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Application of computable general equilibrium (CGE) to climate change mitigation policy: A systematic review

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ABSTRACT

With the growing literature related to climate change mitigation measures and policy interventions, a systematic review of the application of computable general equilibrium (CGE) model is inevitable. Therefore, this article aims to characterise the relevant studies, define a comparative framework to identify the current state-of-the-art and the gaps in applied general equilibrium models. Firstly, the systematic review found a total of 301 research articles from Scopus and Web of Science databases and finally analysed 154 articles based on inclusion and exclusion criteria from 67 refereed journals. The review analysis found that application of CGE model is very vital in addressing climate change mitigation issues at the national, regional and global levels. However, China attracted the most substantial research interests followed by the USA, India and Australia, among others, which are in line with their share of greenhouse gas emissions in the world. Most of the research themes focus on the carbon tax, emission reduction target, emission trading, renewable energy, energy efficiency, and carbon capture and storage as primary drivers of low carbon economy. Nevertheless, there is a trend of employing more static CGE model compared to the dynamic CGE, although application of the latter has a limitation of providing right inputs to the macroeconomic policy. Finally, research directions and gaps envision other complementary models such as dynamic stochastic general equilibrium (DSGE) and agent-based model (ABM) for proper policy interventions.

1. Introduction

The greenhouse gas mitigation puzzle links the national policy dynamics directly with the global socio-economic and environmental policy issues. Hence, climate mitigation policy objectives and viewpoints blow hot and cold at global, regional, national and sectoral levels [1]. With global policy modellers seeking long-term climate change stabilization [2,3], regional policymakers are interested in addressing carbon linkages [4], border tax adjustment [5] and transboundary air pollution control [6]; national placing high preference on economic impacts of the transition pathways to low carbon economy [7,8], energy access and security as national goals [9,10], competitiveness and employment are the major policy thrust of the sectoral policy stakeholders. In response to the differences above, United Nation Framework Conference on Climate Change (UNFCCC) has shouldered the responsibility of harmonising climate change related problems at all levels, with its first victory recorded at Kyoto, Japan in 1997. Although, the victory was marred by controversies between developed countries (e.g. USA) and developing countries (e.g. China) about which economy should take the leading role in mitigating greenhouse gas. Since then, efforts have been geared towards having better global deals on climate change and global warming with the most recent conference of parties (COP 21) held in Paris in December 2015. The key outcomes of the conference were the unanimous agreement and a companion decision by party members [11], which has prompted the formal US President, Barak Obama to describe the deal as 'the best chance to save the planet'.

How this breathtaking planet is to be saved is far from clear as many studies point to an increasing amount of energy use and corresponding GHG emissions being from electricity and manufacturing sectors. The US electricity generation, for instance, is responsible for about 39% of all its carbon emissions in 2014 – whose generator mainly relies on coal [12]. In many developing economies, where energy demand has been considerably varied, the noticeable improvement in industrial activities due to the accelerating growth of their economies has led to an unprecedented rise in energy consumption. In China, for example, manufacturing and power generation sectors accounted mainly for the CO_2 emissions with 47% and 32% of all

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China GHG emissions respectively [13]. China, the world's leading CO_2 emitter, however, has been reported as the real force behind the drop in world's carbon dioxide emissions by 0.6% in 2015 [14]. Conversely, India's carbon dioxide emissions have risen due to its power generation, even as global emissions rates dwindle. Therefore, a significant reduction in energy carbon emissions is vital if global CO_2 reduction targets are to be achieved. To do this, a combination of energy efficiency, renewable energy, fossil fuel switching, nuclear and carbon capture and storage (CCS) can lead to given low emissions concentration magnitude with renewables taking the lead [15–17].

As an outcome of the COP 21 in Paris, developed economies are to take full economy-wide mitigation targets, as developing countries are persuaded to gear towards economy-wide emissions reduction target with common core mitigation commitments. Hence, computable general equilibrium (CGE) models have been widely used in simulating the economy-wide effect of climate mitigation policy [18–26]. The literature indicates that bulk of carbon emissions come from the energy sector. Thus, considerable CGE mitigation modelling studies were channelled towards energy system. For example, energy tax [27–32] and energy security [10,33–36] have dominated the climate mitigation literature. However, limited CGE modelling efforts are devoted to other important GHG emitting sectors such as; agriculture with 7.10% of the studies, followed by forestry/forest with 5.20%, industry (3.90%), transport (3.30%), building (1.30%) and lastly, only one research article [37] explores through waste sector based on this review study (see Fig. 1).

To date, there is a lack of systematic literature reviews on the CGE modelling and climate change mitigation policy, despite their rapidly growing literature and debates over the policy intervention becoming unendingly polarised and politicised [38]. Based on the preceding, this article aims to review systematically the relevant literature regarding the application of CGE models on climate change mitigation policy and to characterise the relevant studies, defining a comparative framework to identify the current state-of-the-art and the gaps.

2. The computable general equilibrium (CGE) model

A CGE model is a computer-based simulation which makes use of a system of equations that describe the whole economy and their sectoral interactions. As a multi-sector model, CGE is based on real world data of a single country or a group of national economies. The CGE simulation usually begins with a general equilibrium condition (a business-as-usual) followed by the introduction of a policy shock (e.g. carbon tax or emission trading scheme for climate change mitigation) which by this, the model generates a new general equilibrium reality.

The term ‘computable’ in this model emphasizes the capacity of the model to quantify and ascertain the economy-wide effects of a policy shock via computer simulations. Economists generally rely on a priori information to anticipate the direction of economic policy. However, policy makers may want to know the magnitude of the shock on an economy.

Equilibrium is a household economic jargon which signals a relatively stable economic state. For instance, fluctuations in the supply

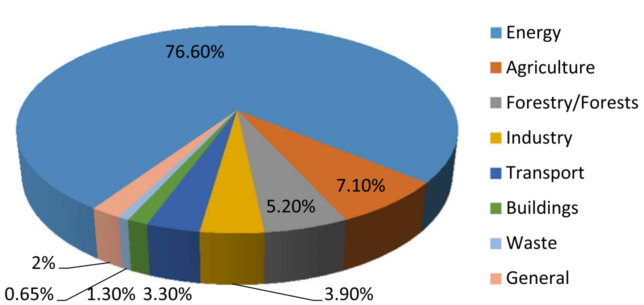

Fig. 1. Applications of CGE on climate change mitigation across sectors.

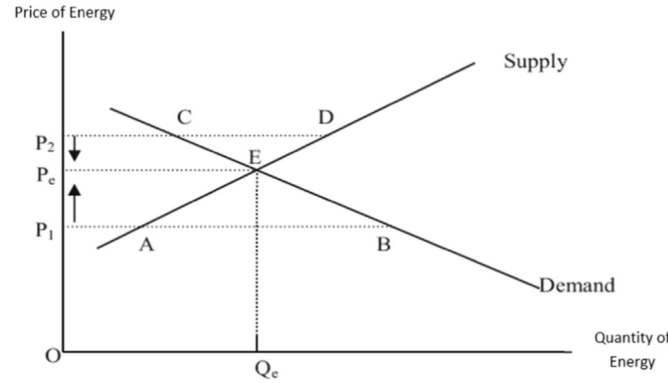

Fig. 2. Market equilibrium.

of and demand for energy (conventional) instigate a change in energy prices and in turn affect the composition of greenhouse gases: when the supply of energy falls short of its demand, energy price goes up; and vice versa. As economic theory posits, the supply and demand over time will converge to a steady state and hence the price of energy will be relatively stable at point E in Fig. 2. Therefore, point E is called the equilibrium in the conventional energy market. But, this graph only reveals the equilibrium in a single market. In reality, several markets are linked and interconnected with one and another. For example, fossil fuel energy market and renewable energy market are closely related. If there is sudden fall in the supply of renewables, their price will increase. With this situation, people tend to use more non-renewable energy and buy fewer renewables. As a consequence, the initial equilibrium in the conventional energy market is affected by the situation in the renewable market. Hence, equilibrium can only be achieved in an economy when all (i.e., general) markets are in equilibrium. Another classical way to understand the interrelationships in a computable general equilibrium model is to view them as a circular flow of spending and income in an economy [39].

2.1. Standard CGE model

A standard CGE model consists of two main components: Model structure and database. As previously argued, the structure of CGE model is a system of equations that take into cognisance all the economic interrelationships in the real world. The economic system comprises different components and thus become very complex in reality. Meanwhile, all sectors and subsectors are directly or indirectly related to demand for and supply of goods and services. All these are fundamental to CGE model. An economic system in a standard CGE model is depicted in Fig. 3 where the key components are those in double lined rectangular text boxes. Capital, labour and intermediate resources are inputs for producing a good or service. At equilibrium, different users such as household, government, investor, intermediate, and foreign, buy this good or service. As shown at the bottom of Fig. 3, these five consumers (demands) represent an important part of the economic system, as all other components are linked to them in multitude ways.

As a data-rich model, CGE database is made up of two parts: the flow of spending and income in an economy and the parameter values. Modeller assigns and fixes the parameter values to the equations while the model is being run. The spending and income flow data for a standard CGE model are usually from the demand for and supply of goods and services. The National statistical department produces these type of data in the form of input-output (I-O) tables. However, for an extended CGE model in which the modeller interest is not limited to the production and consumption activities but also the interrelationship and interconnection between sectors and institutions, more data are needed. Hence, social accounting matrix (SAM) accommodates or allows access to these data [39].

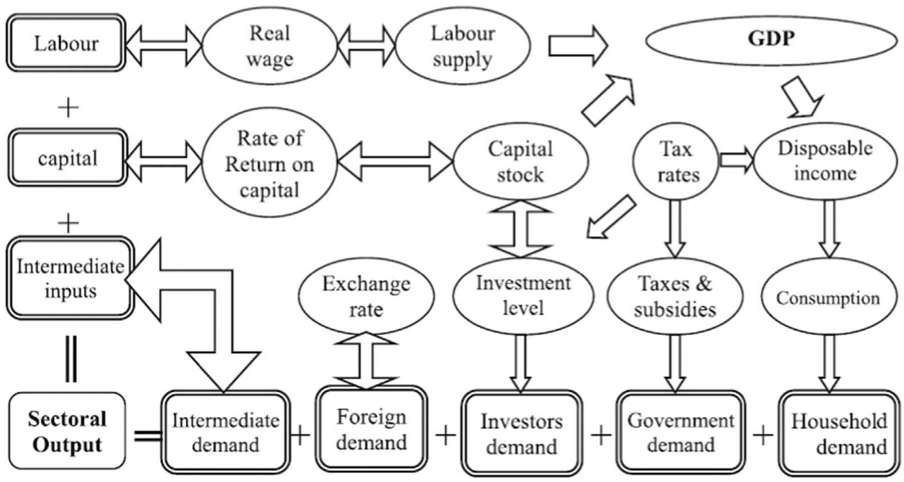

Fig. 3. An economic system in a CGE model [39].

2.2. Types of CGE models

In spite of the aforementioned basic similarities, Individual CGE models defer significantly from one and others, and a number of distinct classifications of the models can be discerned. While different categories can be identified, the difference between static and dynamic CGE models is more suitable for the aim of this study.

2.2.1. Static CGE model

A static CGE model's concern is on the comparison between the initial (before) and final (after) equilibrium of the economy when policy, such as carbon tax changes and causes the economy to reallocate its resources in more efficient ways. Static models provide useful insight into the ultimate losers and gainers from economic shocks though without capturing some costs and benefits related to the transition and so underestimate or overestimate the benefits from the change in climate change mitigation policy. This model is sometimes referred to as a comparative static model. The reason for that is provided by Fig. 4 which shows different levels of GDP against time in years. At the base year 0, the level of GDP is A while B correspond to the year T when economic policy is unchanged. Let us assume there is a policy change, GDP may rise to C, all things being equal. The change from B to C is comparative static rather than static change and it ignores the dynamic pattern (the dashed line): the capital stock is fixed in the short run and adjusted based on the exogenous rates of return. Hence, the model fails to capture the time dimension indicated by the dashed line shown in Fig. 4.

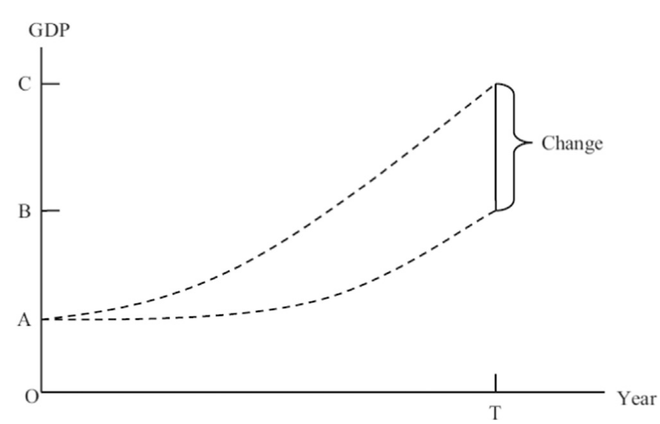

Fig. 4. Comparative static model interpretation.

2.2.2. Dynamic CGE model

Unlike static model, a dynamic modelling means that time variant where capital stocks available for use in year t are shaped by investment in year $t-1$ and before. Dynamic models are models in which household and firms are assumed to be forward-looking and stock accumulation interactions are explicitly considered [40]. There are three key reasons to extend from traditional CGE model to the transitional dynamic approach. First, modellers may want to know those economic forces that lead the economy to a stable state in case it converges. Second, how long (in years) does it take to reach the steady state? Finally, we may want to compare the behaviour of some variables along the transition to actual behaviour.

Therefore, dynamic dimensions are incorporated into CGE model through two major approaches: the recursive dynamic model (i.e. the dynamic ordering of static equilibria) and the completely dynamic model. Recursive dynamic CGE model is employed for multi-period analyses. It obtains solutions for each one of many successive years and the equilibrium solution for year t obtained is used as baseline year for consecutive year $t+1$ without any consideration for intertemporal aspects of decision making of the economic agents. Hence, the economic agents are implicitly faced with myopic or adaptive expectations.

Forward-looking economic agents with perfect foresight can hardly be solved recursively but rather by complete dynamic CGE models. In this case, economic decisions in period t affect parameters in consecutive periods, which, however, rely on the expected values of these parameters. Therefore, a dynamic process is interrelated and the solution has to be sought and solved forward or addressed simultaneously. As a result, these type of CGE models become very complex and less consideration has been placed on its regional and sectoral details.

Finally, in spite of the massive criticisms peddled against static models, most CGE applications are of this sort. The reason could be because dynamic CGE models are theoretically more complex and computationally very difficult to solve.

3. Effectiveness of the CGE model on climate mitigation policy designs

Climate change poses different questions and new challenges for the design of policy in both developed and developing economies, especially as several countries of the world are currently battling with macroeconomic imbalance. Global warming adds new dimensions to the existing list of economic stress such as unequal income distribution, low standard of living (in the case of developing countries), fiscal instability, trade imbalance, crude oil price volatility, and dwindling growth, among other issues, raise serious concerns over the political feasibility of climate change policy measures. Thus, a socially sub-optimal policy response based on models whose mechanisms are theoretically unfounded could result in an irreversible damage to the world at large.

Economists have responded to this great challenge through a number of insightful studies that investigate different individual aspects of climate mitigation responses. Although there is no doubt that these individual efforts have been of immense values, economists have been challenged to put all individual models together and come up with comprehensive one for a concerted and informed action. In the search for a comprehensive approach, Integrated Assessment Models (IAMs) – an approach for examining both the socio-economic and physical effects of climate change - is built. IAMs have provided the useful tool in examining the impacts of climate change since the establishment of the Intergovernmental Panel on Climate Change (IPCC) and its 1st Assessment Report of 1990. The report triggered the first generation of the IAMs such as DICE [41]; RICE [42]; and FUND [43]. Since then, IAMs have been used in the influential reports produced by the IPCC and by many governments in the economic assessment of climate change policies around the world.

As already argued, IAMs possess two key components: physical and economic. The economic aspects of many Integrated Assessment Models are computable general equilibrium (CGE) models that address inter-sectoral mitigation spillovers and country-level climate relationships. Examples of such models are MESSAGE [2]; ENVISAGE [44]; EPPA and Imaclim-R [45] and REMIND [46]. Other organizations including United Nations Environmental Programme (UNEP), European Environmental Agency (EEA), Saudi Environmental Society (SES) and Environmental Protection Agency (EPA) have relied on CGE for a well-informed climate policy response in spite of overwhelming criticism peddled against the model.

4. Methodology

A systematic literature review is a focused review of the literature that succinctly designs question that employs standardized methods to identify, select, organise and critically analyse data from the studies that are included in the review [47–50]. It synthesises existing literature by seeking an answer to a specific research question applying pre-defined eligibility criteria for articles and explicitly outlined and reproducible methods [49,51]. Hence, the crucial stage in developing a systematic review is mapping out a protocol that explicitly draws the aims and objectives of the review, the inclusion and exclusion criteria for research articles, the plan of the analysis, and the way studies are identified. Changes should only be made to the protocol of a review if necessary, else, it will introduce bias [52,53]. The central research questions addressed by this article are;

- What mitigation measures and policies are being built in response to global climate change?
- What types of Computable General Equilibrium Models are being built to simulate mitigation policy options?
- What are the main research gaps after more than five decades of development and application of the CGE model?

4.1. Literature search

All studies with climate mitigation policy focus and where computable general equilibrium (CGE) model was applied were identified via two world renowned indexed electronic databases: Web of Science (WoS) and Scopus, using the following search strings: “mitigation” AND “climat* chang*” AND “computable general equilibrium”, “mitigation” AND “climat* chang*” AND “CGE”, “Low Carbon” AND “computable general equilibrium” and “Low Carbon” AND “CGE”. A research article was considered eligible for inclusion if: (1) it is on climate change mitigation policy; (2) computable general equilibrium is applied to evaluate the economic-wide effect of the mitigation policy, and (3) it is a peer-reviewed article. Papers related principally to climate impacts, vulnerability, adaptation, or general sustainability were excluded, as were studies whose method is other than CGE technique. Finally, article type papers have been preferred to other document types (such as review or proceeding papers). No language or date restrictions were applied, though no non-English [54] except the work of Li et al. [55] which was written in Chinese or pre-1997 articles met final inclusion criteria. Initial searches were conducted between October 2015 and December 2015, and then updated in March 2016 to ensure that all 1997–2015 papers were included.

4.2. Search output

In phase 1, a total of 301 peer-reviewed research articles were retrieved at this stage. Restricting the search to SCOPUS and WoS means that our review is not exhaustive and provides only a sample of the literature on CGE and its application in climate mitigation research. In Phase 2, we scanned titles and abstracts to select articles with clear relevance to climate change mitigation and with implied use of CGE technique. 169 papers were retained and went through full-text review, of which, 154 articles fulfilled the inclusion criteria. One hundred and twenty-five articles were retrieved from Web of Science and only eighty-six from SCOPUS, of which, fifty-seven papers were common to the two databases. This distribution is illustrated in Fig. 5.

4.3. Extraction of data

From each original research article examining CGE application, the following 10 items of information were recorded: (i) author(s), (ii) journal, (iii) publisher, (iv) year of publication, (v) research theme, (vi) study location (country, continent and region), (vii) economic status, (viii) type of CGE model, (ix) scope of the model and (x) mitigation by sector.

We have categorised each study based on a fundamental group of research themes that cut across different mitigation measures such as carbon tax, emission trading scheme, renewable energy, energy efficiency and carbon capture and storage, etc. Based on location, research articles were classified by countries, continents and major regions of the world to find out if geographic patterns exist in the research. United Nations and World Bank classification of the world by regions was used: that is, Central Asia, East Asia & pacific, Europe, Latin America & Caribbean, Middle east & North Africa, North America, South Asia and Sub-Saharan Africa (Fig. 6).

Development taxonomy is a country ordering classification system based on their level of development while development threshold is referred to as its associated criterion [56]. Each study was classified based on country's economic development. The taxonomy used in this

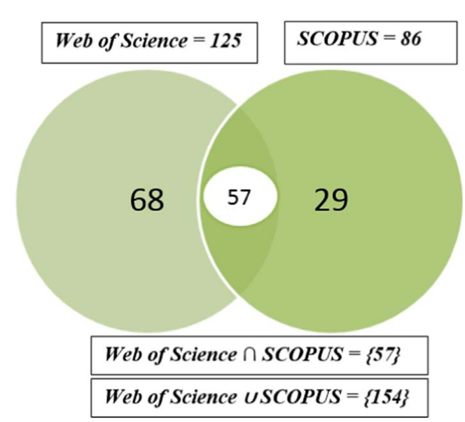

Fig. 5. Distribution of reviewed articles by database.

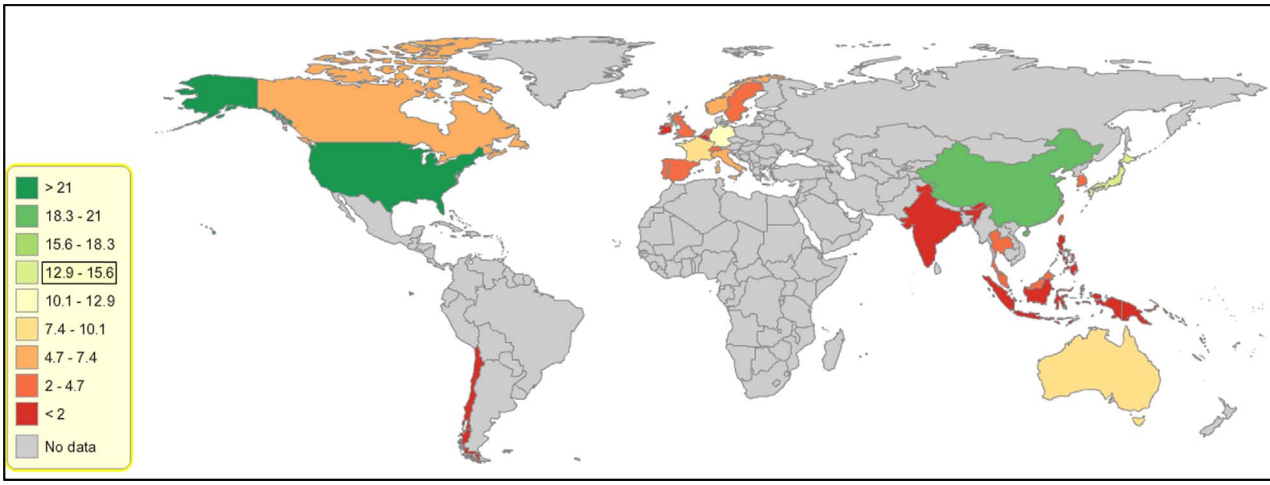

Fig. 6. Geographic distribution of the 154 research papers on CGE and its application to mitigation policies.

study follow the United Nations country classification: that is, developed economies, economies in transition, and developing economies [57]. This is in recognition of its widespread use and not because it is considered appropriate, as it also lacks lucidity concerning how they categorise country classifications [56].

Information relating to CGE models classification has been extracted from each article and assigned to relevant categories. The classification used in this study follows the work of [58], who categorised according to; (i) the nature of the equilibrium they incorporate and (ii) their domain of application. As a consequence, two main classifications were identified, a standard static and dynamic CGE models. The two broad types of dynamic CGE models were further distinguished into a recursive dynamic and forward-looking dynamic CGE. In addition to the static-dynamic mantra, each paper was also classified based on the scope of the CGE application. This includes single-country, regional/multi-country and global models. It goes without saying that models within any of these categories can be dissimilar in many instances, especially on the number of production sectors, primary factors and above all, the specification of international trade relationship.

Finally, mitigating against climate change requires demonstrable efforts from all sectors of the economy. The path to climate sustainability is along with others, as the course of mitigating climate cannot be taken only by government but also spontaneous mitigation by energy consumers [59]. Consequently, key selected mitigating sectors have been identified along with their policy potentials such as energy supply, transport, buildings, industry, agriculture, forestry/forest and waste [60]. However, studies spanning sectors or without sectoral consideration were categorised under the heading – 'others'.

5. Review findings

This study analysed 154 research articles sourced from 67 different journals spanning a broad range of disciplines. The majority were published in Energy Economics (19.48%), Energy Policy (13.64%), The Energy Journal (3.90%), Environmental and Resource Economics (3.25%) and Applied Energy (3.25%). The next most popular journals were Energy, Mitigation and Adaptation Strategies for Global Change, Ecological Economics, Climatic Change, and The B.E. Journal of Economic Analysis & Policy with 4 papers published by each of the journal (Fig. 7). All other journals published three or fewer articles related to the CGE modelling and its application to mitigation policy.

5.1. Number of CGE studies per year

The earliest research was published in Energy Economics by Fisher et al. [27] which coincided with the year Kyoto Protocol was adopted as the most influential environmental conference held in Japan [61]. This was followed by the work of Joos et al. [62] (whose focus was on the significance of carbon cycle representation on the economics of climate change) published in Journal of Environmental Modelling and Assessment. Since then, application of CGE on mitigation measures has escalated substantially with 3.90% published between 1995 and 2001, 14.94% for the period of 2002–2008, and 81.17% published from 2009 to the end of 2015 (see Fig. 8), of which 23 (18.4%) and 18 (14.4%) were published by Energy Economics and Energy Policy respectively.

5.2. Distribution of CGE studies by research themes and sectors

Fig. 9 shows the distribution of studies based on core climate change mitigation research themes. This study reveals that putting a price on carbon via tax remains the central policy instrument for limiting CO_2 emissions [63] with a total of 34 (22% of the total) studies, followed by emission reduction target 21 (14%) research articles as the main national focus [3,64]. Emission trading scheme ranked third most debated policy intervention with 18 (12%) published articles [65,66]. As the campaign towards a low carbon economy gains momentum, renewable energy and energy efficiency have attracted significant attentions with both accounting for about 16% of the reviewed articles. In comparison, other themes such as carbon capture and storage (12), carbon linkages (9), and co-benefit of mitigation measures are fairly represented. A study that focuses on more than one theme is classified as 'other mitigation themes'.

Fig. 10 provides information on the sectoral use of CGE modelling on mitigation policy within the period of 1995 and 2015. The most noteworthy change includes the fact that the proportion of published works on CGE and its application in energy sector fell from 100% in 1995–2001 to 78% in 2002–2008 and to 75% in 2009–2015, with barely similar trend observed in all other sectors, which were clearly under-represented considering their mitigation potentials.

The majority of greenhouse gas emissions (about 71% of the world emission in 2010) come from energy production and use while agriculture ranked second largest source of emissions with 13% in 2010 [67]. As a consequence, Energy sector was the focus of several studies across the regions with East Asia & Pacific recording the highest number of research papers: 45 (80% of the research in the region), followed by Europe: 42 (82%) and North America with a total of 31(66%) peer-reviewed articles. The agricultural sector has however, attracted uneven research attention from among the three regions; North America was well represented, contributing 12.8% of all studies, whereas, European studies were only 6% of the publications. The

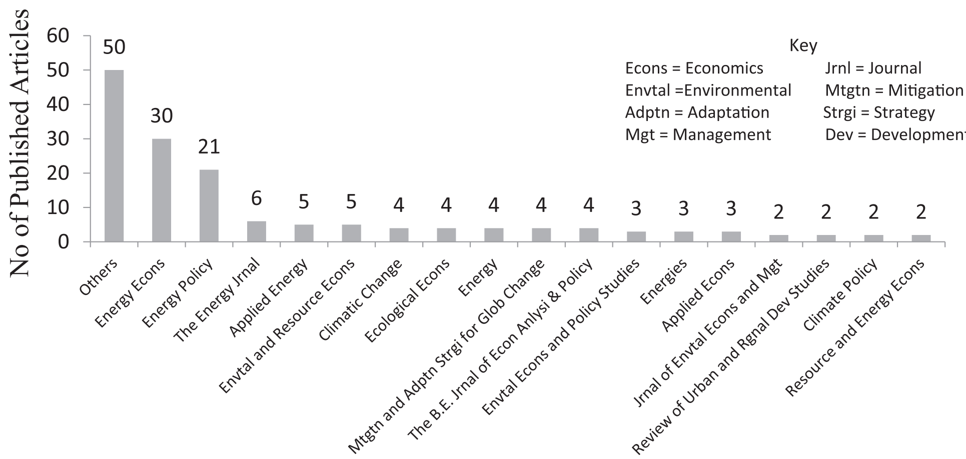

Fig. 7. Articles distribution by journal.

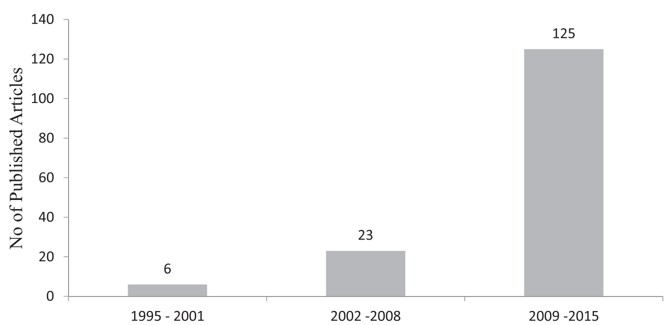

Fig. 8. Number of CGE studies/year.

industrial sector was next in pecking order after energy with a total of 5 studies followed by transport, forestry, and agriculture producing two articles each in East Asia & Pacific. This is because about 61% of countries in this region are either in economic transition or developing stage.

5.3. CGE studies by country

Given the potential threat of climate change across all geographical regions, climate change is expected to amplify regional differences in world's natural resources, assets and the ability of societal and environmental systems to mitigate or adapt to change [68]. Therefore, CGE and its application on mitigation policy have attracted diverse scholarly interest across the globe. The greater number of the studies have been carried out in three regions: East Asia & Pacific (36.4%), Europe (31.8%) and North America (30.5%) with a total of 98.7% of the reviewed papers (see Fig. 6). In comparison, South Asia and Latin America & Caribbean were evidently under-represented and Central Asia, Middle East & North Africa and Sub-Saharan Africa were clearly unrepresented in the peer-reviewed literature considering the magnitude of effects and burden they could shoulder if temperatures were to rise, with the poorest regions likely to be affected the most [60,69]. Our results confirm the positive response from regions above to the report from the United States Environmental Protection Agency (EPA) that Asia, Europe, and the United States are the leading emitters, with 82% of the global emissions in 2011 [67].

Regarding CGE studies by country of origin, the 2001–2008 period reveals that the USA remained the largest source of CGE application on climate change mitigation research. However, USA dominance has been worn away considerably since then (see Fig. 11). The proportion of peer-review articles emanating from the USA, although improved from 33% in 1995–2001 to 44% in 2002–2008 has fallen to 22% in 2009–2015. More so, the proportion of studies emanating from Germany fell from 17% in 1995–2001 to 13% in 2002–2008, and to 6% in 2009–2015.

Comparing 2002–2008 with 2009–2015, an increased number of analyses now originate in China, Australia, Italy, Canada, the Netherlands, Republic of Korea, France, and The United Kingdom. Conversely, CGE application to mitigation measures is evidently low in Malaysia with less than 2% of the total published works between 1997 and 2015. There was also an increase in studies coming from ‘other’ countries (9% in 2002–2008 compared to 13% in 2009–2015), reflecting an increasing trend towards applying CGE across a range of high, middle, and low-income countries.

Meanwhile, China, the world's largest CO_2 emitter attracted the

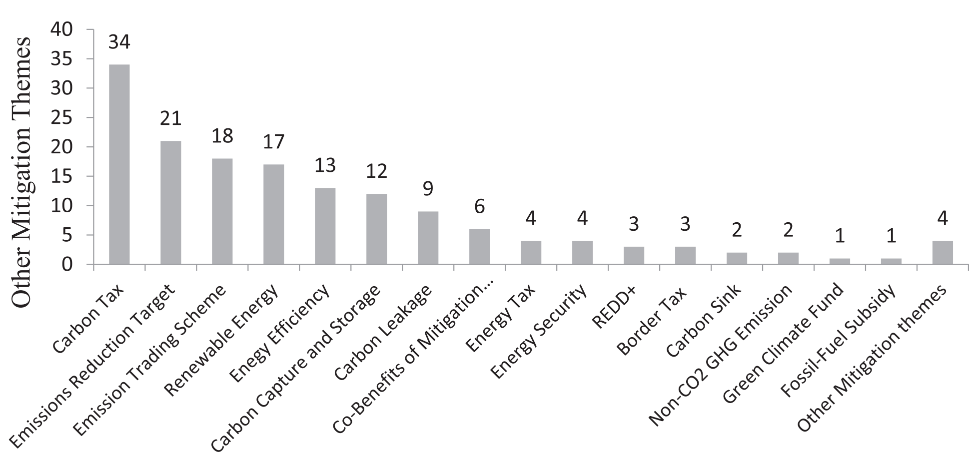

Fig. 9. Distribution of studies by research themes.

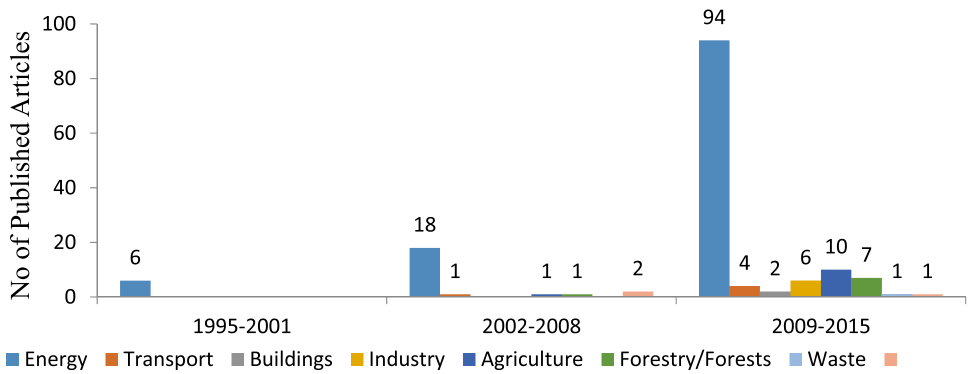

Fig. 10. Application of CGE by sector.

most substantial research interest with about 16% of all articles analysed in this study, followed by the USA with about 10%, Australia and India accounted for approximately 3% of the studies each. The United States is under-represented, given its contribution to the global greenhouse gas emission growth. Our review confirms Europe as the leading region in terms of mitigation of climate change (Fig. 12).

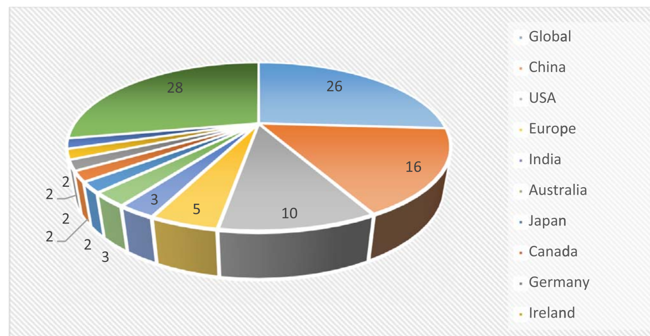

Fig. 12. CGE studies on domain country and regions.

5.4. Application of CGE model by categories

A dramatic shift in the paradigm of economic modelling from simple partial equilibrium models to general equilibrium models with multi-sectors and complex behaviours began with the Leontief studies on static input-output models [70–72]. Despite the fact that quantitative economic technique is more than three centuries old [73], Computable General Equilibrium (CGE) as a recognized and widely accepted tool of economic analysis only began to emerge in the 1960s [74,75] and the 1970s [76–78] with its theoretical basis drawn from Walrasian general equilibrium structure [79]. There is a consensus among economic modellers that the first empirically based CGE model was built by Johansen in 1960 [80–86].

Fig. 13 shows the information on the category of CGE models used across the review periods based on the classification of Devarajan and Robinson [58]. The 1995–2001 reveals that static CGE is the most widely used models in climate mitigation research. However, its dominance has been consumed significantly since then (see Fig. 13). The proportion of published works employing static model fell from 67% in 1995–2001to 61% in 2002–2008 and to 46% in 2009–2015. More so, the proportion of studies using dynamic models has also fallen from 33% in 1995–2001 to 17% in 2002–2008, although it marginally improved to 18% in 2009–2015. The recursive dynamic model did not see the light of the day until the publication of Klepper and Springer [87] and since then, attention has been drawn to its application with a mean of less than 1(22%) between 2002 and 2008 per year to an average of 6.4 (36%) in 2009–2015.

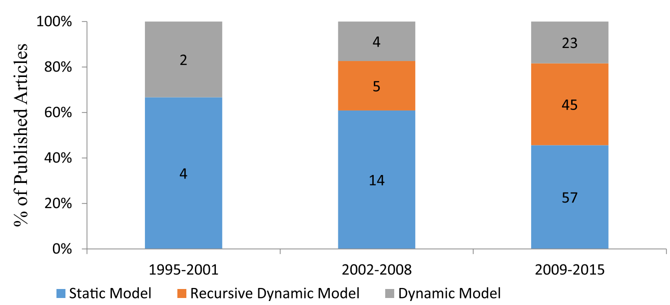

Fig. 13. Category of CGE models.

Fig. 14 provides information on the application of the three types of

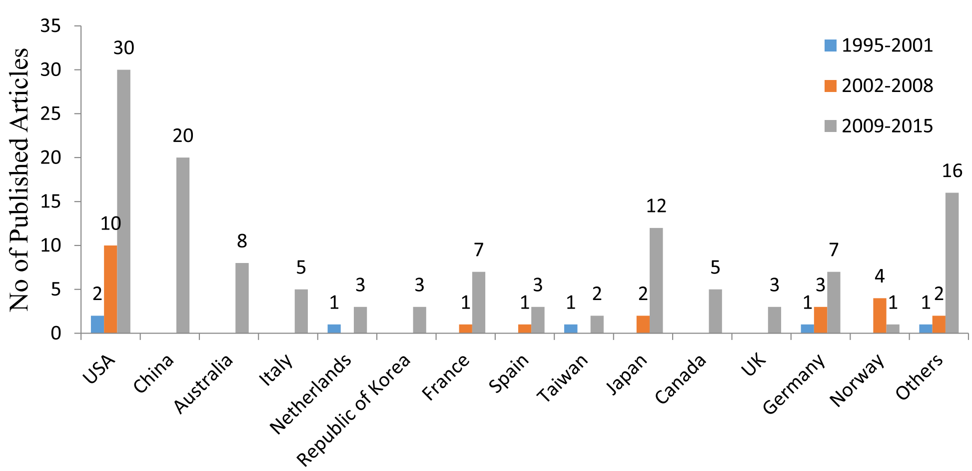

Fig. 11. CGE publications by country.

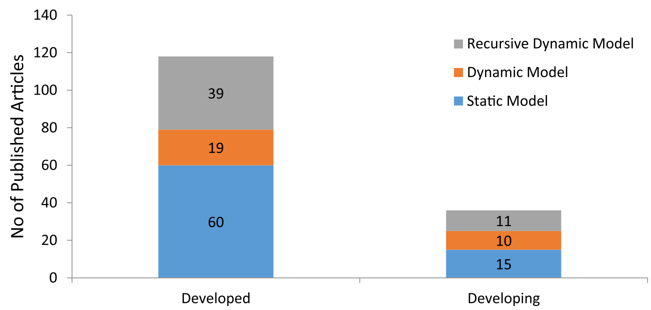

Fig. 14. CGE application by economic status.

CGE model between developed and developing economies. This review reveals that studies from developed countries are the primary sources of CGE application on mitigation policy with about 77% published articles from 1997 to 2015. In contrast, developing countries produced the remaining 23% and more than half of published works from developed countries employ static model, 33% employed recursive dynamic models and 16% went for full dynamic models. However, the distribution according to modelling type has been relatively even for developing economies with 42%, 33%, and 28% for static, recursive dynamic and dynamic models respectively.

Information on the scope of the models is depicted in Fig. 15. In 1995–2001, 67% of analyses employed single country model, rising to 78% of study in 2002–2008 before falling to 60% in 2009–2015. This is not unconnected with the fact that modellers have moved towards multi–country studies. Evidently, the proportion of studies on regional CGE model rises from 4% in 2002–2008 to 15% in 2009–2015 with the first application of the multi-country model in climate mitigation research reported from Germany [88]. More so, the use of CGE models on the global economy has witnessed fluctuating trend over time; 33% studies applied it in 1995–2001, only 17% of published works took a global assessment in 2002–2008, before rising again to 22% in 2012 until 2015.

The majority of Computable General Equilibrium models have been employed to simulate comparative static outcomes of a change in national mitigation policies (see Fig. 14 and Fig. 15). Most recent contributions [23,25,26,89–92] used single-country models in details with respect to the sectors and household types. However, the distribution of studies that took global scale by model's type has been unique, with recursive dynamic models [20,93] employing more than its close rival static model [94,95]. Finally, 48% of the regional multi-country studies used static comparative model, 39% employed recursive dynamic model while only 13% used intertemporal dynamic CGE model.

6. Discussion and conclusion

With CGE and its application in climate change mitigation literature growing expeditiously and controversy over the policy intervention getting unceasingly more polarised and politicised, this study, therefore, reviews selected application works of the CGE modelling in the climate change mitigation literature between 1997 and 2015. Some empirical studies in the literature reported that an unpriced greenhouse gas emissions lead to a negative externality and a carbon price shifts these burden from society to those who trade in carbon-intensive goods [65,66,96,97]. Our results confirm that carbon price vis-a-vis carbon tax and carbon emissions trading is the central research theme in climate change mitigation policies and also affirms the fact that emission reduction target remains a top priority of the national climate change stakeholders. A considerable amount of literature has been published on renewable energy and energy efficiency and identified the two as the main drivers of low-carbon economic transition. Other themes such as carbon capture and storage, carbon linkages, and co-benefit of mitigation measures are shown to be key mitigating options.

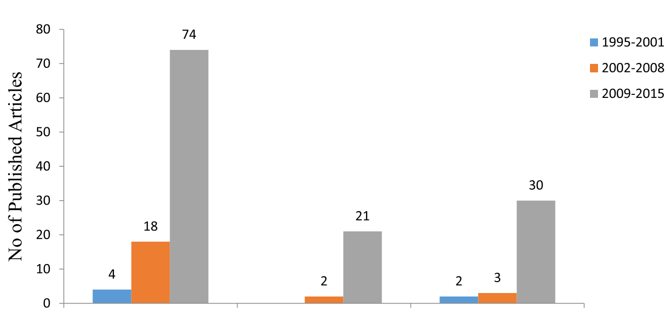

Fig. 15. Distribution of CGE models.

Studies of CGE and its application on climate mitigation policy are predominantly restricted to East Asia & Pacific, Europe and North America, with the United States, China, Japan, and Germany leading the CGE research destinations while CGE applications in other countries or regions have received little to no attention to date. However, these four countries are major emitters of CO_2 emissions; accounting for 28%, 16%, 4% and 2% of gross emissions respectively across the world [98] and research into these countries can provide a useful roadmap for global emission reduction. However, other regions constitute almost half of the global carbon emissions, hence, attention in these areas is urgently needed. In all, USA remained the largest source of CGE application in climate change mitigation research, as does China as the leading research recipient.

Many studies focus on sectoral analyses in the key emitting sectors such as energy [99], agriculture [100], forestry/forest [101], and transport sector [102], with the aim of offering purposive insight into the specific sectoral mitigation policy measures. Energy production and use are undoubtedly the largest sources of greenhouse gas emission and many studies have tried to simulate its roadmap to a low carbon sector [103–110]. However, research on another sector such as; agriculture, industry, forestry/forest, transport, buildings, and waste has been under-represented, given their high economic mitigation potentials as reported by International Panel on Climate Change (IPCC) in 2014 [111]. More CGE applications are needed in other key emitting sectors towards providing right inputs into the national and global policy formation process towards agreeable global greenhouse gas emission reduction.

Static CGE model has dominated the literature since the 1990s, with recursive-dynamic gaining momentum and full dynamic model barely applied to climate mitigation. Therefore, its applications are very diverse and pay more attention to national issues and sizable modelling efforts are devoted to regional and global mitigation scenarios. However, the standard static CGE models do not carve in time and expect that adjustment occurs spontaneously. Hence, the static model has been described as analytically inconsistent [112] and recursive dynamic model termed myopic by Manne [113]. Since the problem of climate change is for an extended period [114], further research is required to employ other macroeconomic models so as to explicitly simulate each variable through time, which is considered more realistic. CGE models, although used in the dynamic macroeconomic analysis, lack necessary toolkit to fit in with the contemporary macroeconomics that rather concentrates on Dynamic Stochastic General Equilibrium (DSGE) models [24]. The CGE and DSGE as neoclassical models rely heavily on logically inconsistent assumptions [115–117], hence, more research is needed to explore other models such as Agent-Based Model (ABM) technique. ABM is ideally suited to such a task by providing more realistic representations, a dynamic and spatial environment in which a large number of heterogeneous and complex agents can interact and evolve [118–121].

7. Directions for future research

Several CGE models dominate many climate change policy debates, particularly in the economics of climate change mitigation. The key of modern CGE approaches presented above is their huge data coverage and detailed application of accounting identities that ensure accurate representation and tractability of the flows and the stocks. However, there have been several challenges to the standard macroeconomics underlying most modern CGE models. These challenges cluster around the use of assumptions such as rational and representative agent with immense computational capacities, cost less and perfect information, complete markets and aggregate production functions. These weaknesses are acute enough in simulating climate change mitigation measures, and could potentially lead to wrong policy response [121].

As already explained above, agent-based simulation models seek to address some of the challenges of microeconomic theories by employing heterogeneous agents with imperfect information and bounded rationality, who is adaptive in a dynamic setting. It is meanwhile, worth noting that ABMs are not completely immune from the difficulty of detailed knowledge on the behaviour of the agents, interpretation, estimation, testing and generalisation of the results [122–124]. While standard CGE may be attacked for relying on a representative agent, ABM in some recent studies has engaged in some aggregation as well [124]. Therefore, ABM is rich in some area and poor in others.

The trade-off between burdensome complexity and the desire for realism suggest that links between ABMs and dynamic CGE models are envisioned to offer a useful way to achieving these competing aims. CGE models can simulate the connections across all sectors of the economy in a transparent way, while ABMs zoom into the specific sector such as energy where uncertainty and heterogeneity are known to be significant. Therefore, further research is required to adopt hybrid models to study climate change mitigation policy measures with a few to come up with detailed and comprehensive mitigation plans at national and global stages.

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