a long period of time (normally one year). Therefore, GTEM-C is not well suited to addressing short-term political and business concerns over the economic cost of mitigation efforts, for example, heightened recently by the Global Financial Crisis. This indicates an important area in which the model can be continuously improved.

Second, GTEM-C parameters are estimated and calibrated against historical data. Economic data for many countries, particularly those outside the OECD are very often of poor quality. Therefore, validation by post-diction and uncertainty analysis are critical when using the model. In the previous section, we have shown how the model's baseline prediction can be validated against recent historic data that are available from international organizations. In the scope of the paper, the post-validation has been done at the global scale; but for future research we also recognize the importance of post-validation at both national and sectoral scales. We have also provided an example of sensitivity analysis on the model parameter¹³ that is related to the pace of electrification in energy in Section 4 of this paper. We find that the model's estimate for carbon price and the associated economic impacts can vary significantly due to the choice of parameters. Such uncertainties associated with technology change and energy consumption pattern must be addressed when using GTEM-C for similar policy analyses.

Despite these limitations, GTEM-C provides a rigorous tool to analyse the energy-carbon-environment nexus, and more importantly, a platform to integrate trans-disciplinary knowledge about human societies and the biophysical world. The integration is not a static but dynamic

¹³ These are the α_i values in the CRESH functions for private and industrial energy use.

process, and the GTEM-C model can be extended in several ways for future research. One possible direction is to include the physical and socio-economic interactions between fossil fuel use and air quality. The World Health Organisation (WHO) estimates that in 2012 around 7 million premature deaths resulted from air pollution¹⁴, and the recent Lima Climate Change conference has for the first time added health to the set of climate-related issues that must be explicitly considered by signatory nations¹⁵. It is therefore important to incorporate the atmospheric chemical reactions between constituents of smog and greenhouse gases such as methane, as well as the economic interactions between policy measures for pollutant control and carbon mitigation. This can be done by linking GTEM-C's energy accounting to pollutant and aerosol emissions, and coupling GTEM-C with an air quality model such as The Air Pollution Model (TAPM) [71].

Another area that GTEM-C can contribute for future research is to include the competition for land between traditional agriculture and bio-fuel production. As we have shown in the paper, imposing a carbon price incurs ancillary costs to economic activities and can potentially reduce economic outputs. A potential solution to alleviate the burden of mitigation is to produce bio-fuels that can substitute for fossil fuels and to sequester the emissions from burning bio-fuels. The growth of bio-fuels feedstock, however, introduces new competitors for land that would be otherwise used for traditional agricultural activities, in particular, food production. The Food and Agriculture Organization of the United Nations (FAO) estimates are that global food production must increase by 60% by 2050 in order to keep up with the pace of population growth [72]. Therefore, the amount of bio-fuel production for climate mitigation globally will be primarily a trade-off between the benefits of reducing global climate change and the costs of feeding the growing world population. Finding an optimal global balance between the uses of land for growth of bio-fuels feedstock and production of food requires us to quantify the associated trade-offs. Currently, our CSIRO team is in the process of coupling GTEM-C with the dynamic version of the GTAP bio fuel model (GDyn-Bio). The GDyn-Bio model explicitly models the substitution between fossil fuels and biofuels, the determination of land cover changes in response to increased biofuel feedstock production, and the changes in crop yields (see Golub et

¹⁴ Source: <http://www.who.int/mediacentre/news/releases/2014/air-pollution/en/>

¹⁵ Source: http://unfccc.int/meetings/lima_dec_2014/meeting/8141/php/view/seors.php

765 al., [73]). Integrating these attractive features of GDyn-Bio with those of GTEM-C on renewable
766 energies will provide an interesting tool for exploring the intersection of issues related to energy,
767 food and climate.

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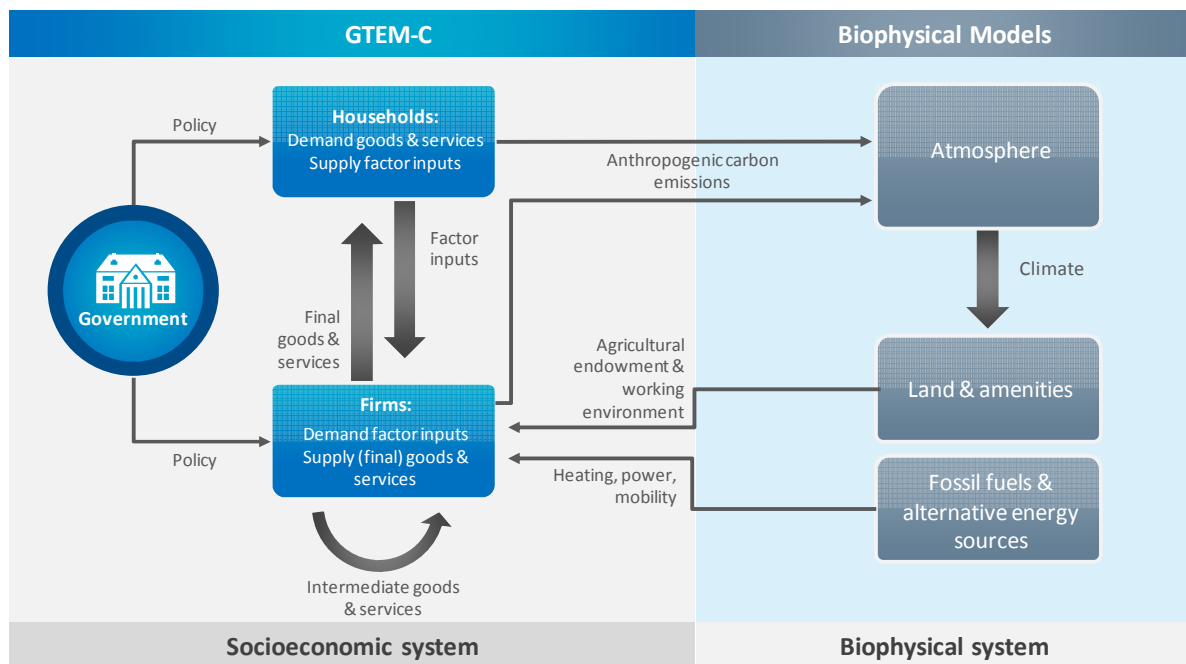
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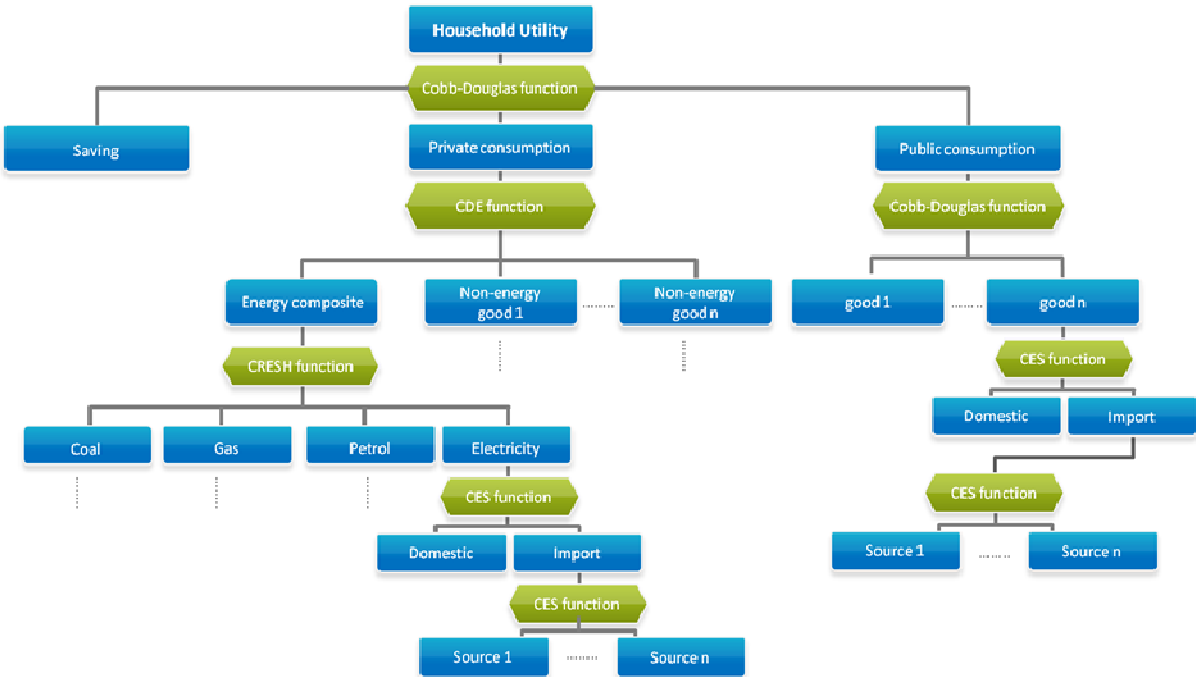
Figure 1. A Schematic Diagram of GTEM-C



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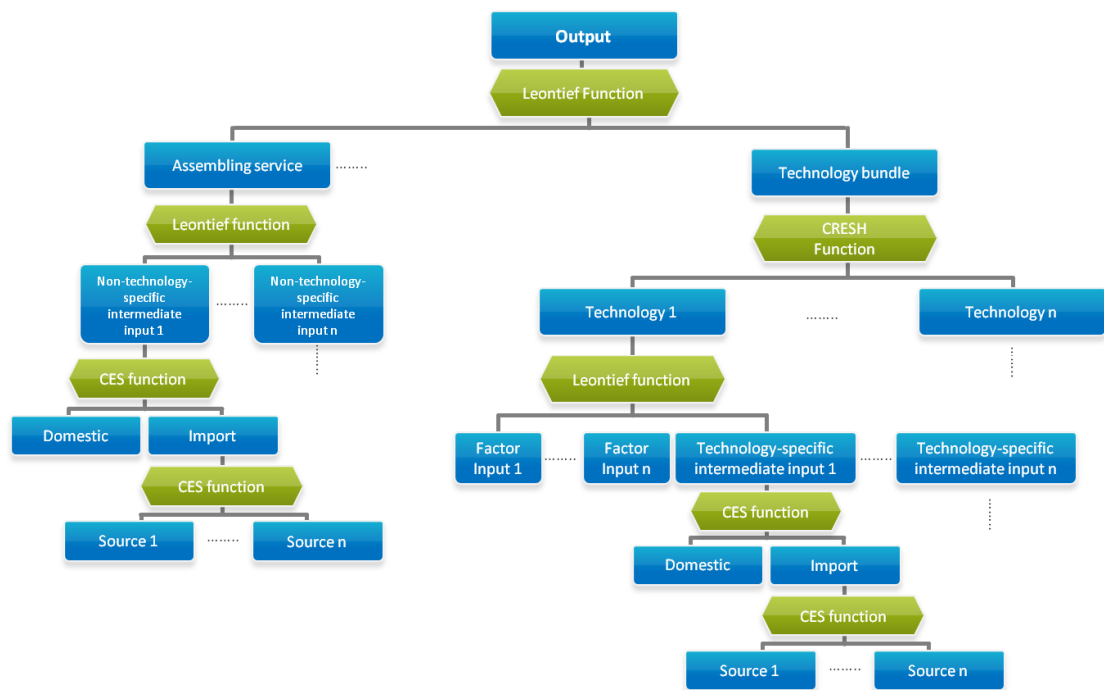
Figure 2: Preference of the Representative Household



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Figure 3. Production Structure of a Technology Bundle Industry



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Figure 4. Production Structure of a Non-Technology Bundle Industry

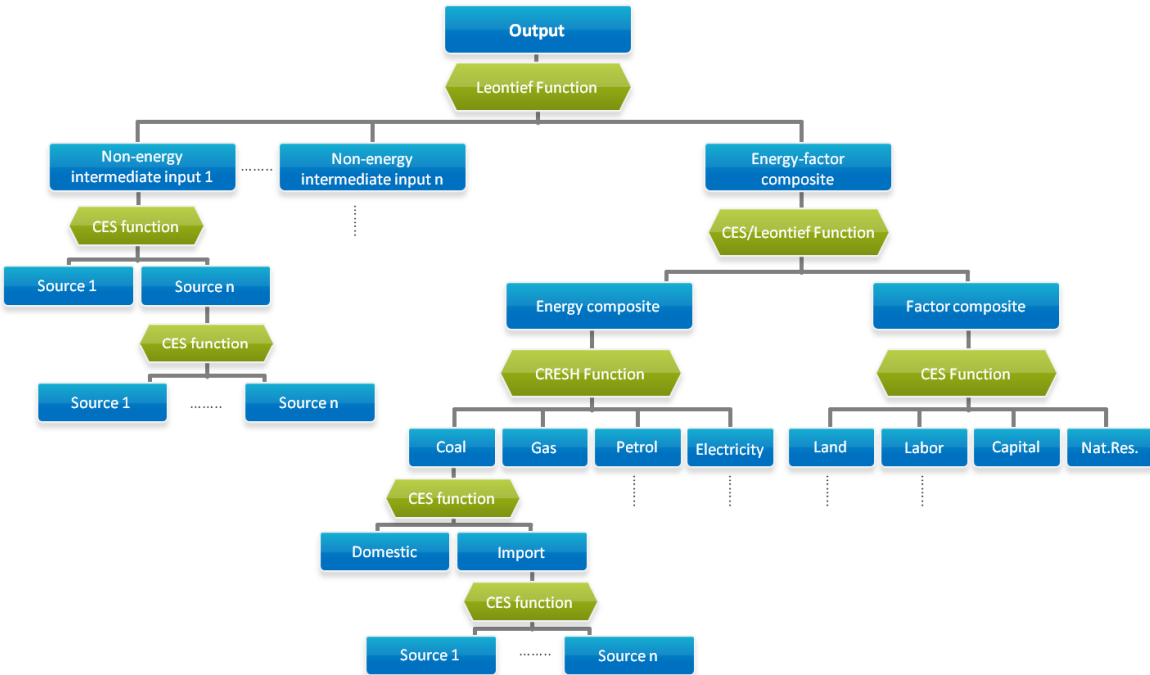
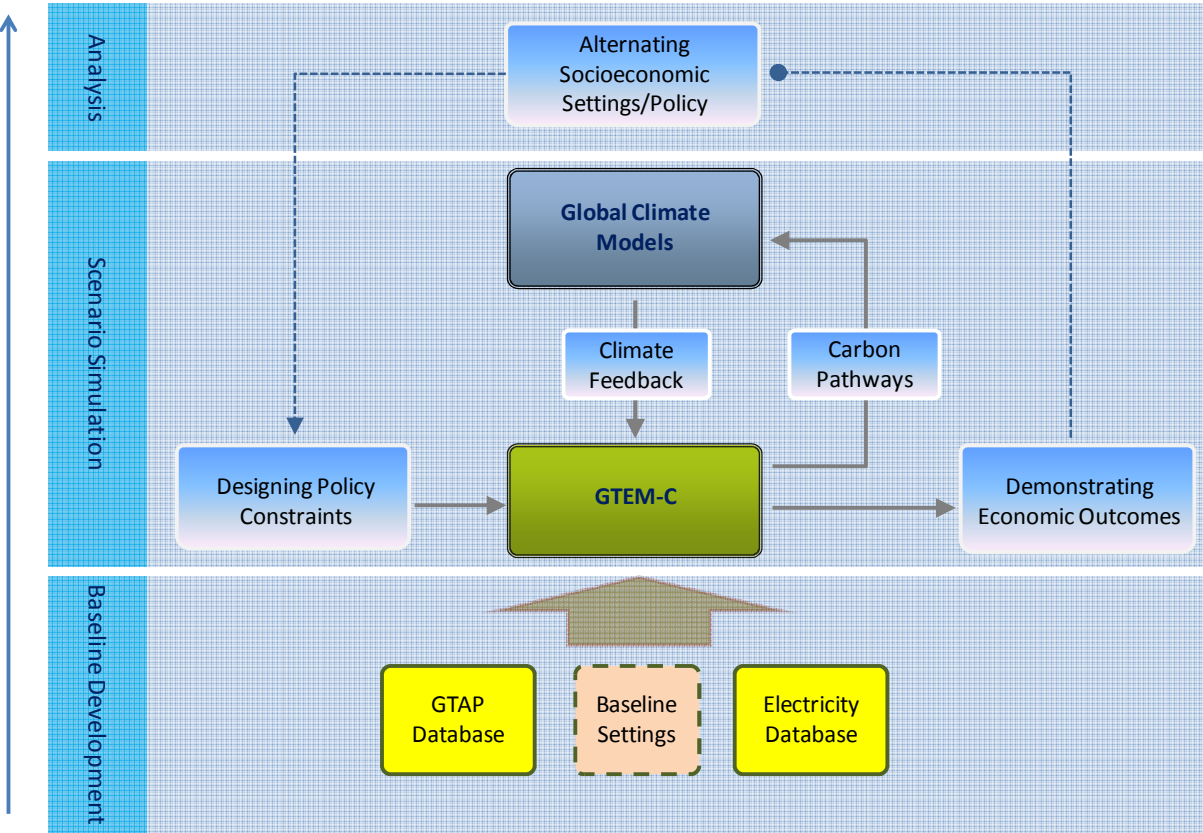
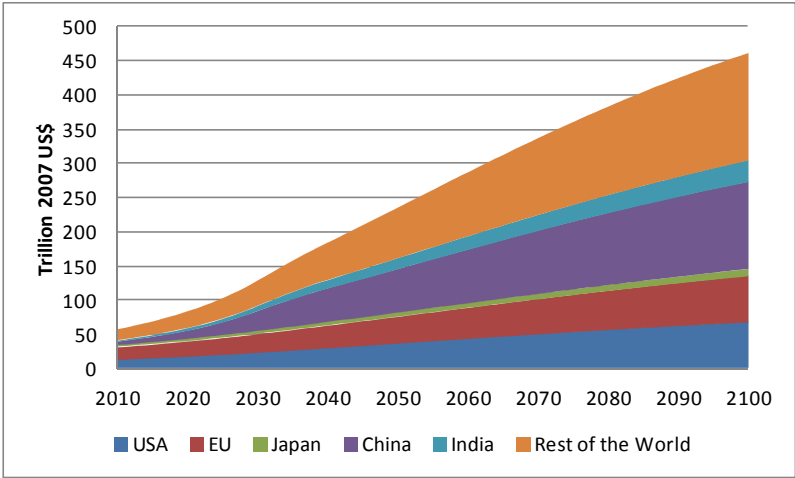


Figure 5. Overview of CSIRO's Global Integrated Assessment Modelling



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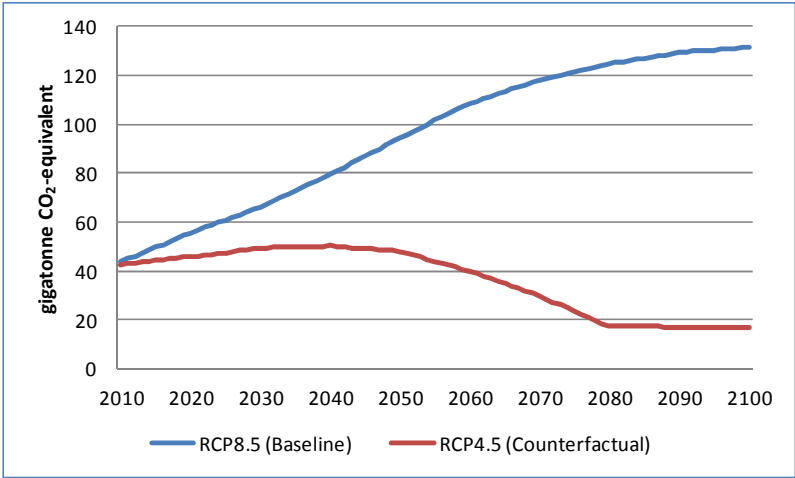
Figure 6. World GDP under the Baseline Scenario



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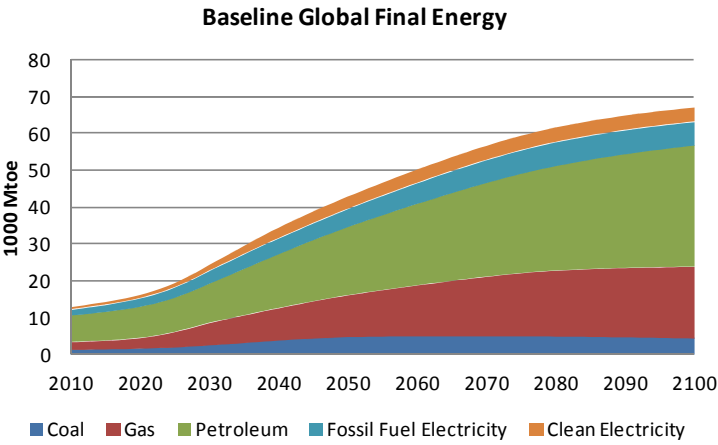
Figure 7. Global GHG Emissions under Alternative Scenarios



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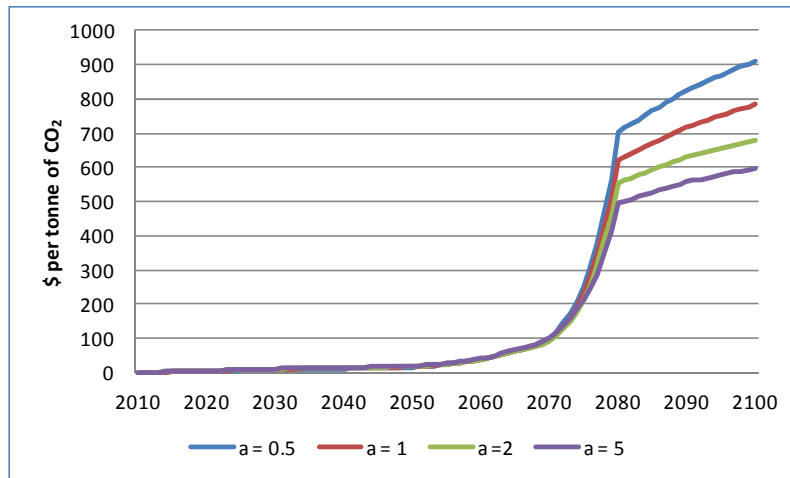
Figure 8. Global Final Energy Consumption under the Baseline Scenario



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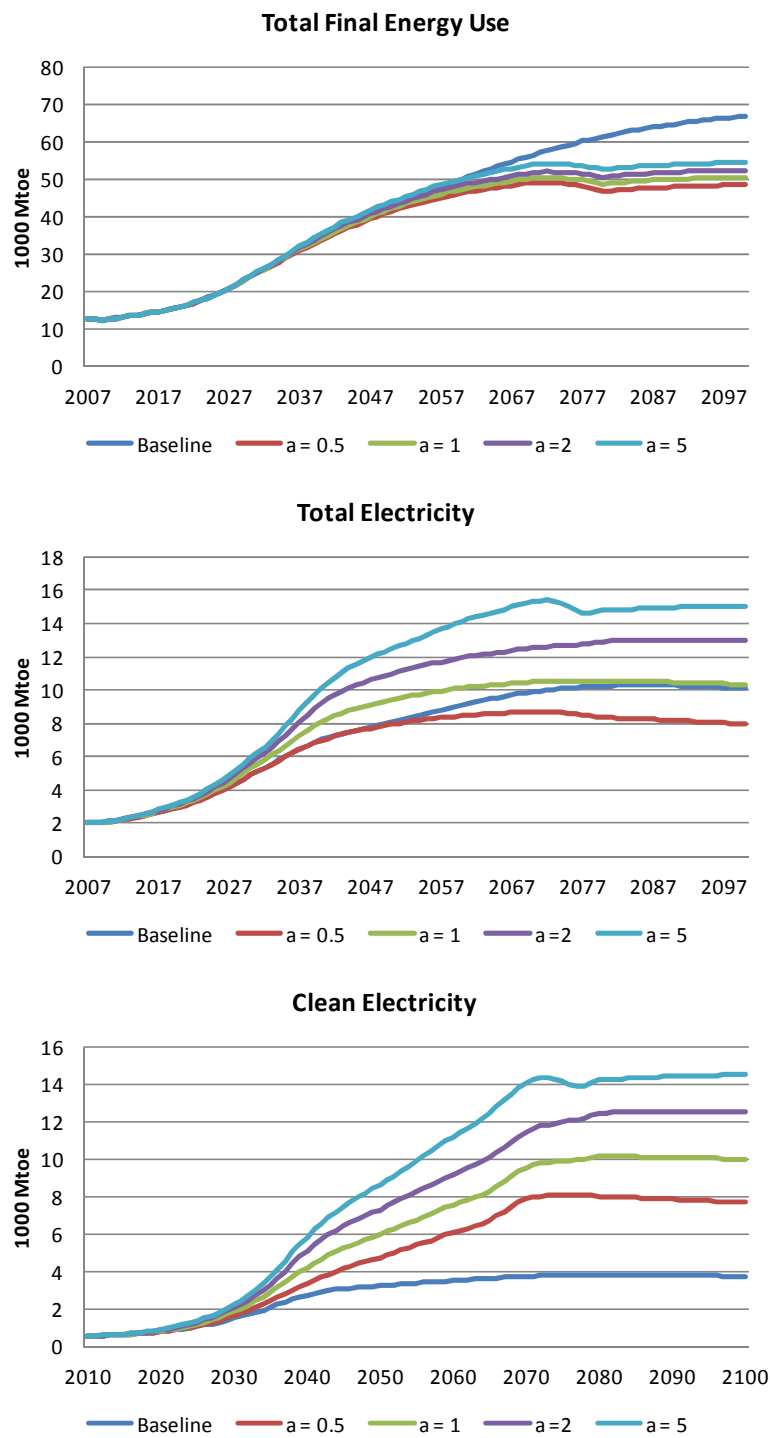
Figure 9. Global Carbon Price under Alternative Scenarios



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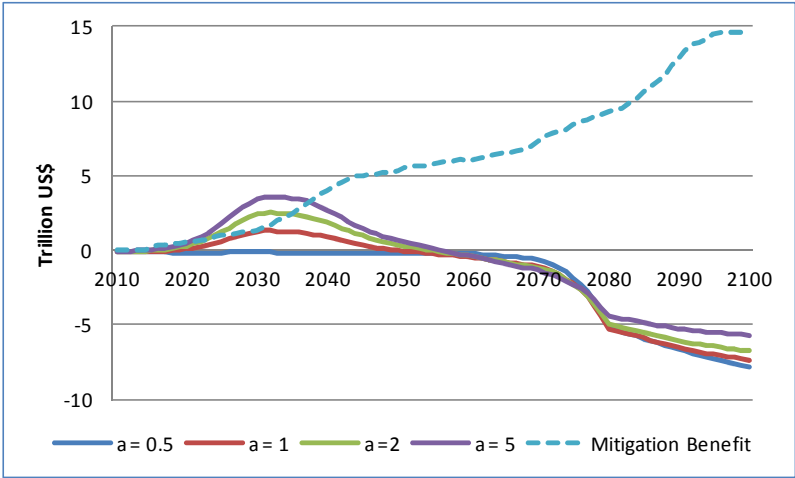
Figure 10. Global Energy Use under Alternative Scenarios



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Figure 11. Deviation of World GDP from Baseline



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Table 1. Regional Aggregation of GTEM-C

Code	Name	Regions
USA	USA	United States of America
EUR	Europe	Albania, Austria, Belarus, Belgium, Bulgaria, Canada, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Rest of EFTA, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, United Kingdom
CHN	China	China, Hong Kong
JPN	Japan	Japan
IND	India	India
BRZ	Brazil	Brazil
CAN	Canada	Canada
AUS	Australia	Australia
NZL	New Zealand	New Zealand
IDN	Indonesia	Indonesia
MEX	Mexico	Mexico and Rest of North America
RLA	Rest of Latin America	Argentina, Bolivia, Caribbean, Chile, Colombia, Costa Rica, Ecuador, El Salvador, Georgia, Guatemala, Honduras, Nicaragua, Panama, Paraguay, Peru, Uruguay, Venezuela, Rest of Central America, Rest of South America
RSA	Rest of South Asia	Bangladesh, Pakistan, Sri Lanka, Rest of South Asia
RNEA	Rest of Northeast Asia	Korea, Lao People's Democratic Republic, Malaysia, Mongolia, Nepal, Philippines, Singapore, Taiwan, Thailand, Viet Nam, Rest of ASEAN, Rest of East Asia, Rest of Oceania
FSU	Former Soviet Union	Armenia, Azerbaijan, Georgia, Kazakhstan, Kyrgyzstan, Russian Federation, Ukraine, Rest of Europe
NAF	Northern Africa	Egypt, Morocco, Tunisia, Rest of North Africa
SAF	Southern Africa	Botswana, Cameroon, Cote d'Ivoire, Ethiopia, Ghana, Kenya, Madagascar, Malawi, Mauritius, Mozambique, Namibia, Nigeria, Senegal, South Africa, Tanzania, Uganda, Zambia, Zimbabwe, Central Africa, South Central Africa, Rest of Western Africa, Rest of Eastern Africa, Rest of South African Customs
MDE	Middle East	Bahrain, Islamic Republic of Iran, Israel, Kazakhstan, Kuwait, Oman, Qatar, Saudi Arabia, Turkey, United Arab Emirates, Rest of West Asia

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Table 2. Sectoral Aggregation of GTEM-C

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Code	Description	Contents
COL	Coal	mining and agglomeration of hard coal, lignite and peat
OIL	Oil	crude oil extraction, service activities
GAS	Gas	gas extraction, service activities, distribution
P_C	Petroleum & Coal Products	coke oven products, refined petroleum products, processing of nuclear fuel
ELY	Electricity & Heat	electricity and heat production, collection and distribution
CRP	Chemicals, Rubber and Plastics	chemical, rubber, plastic products
I_S	Iron & Steel	basic production and casting of ferrous metals
NFM	Nonferrous Metal	metals nec
NMM	Non-metallic minerals	mineral products nec
OMN	Other Mining	minerals nec
MANU	Manufacturing	textiles, wearing apparel, leather products, wood products, paper products and publishing, metal products, electronic equipment, motor vehicles and parts, machinery and equipment nec, manufactures nec, transport equipment nec,.
WTP	Water transport	water transport
ATP	Air transport	air transport
OTP	Land transport	road, rail, pipelines, auxiliary transport activities; travel agencies
CROPS	Crops	paddy rice, wheat, cereal, oil seeds, vegetables, fruits, nuts, sugar beet/cane, plant-based fibres, crops nec.
LSTK	Livestock	bovine cattle, sheep and goats, horses, raw milk, wool, silk-worm cocoons
F_F	Fishery &F	fishing, fish farms and service activities; forestry, logging and related service activities
FOOD	Processed Food	processed grains, sugar, vegetable oils and fats, dairy, bovine cattle/sheep/ goat meat products, beverages and tobacco products, food products nec.
SVCE	Services	communication, construction, water service, trade, insurance, dwellings, public admin. and defence, education, health, recreational and other services, business services nec., financial services nec.

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Table 3. Post-Validation for GTEM-C Baseline Predictions

		2007	2008	2009	2010	2011	2012	2013
Global GDP (Trillion 2007 US\$)	GTEM-C Prediction	55.8	56.8	55.7	58.0	60.1	62.3	64.6
	IMF Record	56.8	57.7	56.5	58.9	60.6	62.1	63.6
Global CO ₂ Emissions (Gigatonne)	GTEM-C Prediction	30.6	31.3	32.0	32.7	33.7	34.6	35.6
	GCP Record	31.4	32.2	32.0	33.6	34.7	35.4	36.1
Global Energy Consumption (1000 Mtoe)	GTEM-C Prediction	12.5	12.7	12.4	12.7	13.0	13.2	13.5
	IEA Record	12.1	12.4	12.3	12.9	13.2	13.5	n.a.
Global Power Generation (1000 Mtoe)	GTEM-C Prediction	2.0	2.1	2.0	2.1	2.2	2.2	2.3
	IEA Record	2.0	2.1	2.0	2.2	2.3	2.3	n.a.

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Table 4. Total Discounted Benefits of Carbon Mitigation

A. Without Mitigation Benefit

Trillion US\$	$\rho = 0\%$	$\rho = 1\%$	$\rho = 2\%$	$\rho = 3\%$	$\rho = 4\%$	$\rho = 5\%$
$\alpha = 0.5$	-171.1	-79.3	-38.1	-19.3	-10.4	-6.1
$\alpha = 1$	-147.4	-60.5	-23.1	-7.3	-0.8	1.6
$\alpha = 2$	-110.6	-35.8	-5.7	5.5	8.8	9.0
$\alpha = 5$	-70.7	-11.0	10.9	17.3	17.6	15.7

B. With Mitigation Benefit

Trillion US\$	$\rho = 0\%$	$\rho = 1\%$	$\rho = 2\%$	$\rho = 3\%$	$\rho = 4\%$	$\rho = 5\%$
$\alpha = 0.5$	377.0	220.4	133.9	84.5	55.3	37.5
$\alpha = 1$	400.8	239.2	148.9	96.5	64.9	45.2
$\alpha = 2$	437.6	263.9	166.3	109.2	74.5	52.6
$\alpha = 5$	477.4	288.7	182.9	121.1	83.3	59.3

Note: The parameter α is the price elasticity of substitution for electricity, and ρ is the discount factor.

Symbols	Description
U	per capita aggregate utility
Up	per capita utility from private consumption
Ug	per capita utility from government consumption
Us	per capita utility from saving
α, β, γ	positive parameters for aggregating Up , Ug and Us into U
Ep	per capita private expenditure
Eg	per capita government expenditure
Es	per capita saving
Pp	aggregate price of private consumption
Pg	aggregate price of government consumption
Ps	shadow price of saving
Y	regional income
POP	regional population
B_i	distribution parameter in the household's indirect utility function
ε_i	substitution parameter in the household's indirect utility function
φ_i	expansion parameter in the household's indirect utility function
P_i	commodity price
q_i	percentage change of commodity demand
p_i	percentage change of commodity price
e_p	percentage change of private expenditure
pop	percentage change of regional population
$EP_{i,k}$	cross price elasticity of substitution for private consumption
EY_i	income elasticity for private consumption
X	household's demand for the energy composite
Q_i	commodity demand
D_i, d_i, κ	positive parameters in the CRESH function
q_X	percentage change of the household's aggregate energy demand
a_i	price elasticity of substitution for energy consumption
p_X^*	percentage change of the weighted aggregate energy price
Q_i^{Dom}	demand for domestic goods
Q_i^{Imp}	demand for aggregate imported goods
σ	Armington elasticity of substitution
ρ_{Dom}, ρ_{Imp}	budget share parameters for domestic and imported goods

$Q_{r,i}^{Imp}$	demand for imported goods from a country
ρ_r	budget share parameter for imported goods from a country
η	elasticity of substitution among imports from different sources
Q_i^A	quantity of assembling service in a technology-bundle industry
Q_i^B	quantity of technology bundle in a technology-bundle industry
A_i, B_i	positive scale factors
K	capital stock
I_r	regional investment
δ	depreciate rate
$Qinv_r$	quantity of regional investment
$Pinv_r$	price of regional investment
S_r	gross regional saving
R_r	regional rate of return on capital
$\bar{R}$	global average rate of return on capital
θ, τ, φ_r	positive parameters governing flows of international finance
$\aleph$	global uniform adjustment factor to clear the finance market
DB_r	regional foreign debt
GDP_r	regional gross domestic product (GDP)
N_P	energy use in private consumption
ξ_P	energy intensity of private consumption
N_F	energy use in industrial production
ξ_F	energy intensity of industrial production
M_P	emissions from private consumption
ϵ_P	emissions intensity of private consumption
M_F	emission in industrial production
ϵ_F	emissions intensity of industrial production
C	carbon price mark-up in commodity price
M_O	emissions from industrial process
ϵ_o	emissions intensity of industrial process
ϵ_o	emissions intensity of industrial process
Λ_r	regional climate damage
ϕ, φ	parameters in the regional climate damage function
ΔT	annual variation of global average temperature
ρ	discount factor
