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A hybrid energy-economy model for global integrated assessment of climate change, carbon mitigation and energy transformation

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HIGHLIGHTS

- This paper introduces the design of a hybrid energy-economy model, GTEM-C.
- The model offers a unified tool to analyse the energy-carbon-environment nexus.
- Results are presented on global energy transformation due to carbon mitigation.
- Electrification with renewable energies can contain the spiking of carbon prices.

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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.

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

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Nomenclature

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
$\overline{R}$	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
Λ_r	regional climate damage
ϕ, φ	parameters in the regional climate damage function
ΔT	annual variation of global average temperature
ρ	discount factor

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-CO_2 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 organised as follows. Section 2 offers a brief review of the literature, and highlights the difference and novelty of the