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Enhancing the quality of climate policy analysis in China: Linking bottom-up and top-down models

Govind R. Timilsina^{a,*}, Jun Pang^b, Yang Xi^c

^a The World Bank, Washington, DC, USA

^b Renmin University, Beijing, China

^c China Petroleum University, Beijing, China

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ABSTRACT

Macroeconomic models are the most common analytical tools to assess economy-wide impacts of climate change policies. These models are, however, not capable of representing detailed physical characteristics of energy production and combustion technologies and often lead to the overestimation of economic impacts. One solution to address this problem is to link top-down macroeconomic models with bottom-up energy sector models that can represent technological details. This study develops a hybrid model by linking a top-down computable general equilibrium model with a bottom-up energy sector model and implements it to assess economic impacts of emission reduction targets in China set under the Paris Climate Agreement. Results show that economic impacts assessed by the hybrid model are nearly three times smaller than that assessed by the top-down model alone.

1. Introduction

Macroeconomic models, such as computable general equilibrium (CGE) models, are common analytical tools for estimating economy-wide impacts of climate change or any other policies [1,2]. While [1] presents CGE models analyzing economy-wide impacts of technology adoptions for climate change mitigation [2], presents CGE models to assess impacts of carbon pricing policies. These models are referred to as top-down models in literature because they represent economic agents (e.g., productive sectors, households, and governments) in an aggregated or representative manner. Top-down models cannot incorporate policies that are specific to a sector, a sub-sector, or a technology because specific characteristics of the sector, sub-sector, and technology are omitted. For example, most top-down models represent electricity generation as a single technology, although electricity generation includes different technologies (e.g., hydro, nuclear, solar, wind, coal, oil, and gas). Coal-based power generation technology is highly emission-intensive, whereas renewables (e.g., hydro, solar, wind, and geothermal) and nuclear technologies do not produce emissions directly. The same problem exists in other sectors as well. Fuel consumption and emission rates vary across firms but are lumped together for an industry. In the transportation sector, emission rates vary across the transportation modes (road, rail, water, and air) and within the

mode (e.g., passenger cars, freight trucks in road transportation). The top-down models are incapable of representing physical characteristics of technologies and miss their economic characteristics. The result of not representing the detailed sectoral or technological characteristics is that economic impacts estimated by top-down models are far from actual impacts. They are often overestimated [2].

Other types of models commonly used for energy and climate policy analysis are sectoral or technological models. These models are referred to as bottom-up models. They mostly use engineering techniques for estimating the impacts of a policy. The capability to represent the detailed physical and economic characteristics of technologies is the main strength of these models. However, they ignore behavioral aspects that are critical in projecting energy demand. They also ignore pricing feedback on commodity demand. They cannot estimate economy-wide impacts of a policy and are designed only for a sectoral (e.g., energy) or a technological level (renewable energy generation) analysis.

Linking the top-down and bottom-up models improves the quality of an estimation of economic impacts of climate change policies. Economic modelers have been working on linking the two models for over a decade [1,3]. The linking can be achieved in two ways: hard linking and soft linking. Under the hard linking, detailed sub-sector/technology characteristics are directly reflected in top-down models by disaggregating economic sectors/technologies in the social accounting matrices (SAMs), the main database for calibrating a top-down,

* Corresponding author.

E-mail address: gtimilsina@worldbank.org (G.R. Timilsina).

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Abbreviations

AAG	Average annual growth rate
AEEI	Autonomous energy efficiency improvement
CCS	Carbon capture and storage
CO ₂	Carbon Dioxide
CES	Constant elasticity of substitution
CET	Constant elasticity of transformation
CGE	Computable general equilibrium
GDP	Gross domestic products
GHG	Greenhouse gas
LDV	Light driven vehicles
NDC	Nationally determined contributions
RES	Reference energy system
ROW	Rest of the world
SAM	Social accounting matrix
UNFCCC	United Nations Framework Convention on Climate Change

particularly a CGE model [4]. The resulting model is also referred to as a hybrid model [5,6]. However, hard linking is not always possible due to a lack of data. Moreover, it is applicable only for limited technology, such as electricity generation [4,7].

Soft linking is an iterative process where a top-down model is run first to project driving variables, such as sectoral outputs, value-added, and commodity prices. These variables are then used in a bottom-up model to project energy demand and an optimal energy supply mix. The results from the bottom-up model are then fed into the top-down model to ensure that technological characteristics represented by the bottom-up model are also reflected indirectly in the top-down model. A few iterations are needed to achieve a sufficient convergence between the two models. Examples of studies applying this approach are [3,8]. Our study adopts the soft-linking approach to link an energy sector bottom-up model, TIMES, with a top-down CGE model for China's climate policy analysis. TIMES model is an energy sector optimization model [3] and the CGE model is a macroeconomic model [2]. The details

of these models and their linking will be presented in the methodology section later.

This study investigates the case of meeting China's Nationally Determined Contributions (NDCs) under the Paris Agreement. China's NDCs specify that the country would lower emission intensity (i.e., CO₂ emissions per unit of GDP) by 60%–65% below its 2005 level by 2030. The government has also set a goal of increasing the share of non-fossil fuels to 20% of its total primary energy consumption by 2030 [9]. The study first uses a national CGE model to estimate the economic costs of meeting China's NDCs through a carbon tax. The CGE model is then linked to the bottom-up TIMES model to produce a revised baseline.

The paper is organized as follows. Section 1 presents the context for the study. Section 2 explains the linking principle and presents brief descriptions of the top-down CGE and bottom-up TIMES models. We also elaborate the actual implementation of the soft-linking employed in the study. Section 4 presents and discusses the main results and compares the results with those from literature. Section 4 presents the key conclusions.

2. Methodology

2.1. The linking framework between the CGE and TIMES models

The overall methodological framework is presented in Fig. 1. First, the CGE model projects variables, such as GDP, household income, sectoral output, and energy prices. These variables are drivers of energy demand in the TIMES model. Using these drivers, the demand module of the TIMES model forecasts energy demand by end-use type (space heating and cooling, refrigeration, cooking, lighting, electrical motors, electronic appliances, process heating) in different sectors (households, commercial/service sectors, and industry). The TIMES model also incorporates various assumptions to reflect the existing government policies.

The end-use energy demand projected by the demand module of TIMES, and the energy price indices produced by the CGE model are then used in the supply module of TIMES to produce the optimal energy supply mix. The optimal energy supply mix confirms that it is the least cost among the many possible alternatives.

The energy supply-mix is then used in the CGE model to adjust its

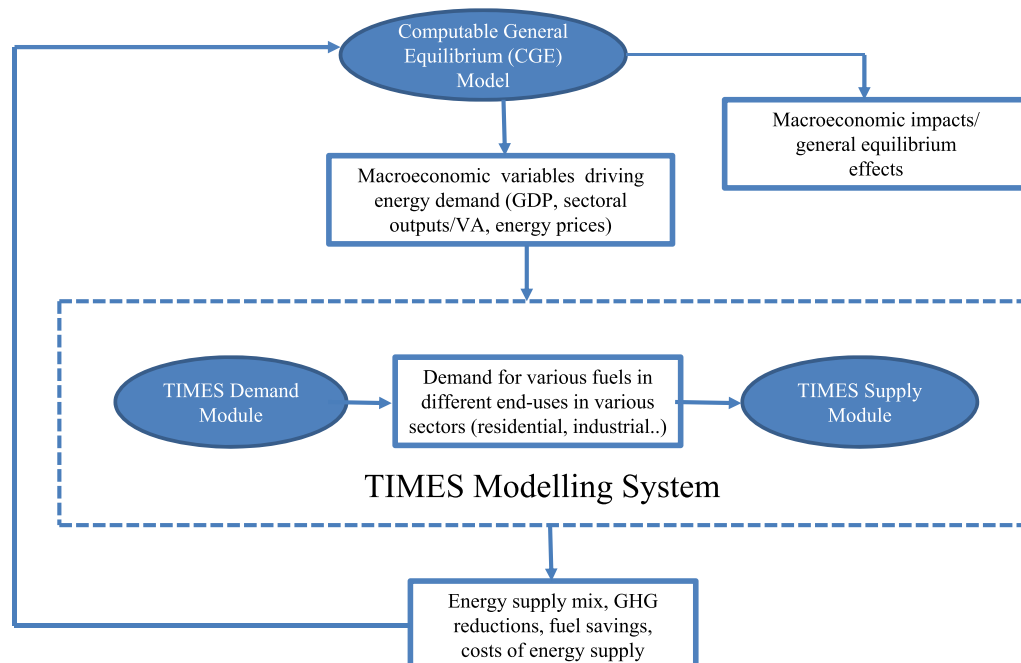


Fig. 1. Process of linking CGE and TIMES models.

parameters (e.g., share parameters) so that the energy supply mix of the TIMES model can be reflected in the CGE model. The adjustments align the growth rates of primary energy commodities (coal, oil, natural gas) in the CGE model with those in the TIMES supply-mix results. The same should be followed for primary electricity. However, our CGE model has only one electricity commodity and does not explicitly represent the primary electricity. Therefore, growth rates of primary electricity in the TIMES model are not reflected in the CGE model. Moreover, new and renewable energy (solar, wind), which are explicit in the TIMES model, are embedded in the total electricity in the CGE model. The growth rate of aggregate electricity (i.e., weighted average growth rates of various electricity generation technologies) obtained from TIMES results are applied to adjust the electricity growth rate in the CGE model.

One would argue that why not disaggregate the electricity sector in the CGE model to various technologies in the same way several CGE models [7] have done. Note that these existing studies do not follow linking the CGE models with bottom-up models. Instead, they disaggregate their electricity sector in their SAMs to allow hard linking instead of soft linking. While the hard linking partially brings technological characteristics of electricity generation technologies into the CGE model, it does not represent one of the main features of electricity sector operation, merit-order or economic load dispatching, which refers to operating of electricity generation plants to meet the demand in a given time based on their operating costs. The soft linking we adopted in this study captures the load dispatching as well. Moreover, even if we disaggregate the electricity sector to various technologies, it is not possible to disaggregate other energy/emission-intensive sectors, such as cement, chemicals, iron, and steel, due to lack of data.

2.2. Top-down CGE model

The top-down CGE model used in the study is a recursive dynamic CGE model to analyze the economic effects of energy and environmental policies in China. Like in most CGE models, it explicitly represents the behavior of households, the government, production sectors, and the rest of the world (ROW). The production sectors are classified into 16 sectors. Five of them are energy supply sectors: coal mining, oil and gas extraction, petroleum refinery, gas processing, and electric power generation. Table 1 presents these sectors. To avoid unnecessary lengthening of the paper, we have not presented a detailed description of the CGE model. Interested readers are encouraged to refer [10].

Fig. 2 illustrates representation of each of the production sectors in the CGE model. The model uses a six-tier nested constant elasticity of substitution (CES) function to represent a production behavior. This multi-tier CES representation provides flexibility to the model by allowing different substitution possibilities across the tiers. Like in most

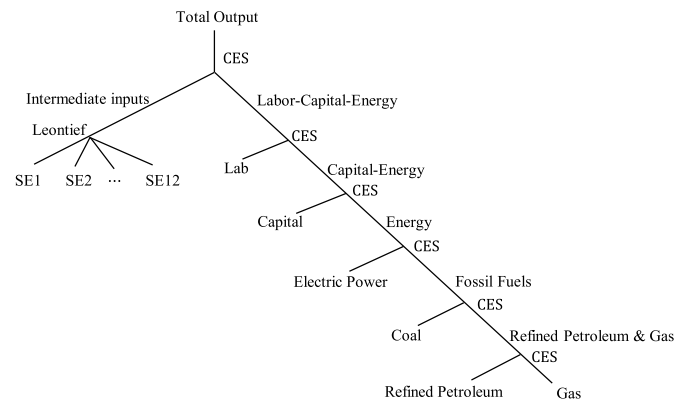


Fig. 2. Structure of production function in the CGE model.

CGE model formulations, the model assumes that the market follows the perfect competition, and the production process follows the constant returns to scale.

The model assumes that domestic production and imports of goods and services are imperfect substitutes. This assumption is popularly known as the Armington assumption [11]. A CES function combines domestically produced and imported components of a good or service. Each tradable commodity or product is allocated between export and domestic markets following a constant elasticity of transformation (CET) function.

Firms (i.e., production sectors) generate their income from capital returns and transfer payments from the government. Part of their after-tax income is transferred to the households, and the remainder is retained as profits. Households behaviors are modeled through a representative household. They generate capital and labor incomes and receive transfers from the government, firms, and abroad. The rate of household savings is determined based on marginal propensity to save, and household expenditure is allocated to various goods and services through a Cobb-Douglas functional form.

The government revenues include indirect taxes and import duties collected from goods/services, personal income tax collected from households, and corporate income taxes collected from firms and transfer payments from other agents (households, firms, and ROW). If a carbon tax is introduced, it is treated as an indirect tax on goods and services, and carbon tax revenue goes to the government, which is recycled to the economy in different ways. Total government expenditure is kept fixed and allocated to the purchase of various goods and services at the same proportion as in the baseline. The government savings are the difference between total government revenue and total government expenditure.

Like in a standard CGE model, total labor supply is equal to total labor demand at the national level, where labor mobility is allowed across the sectors. The same is true for the capital account – total capital demand is equal to total capital supply and capital mobility is allowed across the sectors. Wage rates and capital prices (or user costs of capital) are different across the sectors. Similarly, the total supply of a good/service (imports plus domestic production) is equal to the total demand for that good/service (domestic consumption plus exports). The total investment is equal to total savings: the sum of household-, government-, firms- and foreign-savings (macroeconomic balance).

The model is made dynamic through the population growth rate (i.e., labor supply growth rate) and investment. Total savings of the previous period (or year) is an investment of the current period (year). Demand for the total capital of the current period is determined by the previous period's capital stock plus depreciation and interest payment and new-added investment (which is the previous period's total savings). Total investment is allocated across sectors in proportion to each sector's share in the aggregate capital account, and these proportions are adjusted by the ratio of each sector's profit rate to the average profit rate

Table 1
Sectors and commodities represented in the CGE model.

Sector Name	Definition or coverage
AGRI	Agriculture, forestry, animal husbandry and fishery
COAL	Mining and washing of coal
OILNG	Extraction of petroleum and natural gas
MINE	Mining and processing of metal and non-metal
FTPMF	Food, tobacco, textile, leather, fur, feather, timber, furniture, paper, printing
PETRO	Processing of petroleum, coking, processing of nuclear fuel
CHEMI	Manufacture of chemical products
NMETA	Manufacture of non-metallic mineral products
METAL	Smelting and processing of metals
OTHMF	Other manufacture
ELECT	Production and distribution of electric power and heat power
GAS	Production and distribution of gas
WATER	Production and distribution of tap water
CONST	Construction
TRANS	Transport, storage and postal services
SERVI	Other services

for the whole economy.

2.3. Bottom-up TIMES model

The bottom-up energy sector TIMES model used in this study is an optimization model. It is based on the reference energy system (RES) principle. The RES refers to an optimal energy flow system to meet the end-use useful energy demands (e.g., light, heat, electric traction, motive power, etc.) supplied from alternative sources through various channels or networks (transmission lines, pipelines). Fig. 3 illustrates the RES based on which our TIMES model is developed. In the demand side, various energy utilization technologies that convert final energy to useful energy (e.g., a boiler that converts natural gas to heat, a light bulb that converts electricity to light, an electrical motor that converts electrical energy to mechanical energy) are represented. In the supply side, energy production from primary resources (e.g., oil and gas production) and their transformation (e.g., electricity from coal) are represented. Energy transportation facilities (e.g., pipelines for oil and gas, transmission lines for electricity) carry energy commodities from production locations to demand centers.

The TIMES model used in this study has five demand sectors: agriculture, industry, commercial, residential, and transportation. Energy-intensive industry sectors are further divided into sub-sectors based on technology or fuels. For example, the chemical industry is first subdivided into various sub-sectors based on product types, such as ammonia, ethylene, fertilizers, caustic soda. Each sub-sector is further divided based on the technology or fuel used. Altogether, the model considers 43 industrial sub-sectors and more than 400 technologies. Please see Ref. [10] for a detailed description of the model. There also exist separate TIMES models for China [12,13]. The basic structures of all TIMES models are similar. They are, however, different in terms of the number and types of technologies used for energy production, transformation and utilization.

The building sector is divided into urban residential, rural residential, and commercial categories, and energy demand is further divided into space heating, cooling, water heating, cooking, lighting, and electric appliances. Concerning different climate conditions and building

design standards: four regions, Severe Cold (SC), Cold (C), Hot Summer - Cold Winter (HSCW) and Hot Summer - Warm Winter (HSWW), are considered separately, based on the Standard of Climatic Regionalization for Architecture.

The transport sector is first divided into two categories: passenger and freight. Passenger transport is then divided into five types, and freight transport is divided into four types. Passenger services based on business LDVs owned by government bodies and companies are treated separately from private passenger services. Private passenger transport is disaggregated into four distinct inland passenger transport service types, based on geographical coverage and travel purposes: intercity, urban, rural, and business, and one international passenger service. Automobiles for passenger transportation are further divided by the type of fuel use: gasoline driven, diesel driven, electricity driven, and hybrid. Freight transport encompasses two inland freight transportation services: domestic freight and two international freight transportation services.

Government plans and policies, such as building energy efficiency standards, industrial process energy efficiency standards, vehicle mileage standards, are taken into consideration while projecting the demand. For example, the energy service demand projection in an industry sector (e.g., steel, cement, ammonia, aluminum, paper) is driven by its expected output, expected improvement in energy intensity of the production. In the beginning, the TIMES model uses energy drivers from various sources. When the TIMES model is linked with the CGE model, most of the drivers are taken from the CGE model outputs (e.g., the projection of output of an industry, price indices of the outputs). In the case of energy demand in buildings, a key driving variable to be projected by the CGE model in the baseline is household income. This projection, combined with other assumptions such as population growth, floor space per capita, energy requirement (e.g., lighting or heating energy requirement per unit of floor space) will determine energy demand. The demands for energy for transportation are determined through the projection of transportation services, which is driven by technological, economic, and demographic factors.

The model also considers future technologies, such as coal-fired power plants with carbon capture and storage (CCS) facilities,

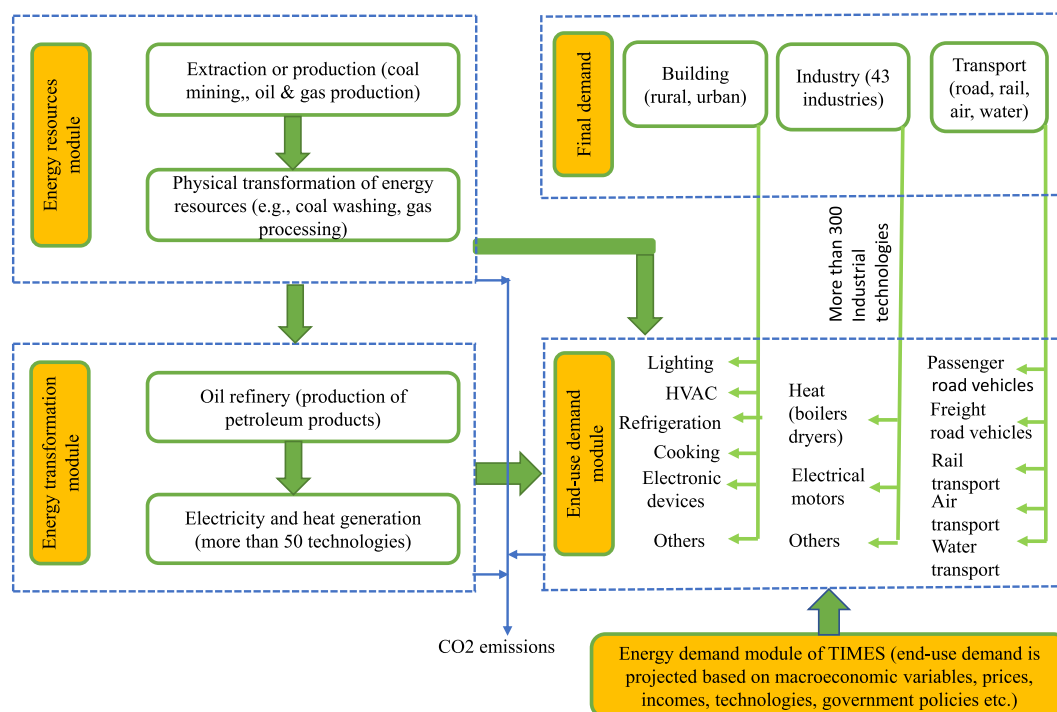


Fig. 3. Res framework – the foundation of a times model.

hydrogen fuel-driven automobiles. The detailed representation of technology allows the substitution possibility between different types of technologies based on their production costs and other technological parameters. It also allows for the model to represent implementing government policies. For example, if the government plans to have a certain percentage of vehicles electricity-driven or hybrid type in a given future year, the model can easily incorporate this policy.

2.4. Implementation of model linking

In order to illustrate how the linkage of the top-down and the bottom-up models enhances the quality of climate change policy impact assessments, this study implements the methodological framework developed above to investigate the economic implications of meeting China's NDC. First, the study considers a case where these two models are not linked. The CGE model is run to produce the baseline, followed by running the CGE model with a carbon tax to meet China's NDC targets. The TIMES model is also run independently, first for the baseline and second with the carbon tax. Note that TIMES results are for the energy sector only as it is incapable of assessing economy-wide impacts.

The results of independent (without linkage) runs of the model show a huge difference in their projections of energy demand and supply growth as the input data used in these two models are different. For example, the average annual growth rate (AAGR) of GDP for the 2015–2030 period is almost one percentage point higher in the CGE model (5.8%) than that in the TIMES model (4.9%). This is because the GDP growth rates used for the CGE model and the TIMES model are driven by different assumptions on the future path of the Chinese economy (independent between the models). The growth rates of energy commodities responsible for carbon emissions (i.e., coal, oil, and natural gas) are different between the CGE and TIMES models for two reasons. First, the growth rate of GDP, the main driver of energy demand, is one percentage point higher (as mentioned above) than that used in the TIMES model. Second, the TIMES model has incorporated technology-specific policies, such as energy efficiency standards, that lower the future energy demand. In contrast, the CGE model is not capable of incorporating detailed technology-specific policies and standards.

The linking process started by using TIMES growth rates of fossil fuel demand in the CGE model. It is also possible to start using the GDP and energy consumption growth of the CGE model in the TIMES model. However, we found more iterations are needed to get convergence of the results of the two models. The growth rates of key economic drivers (GDP, sectoral outputs, electricity prices) projected by the CGE model are then used in the TIMES model. The results of the TIMES model, specifically the growth rates of primary energy commodities (coal, oil, and natural gas) are sent back to the CGE model to re-run it. This process continues until the results from the two models converge.

A large number of sources, more than 50 documents, are used for data. Key data sources include various issues of China's Energy Statistical Yearbook, China Statistical Yearbook, Industrial Statistical Yearbook, China Steel Statistics, China Chemical Industry Yearbook, China Nonferrous Metals Industry Yearbook, Input-output Tables 2012, Automotive Energy Outlook, China Transport Yearbook, China Bulletin on Motor Vehicles Pollution Prevention. A detailed list of data sources is available in Ref. [10]. The detailed descriptions of the models and data are also available electronically as a supplemental document from the webpage of this journal.

3. Model simulations results

This section first presents economy-wide results, which are the changes in various economic variables due to the policy instrument as compared with their values in the baseline. Although the model produces results for other intermediate years, we present the results for the year 2030. The reason is that the NDC target is set for 2030. The policy instrument is a carbon tax required to meet the NDC target. The result

indicators used are the main macroeconomic variables, including economic welfare, GDP, government revenue, household income, household consumption, total sectoral output (gross output), total investment, exports and imports. Also included in the result indicators are the environmental indicators: total emissions and emission intensity. The results at the sectoral level are presented as well. Results from this study are also compared with those from literature.

3.1. Economy-wide impacts

Table 2 presents the key impacts generated by the hybrid model (top-down CGE model linked with the bottom-up and top-down model) and the CGE model alone. When the CGE model is used alone to assess the economic impacts of meeting China's NDC under the Paris Accord, a carbon tax of CN¥372/tCO₂ would be required. The carbon price is expressed in 2012 constant price. In nominal term, it would be CN¥483 in 2030. The nominal price is converted to real price using consumer price index projected by the CGE model. It would reduce GDP and economic welfare in 2030 by, respectively 0.9% and 3.2% from the baseline. The total reductions in emissions and emission intensity in 2030 would be, respectively, 29.8% and 29.2%, from the baseline. The results are substantially different when the top-down CGE model is linked with the bottom-up TIMES model. The carbon tax required under this case would be CN¥110/tCO₂, which is 70% smaller than the case when the CGE model is not linked with the bottom-up model. Similarly, the percentage CO₂ reduction achieved with the linkage is smaller by a factor of 0.58 from that without the linkage. Consequently, most of the other indicators presented in Table 2 under the linkage are 0.58–0.75 times smaller than the corresponding values without the linkage.

The top-down CGE model without the linkage to the bottom-up TIMES model results in higher economic impacts than that in the linked case. The primary reason is that the TIMES model accounts for the energy-efficient technologies used in energy supply chains and energy utilization processes because of its capability to represent the detailed technologies. The deployment of energy-efficient technologies is mainly driven by existing and committed government policies. Committed policies here refer to policies that have been announced but will be implemented at a future date. The results from the hybrid modeling system show that nearly 60% of the emission reductions would be achieved through the implementation of existing or announced policies. The additional policy, here the carbon tax, would be needed only for the remaining portion of the emission reduction required to meet the NDC. Thus, the required carbon tax would be lower by one-third under the linked case. Consequently, the impacts on economic variables are

Table 2
Comparison of impacts on key indicators with and without the linkage.

Indicators	Impacts (% change from the baseline unless specified otherwise)		Difference (Impacts with linkages as a fraction of that without linkage)
	Without linkages	With linkages	
Carbon tax rate (Yuan/tCO ₂)	372	110	0.30
Welfare	−3.2%	−0.9%	0.27
GDP	−0.9%	−0.20%	0.23
Total Emissions	−29.8%	−12.5%	0.42
Emission Intensity	−29.2%	−12.3%	0.42
Government Revenue	8.0%	2.6%	0.32
Household Income	−3.1%	−0.9%	0.28
Household Consumption	−2.8%	−0.8%	0.27
Gross Output	−2.5%	−0.7%	0.30
Total Investment	1.8%	0.4%	0.25
Total Export	−6.9%	−1.9%	0.28
Total Import	−1.2%	−0.3%	0.28

smaller under this case compared to the case in the absence of the linkage.

The advantage of linking the top-down model with the bottom-up model is that it allows the linked model to capture existing or anticipated technological policies, correcting the growth of energy demand and associated CO₂ emissions. Stand-alone top-down models (i.e., top-down models without linkage with bottom-up models) attempt to capture this feature to some extent by introducing a scaling parameter called autonomous energy efficiency improvement (AEEI). Interpretations and values of AEEI used in some top-down models are available in Ref. [14]. The AEEI values used in the existing top-down models have two limitations. First, these values are either chosen randomly or selected to calibrate the models for achieving a specified growth pattern. Second, existing studies assume that energy efficiency improves automatically without causing any cost to an economy. Contrary to this assumption, the bottom-up models capture the costs of energy efficiency improvements, which represent the incremental cost of an energy supply system with energy-efficient technologies instead of their inefficient counterparts.

The linking of top-down and bottom-up models allows estimating the values of AEEI for China for a given timeframe. In the absence of linking China's CO₂ emissions in 2030 would be 11.62 billion tCO₂ in the baseline. With the linkage, it would be 80% smaller. To meet the NDC target, the required CO₂ reduction under the linked case would be approximately one-third of that in the absence of the linkage. To achieve the same level of emission reduction in the baseline without linking the CGE model with the bottom-up model, the value of AEEI would be 1.5% for the 2015–2030 period. Thus, the estimation of the AEEI value by linking a top-down CGE model with a bottom-up TIMES model is also a contribution of this study to the existing literature. This is the first time in the literature the value of AEEI is estimated for China using an innovative and rigorous technique.

Notably, estimating the value of AEEI by linking a top-down model with a bottom-up model is different from calibrating a CGE model with an emissions path projected by a bottom-up energy sector model. In the latter case, the projections of future energy demand path and associated emissions would be different because of different assumptions and data between the two models. Calibrating the AEEI parameter of a CGE model with information from a bottom-up model that is not linked with the CGE model is equivalent to selecting the AEEI parameter randomly, and it does not help enhance the quality of assessments of economic impacts of a climate change policy.

3.2. Sectoral results

Table 3 presents economic impacts at the sectoral and commodity levels under the linkage and without linkage cases. As expected, energy sectors (e.g., coal, oil, petroleum products, gas, and electricity) and energy-intensive sectors (e.g., metals, minerals, non-metals, and chemicals) would face higher percentage reductions of CO₂ emissions and also higher drops of sectoral outputs (Table 3). The sectoral impacts are significantly smaller under the linked case than in the not-linked case. The reasons behind it are the same as explained earlier. In the stand-alone mode, TIMES model assumes that GDP would grow, on average, by 4.9% annually during the 2015–2030 period, whereas the CGE model assumes that it would grow by 5.8% annually during the same period. This one percentage point lower GDP growth rate in the TIMES model has a huge consequence on energy demand for all fuels and in all sectors. Energy demand and associated emissions would be smaller under the TIMES model than the corresponding values in the CGE model. The linking pulls up the demand and emissions in every sector, but they will still not be as high as they are under CGE stand-alone case. The second reason is that TIMES model accounts for the improvements in technologies in energy supply and demand sides. These improvements further dampen the energy demand and associated emissions in the TIMES model. As explained earlier, when the baseline emissions are lower under the linked case and the targeted reduction is fixed based on the 2005 emission level, the amount of emission reductions to meet the NDC target will be much lower, less than a half, than that in the absence of the linkage. The required carbon tax rate to achieve the NDC targets drops by 70% under the linked case compared with that in the absence of the linkage. Thus, the sectoral impacts of the carbon tax would be much lower under the linked case than that in the absence of the linkage.

3.3. Comparison of results with the existing studies

Although a comparison of results from a study with those from the literature may not be appropriate because of differences in underlying assumptions, model structures, and country background, it could be useful to derive a general message if the results are comparable, at least in direction, if not in magnitude. A finding similar to ours is also reported for China in Ref. [5] when linking a global top-down CGE model, AIM, with the global bottom-up TIMES model, TIAM. It shows that the impacts on CO₂ emissions for 2050 estimated by a linked model would be by 8%–25% smaller than that projected without linking the models.

Table 3
Impacts on CO₂ emissions and economic indicators at the sectoral level in 2030 (% change from the baseline).

Sector/Commodity	CO ₂ emissions		Sectoral output		Household consumption		Imports		Exports	
	Not-Linked	Linked	Not-Linked	Linked	Not-Linked	Linked	Not-Linked	Linked	Not-Linked	Linked
Agriculture, Forestry, Animal Husbandry and Fishery	-11.4	-4.1	-0.6	-0.1	-1.0	-0.2	-5.3	-1.5	5.6	1.7
Mining and washing of coal	-53.7	-26.0	-34.5	-15.0	-2.2	-0.5	-9.9	-5.9	-59.0	-26.8
Extraction of petroleum and natural gas	-27.8	-10.9	-12.7	-4.4	-7.7	-2.6	-12.4	-4.2	-13.2	-4.7
Mining and processing of metal and nonmetal	-22.2	-8.6	-5.3	-1.6	-6.0	-1.9	-2.8	-0.6	-9.5	-3.3
Food, tobacco, textile, leather, fur, feather, timber, furniture, paper, printing	-28.5	-11.9	-1.2	-0.2	-8.7	-2.6	-4.2	-1.4	3.7	1.7
Processing of petroleum, coking, processing of nuclear fuel	-32.9	-13.8	-13.7	-5.0	-1.0	-0.2	-3.0	-1.0	-28.6	-11.1
Manufacture of chemical products	-25.4	-10.2	-5.7	-1.8	-2.2	-0.5	6.5	2.2	-15.9	-5.5
Manufacture of non-metallic mineral products	-27.6	-11.9	-3.4	-1.0	-7.7	-2.6	29.7	8.1	-25.2	-8.5
Smelting and processing of metals	-26.8	-11.2	-4.8	-1.4	-	-	10.2	2.7	-21.5	-6.7
Other manufacture	-25.7	-10.2	-2.4	-0.7	-3.7	-1.0	0.3	0.1	-5.3	-1.6
Production and distribution of electric power and heat power	-34.2	-14.8	-18.9	-7.0	-20.6	-7.3	44.8	12.8	-39.8	-15.8
Production and distribution of gas	-39.9	-15.9	-19.2	-5.2	-11.3	-2.7	-	-	-	-
Production and distribution of tap water	-23.6	-9.4	-2.9	-0.9	-3.2	-1.0	-	-	-	-
Construction	-12.2	-4.6	0.7	0.1	-	-	2.6	0.7	-3.0	-1.1
Transport, storage and postal services	-18.5	-5.6	-2.3	-0.6	-3.9	-1.0	-0.4	-0.3	-4.6	-0.9
Other services	-19.3	-6.4	0.7	0.2	-1.5	-0.4	-2.8	-0.8	5.9	1.7

In another study for China [6], a lower reduction of CO₂ emissions resulted when estimated linking the bottom-up and top-down models than that without the linking. Existing studies for China agree that the economic costs of climate change mitigation estimated by the linked model would be smaller than those estimated without the linkage. In Ref. [15], it is found that the level of emission reduction estimated by the linked model would be less than a half of that estimated by the top-down model alone. In Sweden, CO₂ emissions are found 12%–13% lower when estimated linking a CGE model with the bottom-up energy sector model, TIMES, than that in the absence of the linkage [8].

We also review the results of a large number of studies produced by the Stanford University-based energy modeling forum (EMF). EMF includes different types of models; most of them are global macroeconomic models (mostly general equilibrium type), and some models are energy system models, like the bottom-up TIMES model we use here in this study. While comparing the economic costs of stabilizing global GHG concentration (stabilizing the forcing at 4.5 Watt per square meter by the year 2150), it is reported that the percentage reduction of CO₂ emissions and corresponding carbon tax estimated by the energy system models are much smaller than that estimated by CGE models [2]. For example, to meet the stabilization scenario as specified in Ref. [2], global CGE models such as AIM, EPPA, and SGM estimate approximately US\$500/tCO₂ carbon tax in the year 2050, whereas the energy system model MESSAGE estimates it around US\$200/tCO₂. While comparing the economic impacts estimated by different models to achieve a climate stabilization scenario, the percentage changes in gross world products from the baseline estimated by energy system models (DEN-21 and GET-LFL) are 60%–70% lower than that estimated by CGE models, IAM and IMACLIM-R [1].

4. Conclusions and policy implications

Some economic modelers argue that linking bottom-up engineering models with top-down economic models increases the accuracy of economic impact assessments of energy and climate change policies. Our study examines this issue by linking a bottom-up TIMES model with a top-down CGE model to assess economic impacts of meeting China's climate change mitigation targets under the Paris Climate Agreement (i. e. NDC). Our study shows that the economic impacts measured by the linked or hybrid model are around three times as low as those measured by the stand-alone CGE model. When the CGE model alone is used a carbon tax of CN¥372/tCO₂ is required to meet the NDC. On the contrary, if the hybrid model is used, the carbon tax drops by approximately one-third to CN¥110/tCO₂. The required reduction in CO₂ emissions in 2030 estimated by the CGE model without linkage drops by nearly the same factor. The economic impacts measured under the linked case are 67%–75% smaller as than those measured without the linkages. There are two reasons for the different measures of economic impacts between the two cases. First, the projected value of the main economic driver, GDP, is around one percentage point higher in the CGE model case than in the TIMES model. It causes the demands for energy commodities and associated emissions under the CGE to be much higher than under the TIMES model. Second, the CGE model cannot capture the emission reductions achieved by technological improvement stimulated by existing policies, such as energy efficiency improvements mandates and targets. Linking it to the bottom-up model enables it to capture these existing technology-focused policies.

China is serious about reducing the carbon intensity of its economy because it is the largest CO₂ emitter in the world at present. It has set ambitious targets to reduce CO₂ emissions. However, a significant reduction in CO₂ emissions can not be achieved without adverse economic consequences. The adverse economic consequences could be a deterrent for stringent policies and measures moving toward decarbonizing China's energy system, which is highly fossil-fuel dominant at present. The government has introduced several measures, including energy efficiency measures, commitment to increased use of non-CO₂

primary energy sources, and activities to increase carbon sinks. An assessment of economic consequences of pricing policies, such as carbon tax, should account for these initiatives. Therefore, top-down models, which usually cannot account for non-market initiatives, should be complemented by the bottom-up models when assessing the economic and spatial consequences of market-based instruments for GHG reduction in China.

Although some top-down models attempt to capture technological or energy efficiency improvements by introducing a parameter, AEEI, the basis for selecting the parameter value is mostly unknown. The linking of the top-down models with the bottom-up models allows estimating the AEEI values. We find that if the CGE model is used stand-alone, then the value for AEEI to be included in that model would be approximately 1.5% (i.e., the overall energy efficiency in China should be improved by 1.5% annually).

Although linking top-down models with bottom-up models brings more preciseness to the estimates of economic impacts of a climate change policy, the estimates could be influenced by the limitations of the bottom-up models. For example, the initial projections of the energy-supply mix produced by the bottom-up model are sensitive to the modelers' assumptions or anticipations on energy efficiency improvements. If so, then the corrections of the economic impacts brought by the linkage are affected by the assumptions. The results of a hybrid model would be reliable only when the bottom-up model is robust in terms of its data and underlying assumptions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.rser.2021.111551>.

Author contribution

Govinda Timilsina: Conceptualization, Methodology, Writing – original draft preparation. Jun Pang: Development of the top-down, CGE model. Yang Xi: Development of the bottom-up, TIMES model.

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