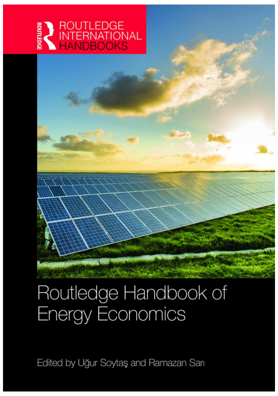

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CGE models in energy economics

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CGE models in energy economics

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1 Introduction

Energy is one of the most important drivers for the modern economy and its role has become even more important in the last couple of decades. The sufficient energy supply is essential particularly for the industrialized economy. Energy supply and demand structures are complex. Supply side is related to fossil fuel resource reservoir and depletion, renewable potential, and geographical location. The energy conversion technology such as power generation technologies and fuel refineries determines the efficiency and also the environmental aspects (greenhouse gas (GHG) and air pollutants emissions). Demand side is determined by energy end-use technology, activity level (e.g. passenger transport), human behavior responding to the price changes, and so on. Those things are interacting with each other in conjunction with costs, energy prices, and relevant policies. Because of such close relationship between energy and economy, energy issues have been major topics in economics.

In economic analysis, energy issues (e.g. prices, resource depletion, and environment) have been analyzed by various economic methodology (see also other chapters in this book). A computable general equilibrium (CGE) model is one of them and has played significant roles in the economic research in order to better understand entire economic response to particular policy intervention or other relevant shocks to the economy. This chapter introduces CGE modeling studies in energy economics.

Section 2 of the chapter describes the overview of CGE models, including basics of the models. In Section 3, we show the reviews of research articles in energy economics with various CGE models, although we can only introduce a limited number of articles because a huge number of studies exist. Section 4 concludes this chapter with insights for future works.

2 Overview of CGE models

2.1 Brief explanation of CGE models

CGE models are a type of economic models that use actual economic data to simulate how economic conditions are affected by changes in policy, technology, or other external factors (external shocks). CGE models are also called applied general equilibrium (AGE) models.

A CGE model consists of equations describing model variables and a database consistent with the equations. The formulation is based on neo-classical theory, assuming optimization behavior of economic agents where producers and consumers are supposed to maximize profit and welfare respectively. CGE models are numerical models based on general equilibrium theory pioneered by Herbert Scarf in 1967 [1,2]. This method was first used by Shoven and Whalley [3,4].

CGE models target whole economy of a country, region, or the world. This means that unlike partial equilibrium analysis, which focuses on a market of a specific goods or service, CGE models describe economic activities of all sectors including industrial sectors, household, and government. Industrial sectors are usually aggregated and the level of aggregation depends on the model targets (e.g., global or national model) and aims of the studies (e.g., power generation sectors are highly disaggregated if the energy is the focus). Thus, CGE models estimate the impact of changes in one part of the economy not only to that part but also to the other part of the economy. For example, a gasoline tax might affect energy prices and energy demand for vehicles, thus might also affect demand for other transportation, transportation equipment manufacture, and whole economic activities. CGE models are similar to input-output (IO) models (Chapter 31 in this book) in the sense that both of them use IO database, but prices have a more important role in CGE, where substitutions among inputs via price changes are represented, whereas IO models freeze the input coefficient.

CGE models are basically a type of economic models. Thus, they were originally applied for economic policies, including trade policy and taxes. However, as energy and climate change issues have been highly demanded recently, they have been used for analysis of energy efficiency improvement and GHG emission reduction.

2.2 Models and data

In order to conduct CGE analysis, the model itself (model equations) and databases are required. CGE models are often developed using nested CES (constant elasticity of substitution) production and utility functions, but other forms of functions such as linear expenditure system are also applied. Early CGE models were developed by using programing language such as C and FORTRAN, which was expensive for development. However, in recent years models are developed by numerical software such as the GAMS (General Algebraic Modeling System)[1] and GEMPACK (General Equilibrium Modelling PACKage).[2] Therefore, the cost for modeling is lowered.

Databases used in CGE models usually consist of economic activities and elasticities. Because CGE models usually need data of a single period (i.e., no time series data are necessary), no historical time series data are often unnecessary.

Economic activities of individual sectors (i.e., industry, household, and government) in monetary terms (e.g., input and output of production, consumption, trade, labor supply, and investment) are supplied as a form of IO table or social accounting matrix (SAM). It covers the whole economy of a country or the whole world. Sectoral coverage depends on the models from relatively simple to highly detailed such as by disaggregating technology of power sectors.

Elasticities are parameters that capture the response of the economy (e.g., 1% of change in relative price of A and B changes the ratio of the consumption of A and B) in CES functions. These elasticities usually include elasticities of substitution, elasticities of transformation, Armington elasticities for imports, and income elasticities of demand. For example, elasticities of substitution indicate how easy inputs to production may be substituted for another input.

Furthermore, additional data such as energy (including power generation by technology) and GHG emissions are necessary for analysis of energy and environmental analyses. Because the recent Global Trade Analysis Project (GTAP) databases also cover energy and GHG emissions, the barrier to develop CGE models for these fields is lowered.

2.3 Types of CGE models

CGE models can be classified into multiple categories. The important aspects of the models are how to handle geographical regions and time scale. From the geographical perspective, the models can be classified into "country" and "global" models.[3]

- *Country models*: Country models focus on economy of a specific country. This type of model is often used in policy analysis of a country of interest. The models can be classified into single country and multi-region models. Single country models, which handle the country as an only region in the model, is the most orthodox type of the country models. On the other hand, multi-region models disaggregate the country into multiple regions such as states, provinces, prefectures, or other defined regions in the country, thus interaction among the regions are taken into account. Compared with global models, they have advantages on data and sectoral details, particularly for the single country models. Because the model targets one country, only SAM or IO table (and energy and CO_2 emissions if necessary) of the country is needed. These data are usually available at the statistical bureau of the country. From the viewpoint of sectoral details, because of the data availability in detailed sectors for country data and less computational costs (due to the less number of geographical regions), the models can handle higher resolution of the sectors. On the other hand, their disadvantages are as follows. Because the rest of the world is usually out of the scope in country models, international trade and impact of external shocks of the country to other counties are weak.
- *Global models*: Global CGE models cover the whole world. Therefore, impact of sector(s) of one country to the other countries can be analyzed. The most difficult aspect of this type of models is data, because consistent data (not only domestic economic activities but also international trade) for all countries in the world are necessary. However, thanks to the GTAP of Purdue University,[4] global IO tables for CGE analysis have been available since 1992. However, sectoral coverage of global CGE models is still less detailed than country models. The resolution of global CGE models are thus usually around 20 for both industrial sectors and geographical regions.

From the temporal perspective, the models can be classified into "static" and "dynamic" models. CGE models of early years were static (also called comparative static). However, in recent year, particularly in energy economics, dynamic models have frequently been used.

- *Static models*: Static models are the basic type of the model and are also called comparative static. The static type considers economy at one time point. Thus, the model analyzes, for example for policy analysis such as carbon tax, how economy reacts to external shocks or introduction of policies. The results of the analysis show how economy changes after achieving new equilibrium conditions due to the shocks or policies (i.e. economy is adjusted to a new equilibrium). Therefore, it can be either short-term or long-term equilibrium depending on the modeling, although time-scale is not explicitly considered in this type.

- *Dynamic models*: In contrast, dynamic CGE models explicitly considers "time" in the future, which is often at annual, five-year, or ten-year intervals. Dynamic models can be classified into two types: recursive dynamic and forward looking (or optimization). Recursive-dynamic models are accumulation of static CGE models. This means that models are solved sequentially along with time (time t, $t + 1$, $t + 2$, . . .). They assume that behavior of economic agents depends only on current and past states of the economy, thus myopic agents. On the other hand, forward-looking models are that behavior of agents depend not only on current and past economic states but also on future economic states. Therefore, different from recursive-dynamic models, the models are solved the whole periods considered simultaneously, thus more computational power is required. Comparing with static CGE models, development of dynamic models is more challenging because it needs assumptions for the future, such as economic growth and population change. In particular, to model long-time future (e.g., 100 years) in energy economics, further assumptions such as energy efficiency improvement and new energy technologies are required. Despite such huge challenges, this type of model (either recursive dynamic or forward looking) is more frequently used than the static type in recent energy economic studies.

2.4 Strengths and weaknesses of CGE models

The most noticeable strength of the CGE modeling approach is that it handles the whole economic activities of the world (or a country or regions). This means that unlike a partial equilibrium approach the models can analyze an exogenous shock (or impact or change) in one sector to the whole economy. For example, this approach is useful to evaluate the impact of increase in oil price not only on oil and energy demand but also on the other sectors such as the prices of and demand for other goods and services and final demand that would help to understand macroeconomic response (e.g., GDP and welfare).

However, CGE is not of course the perfect tool, but it has its weaknesses. From the economic aspect, validation of model accuracy and parameter estimations are the issues. In CGE models, most of the parameters in the models are calibrated with single year data (SAM) and the other parameters (elasticities) are often taken from literature or existing models. Thus, accuracy of models from time series perspective is an issue of CGE. This also means that the parameter calibration strongly relies on single year snapshot that could have extreme condition. The obvious example is that if the parameters are calibrated on the SAM in year 2008, the parameters could involve more or less characteristics of financial crisis of 2007–2008. This kind of disadvantage could lead a bias in the CGE simulation.

From the energy aspect, top-down models like CGE models usually do not have details in energy technology compared to bottom-up approaches such as energy technology models. Considering detailed technology is essential particularly when the models consider long-term future such as the analysis of climate policy. Recently, there exist studies that couple CGE and energy technology models [5,6], but such studies are still rare (Chapter 32 in this book).

3 CGE modeling research in energy economics

3.1 Features of CGE models in energy economics

CGE models used in the field of energy economics are usually much more complicated than those used in pure economic analysis. In pure economic CGE models, the models are developed based only on economic data, usually IO tables or system of national account.

However, for the CGE models in energy economics, further components are indispensable to analyze energy and the related issues. The most important sectors are energy sectors, particularly power generation. In usual CGE models, power generation is often represented by a single electricity sector. However, to adequately analyze energy related topics and policy, understanding substitution among power sources is an important factor, particularly when analyzing future scenarios of climate mitigation policy. Furthermore, with regard to power sector in the long-term analysis, technologies such as biomass and carbon capture and storage will also play important roles. Thus, incorporating these components or factors into CGE models are essential.

One more important aspect for the CGE models in energy economics is the treatment of land use [7]. Land-use is important in terms of energy studies from two points: CO_2 emissions from land use and land-use change [8]; and competition of agricultural areas between food production and energy crop. Recent climate mitigation studies have shifted towards more radical emissions reduction scenarios (e.g., 2 °C goal) which requires zero or negative emissions in the latter half of this century. That would essentially mean that land-related CO_2 emissions play an critically important role as well as energy related emissions. In other words, if emissions from land use or land-use change changed, possible emissions from energy use should be simultaneously changed if allowable CO_2 emissions are fixed.

The second point is directly related to energy use. It is considered that biomass energy plays an important role in climate mitigation, particularly for a large emission reduction [9–11]. The biomass energy will be produced as energy crops; thus they will compete with agricultural (food) production. This leads a question if sufficient agricultural and energy crops can be produced subject to the limited land areas under climate mitigation policy and Hasegawa et al. [12] pointed out that mitigation policy could worsen food security. Therefore, in order to consistently analyze these points, considering land use and land-use change in CGE models in energy economics, particularly in climate mitigation analysis, is significant.

There are a huge number of CGE models used in the literature.[5] The selected key models (all the models are a global type) are the AIM/CGE model (National Institute of Environmental Studies, Japan) [13,14], the EPPA model (Massachusetts Institute of Technology, the United States) [15,16], the ENV-Linkages model (Organisation for Economic Co-operation and Development) [17], the IMACLIM model (International Research Center on Environment and Development, France) [18,19], the GEM-E3 model (European Commission) [20,21], WorldScan (Netherlands Bureau for Economic Policy Analysis, the Netherlands) [22,23], and the PET model (National Center for Atmospheric Research, the United States) [24,25].

3.2 Review of CGE modeling research

CGE models have been used in energy economic research for more than 30 years, and more and more research articles are published in recent years, particularly in relation with climate change.

By searching research articles on energy research of CGE models,[6] we found 517 documents (as of 16 May 2017). Figure 30.1 shows the number of articles found in three well-known databases. As it shows, the first article was published in the early 1980s. The number of articles related to energy research using CGE models published is increasing from just double digits in 1980s to more than thousand in 2010s.

The first article found in Scopus was published in 1984 [26].[7] Dick et al. [26] use multiple static national CGE models to analyze economic impact of oil-price increases in developing countries. Similar to this study, CGE studies in the early period mainly focuses on economic

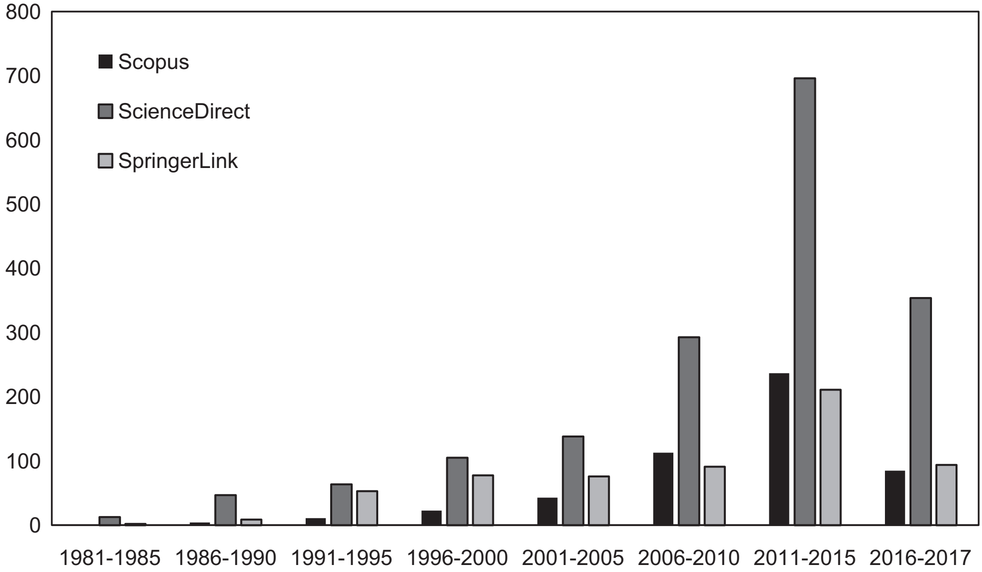

Figure 30.1 The number of articles found in three well-known databases. Scopus includes title, keywords, and abstract of journals from broader publishers, although full papers are not searchable. In contrast, the articles found in ScienceDirect and SpringerLink are limited to specific publishers, but the full papers are searchable.

Source: www.scopus.com/home.uri,www.sciencedirect.com/, and link.springer.com/.

Table 30.1 Features of selected papers of CGE models in energy economics

No.	*Article*	*Main topic*	*Global or country*	*Geographical coverage*	*Time scale*
1	Bergman [34]	Nuclear power	Country (Sweden)	Single	Static
2	Dick et al. [26]	Oil price	Country (four developing countries)	Four single	Static
3	Despotakis and Fisher [27]	Oil price	Local (California)	Single	Static
4	Fisher and Despotakis [28]	Energy tax	Local (California)	Single	Static
5	Boyd and Uri [29]	Energy tax	Country (US)	Single	Static
6	Uri and Boyd [30]	Gasoline tax	Country (US)	Single	Static
7	Uri and Boyd [31]	Tax on refined petroleum products (elimination)	Country (Philippines)	Single	Static
8	Semboja [32]	Energy tax	Country (Kenya)	Single	Static
9	Semboja [33]	Energy efficiency	Country (Kenya)	Single	Static
10	Li and Rose [35]	Carbon tax	Local (Pennsylvania)	Single	Static

No.	*Article*	*Main topic*	*Global or country*	*Geographical coverage*	*Time scale*
11	Welsch [36]	Carbon/energy tax	Region (EU)	Two regions	Dynamic
12	Uri and Boyd [37]	Motor fuels excise tax	Country (USA)	Single	Static
13	Naqvi [38]	Energy, economy, and equity	Country (Pakistan)	Single	Static
14	Galinis and van Leeuwen [39]	Nuclear power	Country (Lithuania)	Single	Static
15	Bach [40]	Environmental fiscal reform	Country (Germany)	Single	Dynamic
16	Steininger and Voraberger [41]	Biomass energy	Country (Austria)	Single	Static
17	Hanley et al. [42]	Energy efficiency	Local (Scotland)	Single	Dynamic
18	Kiuila et al. [43]	Ecological tax reform	Country (Poland)	Single	Static
19	Müller-Fürstenberger and Stephan [44]	Climate change and technological innovation	Global	Two regions	Dynamic
20	Otto et al. [45]	Energy and technology	Illustrative data	Single	Dynamic
21	Otto et al. [46]	Climate mitigation	Country (Netherlands)	Single	Dynamic
22	Löschel and Otto [47]	Climate mitigation	Country (Netherlands)	Single	Dynamic
23	Wang et al. [48]	Climate mitigation	Country (China)	Single	Dynamic
24	Matsumoto [49]	Climate mitigation	Country (Japan)	Single	Dynamic
25	Timilsina et al. [50]	Oil price and biomass	Global	25 regions	Dynamic
26	O'Neill et al. [25]	Urbanization	Global	Nine regions	Dynamic
27	Solaymani and Kari [51]	Energy subsidy reform	Country (Malaysia)	Single	Static
28	Broberg et al. [52]	Energy efficiency and rebound effect	Country (Sweden)	Single	Static

impact of energy-related taxes, energy price increases, and energy efficiency [27–33]. Furthermore, because of the computational power in those days, the models were much simpler (in terms of types of energy, geographical coverage, and time scale) than those used in recent years.

From the mid-1990s, energy research in terms of climate change has been increasing because of the United Nations Framework Convention on Climate Change entered into force in 1992 and the Kyoto Protocol adopted in 1997. For example, Li and Rose [35] analyzed the impact of carbon tax on economy and energy in Pennsylvania. Similarly, Welsch [36] analyzed the impact of carbon tax on European economy, particularly focusing on different tax recycling methods. There are a lot of other studies on climate change analyses (the main topic in energy economics), but they are reviewed in Section 3.3.

Other types of studies after the mid-1990s include price (including) aspects (motor fuels excise tax [37]; environmental fiscal reform [40]; ecological tax reform [43]; oil price and biomass [50]; energy subsidy reform [51]), specific energy sources (nuclear power [39]; biomass [41]), and others (energy, economy, and equity [38]; energy efficiency [42]; urbanization [25]; energy efficiency and rebound effect [52]).

When energy efficiency is handled in CGE models (as a research topic to analyze the effect of energy efficiency or as an assumption for the future), autonomous energy efficiency improvement (AEEI), which exogenously handles energy efficiency improvement (e.g., 2% per annum), is frequently used. However, this approach does not take into account the source of energy efficiency improvement, meaning that energy efficiency improves without explicit costs for the improvement. To address such an issue, the models that consider endogenous technological change have been developed [44–49]. There are two ways to express endogenous technological change in the literature: research and technology (R&D) investment and learning by doing (LbD). The R&D approach, which essentially is based on the growth theory [53], views innovation as a function of expenditure in R&D. This means that technological knowledge can be produced by investing resources into R&D activities [44]. The LbD approach assumes that the accumulation of technological knowledge is a side-product of applying certain technologies [44]. As far as the authors searched articles, most of the studies of CGE models with endogenous technological change in energy economics have been implemented in terms of climate change (see also the special issue on endogenous technological change from the Energy Journal published in 2006). Otto et al. [45] were one exception, which analyzed the relationship between energy and technological change focusing on energy biased technological change.

3.3 Global CGE modeling and its role in climate change mitigation analysis

A number of CGE models have been developed and applied to the global mitigation analysis which has been a major application filed for the CGE models which focus on energy markets last a couple of decades. Integrated assessment models (IAMs) community have been made tens of model inter-comparison exercises and CGE models were involved in. The most well-known exercise is energy modeling forum (EMF),[8] which deals with various relevant and timely topics (mostly related to climate policy). For example, EMF27 presents the technological uncertainty and its implications for the long-term climate mitigation [54]. The other series of model inter-comparison recently taken is led by EU: AMPERE [55], LIMITS [56], and ADVANCE [57,58]. Here we list the global CGE models recently joining these exercises.

In the context of climate mitigation studies, power generation is one of the major CO_2 emissions sources and therefore, most models represent electricity sector in detailed. Until the early 2000s, IAMs were required to represent energy related CO_2. Since non-energy related CO_2 emissions and non-CO_2 emissions along with biomass energy have been focused [59,60], IAMs have been required to represent those things and the involved CGEs are not the exception. Such modeling trend is reflected in the recent CGE model features where land, agricultural and other emissions species are more or less implemented. Furthermore, more interactions with other models (e.g., Earth system models) have been carried out so that the weakness of CGE model is complemented.

Other than the above, there are several topics that have been dealt with by global CGE models within the context of climate mitigation analysis. First, the assessment of emission trading is one of the research area where CGE models are good at. The most recent article would be Fujimori et al. [61], but many articles are accumulated [62–65]. Unemployment is always the concern for the social security and some models have tried to represent it [66,67].

Table 30.2 List of global CGE models in recent IAM model inter-comparison exercises

Model name	*Article*	*Interaction with other model*	*Number of regions*	*Agriculture/ Land*	*Power sector*	*Emissions*	*Other features*
AIM/CGE	Fujimori et al.[a]	Climate, land allocation, agriculture, water models	17	9 sectors/ 9 AEZs	12 sectors	GHGs[b], APs[c]	Recursive dynamic
EPPA	Paltsev et al.[d]	Earth System model	16	2 sectors/ single	10 sectors	GHGs, APs,	Recursive dynamic
ENV-LINKAGE	Château et al.[e]	–	15	?	7 sectors	GHGs, APs	Recursive dynamic
FARM	Sands et al.[f]	–	15	11 sectors/ 18 AEZs	9 sectors	CO_2	Recursive dynamic
IMACLIM	Waisman et al.[g]	Land use and energy models	12	2 sectors/ single	13 sectors	CO_2	Recursive dynamic
iPETS	Ren et al.[h]	Land use and land surface models	9	2 sectors/ single	1 sector	CO_2	Intertemporal optimization
GEM-E3	Capros et al.[i]	Energy model	38	1 sector/ No	10 sectors	GHGs, SOx and NOx	Recursive dynamic

a: www.nies.go.jp/social/dp/pdf/2012-01.pdf.
b: CO_2, CH_4, N_2O, SF_6, HFCs, and PFCs.
c: BC, OC, CO, VOC, NO_X, SO_2, and NH_3.
d: web.mit.edu/globalchange/www/MITJPSPGC_Rpt125.pdf.
e: Château et al. [17].
f: Sand et al. [68].
g: Waisman et al. [6] and www2.centre-cired.fr/IMACLIM/?lang=en.
h: Ren et al. [69].
i: Capros et al. [70].

4 Conclusions: insights for future works

In this chapter, after briefly introduced CGE models and those used in energy economics, we reviewed research articles' CGE modeling research in the field. In the early phase (1980s to early 1990s), energy prices and tax and energy efficiency were the main topic. In that period, the number of the related studies was limited. After 1990s, because climate change has been a vital issue, research on energy issues in terms of climate mitigation has been the most popular topic in energy economics. In addition, large-scale dynamic global CGE models have been frequently used in such studies. For future studies in this field, it is expected that models and data will be more advanced. The important points will be as follows.

- *Resolution of sectors and geographical regions*: In country models, which mainly relies on IO table or SAM of the country, the resolution of industrial sector is usually high enough for desired analyses. For global model, with the development of GTAP model and database, the resolution of both industrial sectors and geographical regions has been improved (57 sectors and 140 regions in GTAP 9). However, its resolution may not be enough for analyzing specific areas. The models with higher resolution need huge computational power. Because of rapid evolution of computers, this will be a less significant issue in the near future.

- *Coupling a CGE model with other types of model*: CGE models in energy economics have various modules in them such as energy, environment (GHG emissions), and land use. However, these modules need to be more or less a simplified form when directly modeling such modules in CGE models. As the choice of energy sources and technologies is diversified and analysis assuming large-scale changes in energy system is required particularly in the context of climate mitigation, it is required to detailed information of energy system, which is not possible only with CGE models. Thus, a CGE model combined with a bottom-up energy technology model is an urgent requirement. In addition, for long-term analysis, it is required to improve estimation of for example materials, transportation, and agricultural products, which are closely related to climate change and energy. Therefore, coupling physical models (i.e., non-economic models) into a CGE model is an important point to evolve the models.
- *Validation of CGE accuracy and parameter estimations*: Since parameters are calibrated by single year data SAM, CGE is rarely validated with the time series data. Although a few attempts exist [71,72], the validation is still the remained tasks for the CGE model.

These issues will help promoting CGE models not only in energy economics but also in the broader field in economics.

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Notes

1 GAMS Development Corporation, GAMS, www.gams.com/.
2 Centre of Policy Studies, GEMPACK General Equilibrium Modelling Software, www.copsmodels.com/gempack.htm.
3 In between the two categories, there exist regional models, such as that of the European Union [36].
4 Center for Global Trade Analysis, GTAP: Global Trade Analysis Project www.gtap.agecon.purdue.edu/.
5 These models are explained in detail in Section 3.3.
6 Here, we searched articles using "computable general equilibrium" AND "energy" for searching phrases in article title, abstract, or keywords (www.scopus.com/home.uri). By using ScienceDirect provided by Elsevier (www.sciencedirect.com/), we can find 1,704 articles (only full research articles and review articles). Similarly, from SpringerLink provided by Springer (link.springer.com/), we could find 614 documents (only English articles). We did not include "CGE" as a phrase for this search because CGE was also used for the abbreviation of different phrases. The number of searched results include articles irrelevant to CGE research or energy research.
7 By searching ScienceDirect, we can find a few more older articles on energy with CGE models. The oldest one in the database is Bergman [34], which analyzed the impact of discontinuation of nuclear power in Sweden.
8 Energy Modeling Forum, emf.stanford.edu/.

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