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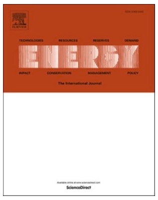

Integration of energy system and computable general equilibrium models: An approach complementing energy and economic representations for mitigation analysis

Osamu Nishiura [a,*], Volker Krey [b,c], Oliver Fricko [b], Bas van Ruijven [b], Shinichiro Fujimori [a]

[a] *Kyoto University, C1-3, Kyotodaigaku-Katsura, Nishikyo-ku, Kyoto, Japan*
[b] *International Institute for Applied System Analysis, Schlossplatz 1, A-2361, Laxenburg, Austria*
[c] *Industrial Ecology Programme and Energy Transitions Initiative Norwegian University of Science and Technology, NO-7491, Trondheim, Norway*

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ABSTRACT

Energy system and computable general equilibrium (CGE) models play vital roles in climate change mitigation studies. These models have advantages and disadvantages, and attempts have been made to integrate them. This study aimed to describe the method for integrating energy system and CGE models and demonstrate the new model that captures the strengths of both models. The method developed in this study ensured the detailed convergence of the energy system by exchanging the results iteratively. We demonstrated the model integration by adopting the method to MESSAGEix-GLOBIOM and AIM/Hub and estimating a mitigation scenario that limits the temperature rise to below 2 °C under the middle-of-the-road socioeconomic projection in Shared Socio-economic Pathways. As a result of the integration, the index showing the difference between the two models proposed in this study decreased from 1.0 to 0.066. Therefore, we confirmed that these models estimated consistent scenarios. The diagnostic indicators showed that compared to its counterpart CGE model, the newly-developed model was characterized by a higher contribution of demand-side reductions, a lesser alteration in the primary energy supply composition, and lower abatement costs. Given the convergence and advantages of the integrated framework, the proposed method is useful for further application to mitigation studies.

1. Introduction

The Paris Agreement set long-term goals of limiting the global temperature increase to well below 2 °C, and the pursuit of efforts to limit it to 1.5 °C, both of which will require substantial reductions in greenhouse gas (GHG) emissions. As a result, there has been increased attention given to developing practical strategies to reduce greenhouse gas (GHG) emissions substantially, and the economic impacts that will be required to achieve these goals. Integrated Assessment Models (IAMs) have been used for such assessments of the technological and economic implications of mitigation measures, as summarized in recent reports of the Intergovernmental Panel on Climate Change (IPCC) [1].

Integrated Assessment Models can be classified into two types: detailed process (DP) and cost-benefit analysis models [2]. The DP IAMs play a major role in predicting the implications of energy, economy, land use, and health in climate change mitigation studies [1]. A DP model can be classified in multiple ways, one of them being whether the core model is a multi-sectoral computable general equilibrium (CGE) model, an energy system model, or a growth model. The advantages and disadvantages of CGE and energy system models vary substantially. CGE models describe the details of economic interactions, such as how equilibrium in demand, supply, and price is attained across an entire economy, with representative institutional sectors, including households, enterprises, and government, optimizing their respective objectives based on assumed production and demand functions. The models simulate the changes in prices and consumption for all goods associated with policy interventions such as environmental taxation or emission trading, considering sectoral interaction and international trade based on social accounting matrices. Asian-Pacific Integrated Modeling/Hub (AIM/Hub) [3], Emissions Prediction and Policy Analysis (EPPA) [4], IMACLIM [5], FARM [6], and GEM-E3 [7,8] are examples of CGE-based IAMs. Because the models are economic models that encompass multiple sectors and goods, they can compute economic losses and gains for each sector and price changes for each good, considering ripple effects due to

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* Corresponding author.
E-mail address: ihatewiiu@outlook.jp (O. Nishiura).

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the sectoral and regional connections, in addition to changes in the macroeconomic indicators associated with emission reductions. This feature enables the calculation of changes in the consumption of each good by households due to the policy, along with factors such as income and the price of each good, and its application to research relevant to the sustainable development goals [9]. In contrast, energy system models are partial equilibrium models that estimate the energy system that minimizes costs in meeting certain energy demands. Only the energy sector is covered, enabling a more detailed representation of the energy system. MESSAGEix-GLOBIOM [10,11], MARKAL/TIMES [12], GCAM [13], and AIM/Technology [14] are examples of energy system models. A standalone energy system model, which is not integrated with an economic model, typically does not consider the economic impacts of changes in the energy system (such as changes in energy demand). Therefore, model results are affected by exogenously input energy demand. Some energy system models incorporate a simplified economic model [10–12] for sectors outside the energy system. Coupled with simplified economic models, for example, the quantification of mitigation scenarios can consider macroeconomic feedback due to emission reductions, and the analysis of new abatement technologies can include a macroeconomic perspective. However, these are typically much more aggregated compared to fully-fledged CGEs. Compared to CGEs, energy system models have the advantage of providing a detailed representation of energy demand and supply technologies.

The integration of multiple types of models can broaden the model scope or provide a more detailed analysis of individual sectors. Previous studies have demonstrated the benefits of integrating CGE models with energy system models or other partial equilibrium models for sectors such as transportation and electricity generation. For a global scale analysis that targets the whole energy system, Vandyck et al. [15] integrated a CGE model and an energy system model to examine the economic impacts of Intended Nationally Determined Contributions (INDCs), including the impact on trade flows and employment. Labri et al. [16] also integrated a CGE and energy system model to analyze the global and partial climate agreement. Waisman et al. [17] integrated a CGE model with a technology selection model, examining the consequences of incomplete foresight and technological system inertia on climate change mitigation costs by comparing the results with those obtained from existing intertemporal optimization models. Some studies have analyzed mitigation scenarios using partial equilibrium models coupled with CGE models for specific countries and sectors. Dai et al. [18] and Fujimori et al. [19] compared the results of a standalone CGE model with those of a model integrating a CGE model and energy system model for China and Japan, respectively, and analyzed the factors causing the differences in the results from the structure of the models. As other examples, the integration of the two models has been conducted in studies for European countries [20], the United States [21], South Africa [22], and South Korea [23], as well as for the power generation sector [24], the transportation sector [25], and the concrete sector [26].

In the above studies, the integration of the two models has been achieved in various ways. The methods of integration can be classified into three categories [27], as shown in Table S1. The first method is a hard link in which one model, usually a reduced version, is implemented into the master model, and both models run simultaneously. The second is to integrate two models through a unified mathematical approach. An example is Bohringer et al. [27], which formulate a market equilibrium as a mixed complementarity problem to implement a feature of the partial equilibrium model in a CGE model. This approach is used to develop a CGE model considering a feature of the electricity generation model for a specific region [28]. Soft link is a method that uses two individual models. The two models are combined by manually introducing the results of one model into the other. Soft link is superior in terms of model transparency, practicality, and promotion of understanding of each model, while the other two methods are superior in consistency and efficiency. Researchers can use each method according to the purpose of the research.

Soft link can be further classified into two types: one way, where the results of one model are input to the other, and two-way, where the data from each model is exchanged iteratively [29]. In one way, one model serves as an exogenous variable in the other model, but consistency is generally not achieved. The two-way soft link approach allows for greater convergence of the variables to be exchanged by considering feedback between models. Krook-Riekkola et al. [20] is an example of a study that developed a two-way soft link methodology for integrating a CGE model and an energy system model for Sweden and applied it to a climate policy scenario. The Environmental Medium term Economic model (EMEC) model is employed as the CGE model, and the TIMES-Sweden model as the energy system model. The EMEC model considers 26 production sectors and 33 composite commodities, including 7 energy commodities, and is characterized by a detailed description of energy use compared to many other CGE models. TIMES-Sweden, which covers the entire Swedish energy system, describes the Swedish energy system divided into 5 energy demand sectors and 2 energy conversion sectors. During data exchange, energy demand is calculated from the production of commodities and energy consumption in each sector, which is the result of the EMEC model, and introduced into the energy system model. From the results of the energy system model, information on energy efficiency, energy mix, and energy price is introduced into the CGE model. This data exchange is repeated until the variables used in the data exchange converge between the models. Due to the large number of variables exchanged, Krook-Riekkola et al. [20] did not establish specific criteria for convergence but instead determined convergence by reviewing the changes in the variables exchanged after each iteration. This study is unique because detailed economic sector and energy system information is exchanged between models, and specific methods and convergence processes are reported (see Table S1).

Previous studies using integrated models have largely been limited to specific countries, regions, or sectors [18–26]. Most studies integrating CGE and energy system models for the entire world have adopted the one-way soft link [15,30]. Some studies using a two-way soft link approach often exchange information about high-level indicators, such as total emissions or energy use, [16,17]. In addition, many studies lack sufficient detail in explaining the process used to integrate models, and what indicators are chosen, and how they are converged, hindering replicability [29]. The objective of this study was to develop a specific method for integrating global scale CGE and energy system models, and to demonstrate how the results of the new model captured the strengths of both models. The integrated model estimated a mitigation scenario that accounted for the detailed representation of energy-related technologies, and simultaneously provided economic indicators for disaggregated goods and sectors (Table 2). Assuming that it is possible to adopt a model with a more detailed representation of a particular sector when estimating scenarios for that sector, the model developed in this study would be more suitable to estimate the impact of emission reductions on the energy system and its economic impact, compared to the models before integration. This study tackles the coupling of a global-scale CGE model and an energy system model using a method classified as two-way soft link, which has yet to be practiced in the coupling of CGE models and sector models (Table 3). This study applied AIM/Hub as a CGE and MESSAGEix-GLOBIOM as an integrated energy system model; however, the method itself was general and could be applicable to other model integrations.

The remaining sections are as follows. Section 2 reports the structure of AIM/Hub and MESSAGEix-GLOBIOM that were integrated as the CGE and energy system models. The method used to integrate these two models and the mitigation scenario used in this study are also explained in this section. Section 3 has three parts. The first part presents the results of the integrated model (MESSAGEix-AIM/Hub) for carbon dioxide emissions and the energy system structure and evaluates how the results differ from those of the AIM/Hub and MESSAGEix-GLOBIOM models. The second part reports the economic impact due to emission reduction,

Table 1
Nomenclature.

Abbreviations	
GHG	Green House Gas
IAMs	Integrated Assessment Models
IPCC	Intergovernmental Panel on Climate Change
DP	Detailed Process
CGE	Computable General Equilibrium
AIM	Asian-Pacific Integrated Modeling
INDCs	Intended Nationally Determined Contributions
EPPA	Emissions Prediction and Policy Analysis
EMEC	Environmental Medium term Economic model
RCPs	representative concentration pathways
SSPs	shared socio-economic pathways
GAMS	general algebraic modeling system
MCP	mixed complementarity problem
CES	constant elasticity substitution
GTAP	Global Trade Analysis Project
IEA	International Energy Agency
AEEI	autonomous energy efficiency improvement
CCS	Carbon Capture and Storage
Parameters	
v	variable
y	year
r	region
s	sector
m	model
c	commodity
sc	Scenario (baseline, mitigation)
$S1$	The set of three sectors (industry, transportation, and buildings)
$S2$	the set of three sectors plus the power generation sector
R	the set of seven regions (Pacific OECD, Asia, Europe, the former Soviet Union, Middle East and Africa, North America, and South America)
Y	the set of years covered by the calculation from 2020 to 2050
C	the set of energy goods
P	the set of four energy supply methods (fossil fuel, nuclear, biomass, and renewable energy excluding biomass)
Xgr_dif_v	The indicator to quantify the difference in the growth rate of final energy consumption and energy demand
$Xgr_{v,m,y,r,s}$	the relative ratio of the variable v in year y in region r and sector s calculated by model m to that of 2015
Xsh_dif_v	The indicator to quantify the differences in the final energy composition and power generation share
$Xsh_{v,m,y,r,s,c}$	The share of energy good c in year y in region r and sector s calculated in model m
RAI	relative abatement Index
ERT	emission reduction type index
TI	transformation index
FFR	fossil fuel reduction
CAV	cost per abatement value
$Mitigation\ Cost_y$	The change in GDP compared to the baseline in the year y
$CO2\ Ene\&Ind_{y,sc}$	CO_2 emissions from energy and industrial process in the year y and in the scenario sc
$Cabon\ Intensity_{y,sc}$	Carbon intensity in the year y and in the scenario sc
$Energy\ Intensity_{y,sc}$	Energy intensity in the year y and in the scenario sc
$PrimaryEnergyShare_{y,p}$	Primary energy share of the energy source p in the year y
$Primary\ Energy_{\ y,p}$	Primary energy supply of the energy source p in the year y
$GHG\ Reduction_y$	GHG emissions reductions compared to the baseline in the year y
$Carbon\ Price_y$	Carbon price in the year y

such as goods prices and sectoral economic impacts, as the main benefit of the model integration. The third part summarizes the characteristics of the model developed in this study based on the results of the diagnostic indices proposed by Kriegler et al. [31] and Harmsen et al. [32]. In the first part of Section 4, we discuss how the energy system changes required for emission reduction and their economic implications estimated by MESSAGEix-AIM/Hub differed from those of the AIM/Hub and MESSAGEix-GLOBIOM models. The second part of Section 4 considers the method proposed by this study and its limitations. The final section summarizes the conclusions of this study.

Table 2
Features of CGE model, energy system model and the integrated model.

Model types	Advantage	Disadvantage
Energy system model	Detailed representation of technologies related to energy supply and demand	Simulate only for the energy sector Weak representation on the economy
CGE model	Simulates the entire economy Detailed representation of economic sectors and goods	Weak representation of energy supply and demand
Integrated model	Combines the advantages of the energy system model and the CGE model	No method has been established to converge the detailed results of the two models Large computational load

Table 3
Global scale CGE and partial equilibrium model integration approach.

Literature	Model types linked with CGE	Integration approach
Vandyck et al. [15]	Energy system model	One-way soft link
Labri et al. [16]	Energy system model	Two-way soft link exchanging information on high-level indicators
Waisman et al. [17]	Technology selection model (reduced form)	Two-way soft link exchanging information only one time
Zhang et al. [25]	Transport model	Two-way soft link with transport model
Böhringer et al. [27]	Electricity sector	Mathematical approach
Weitzel et al. [30]	Energy system model	One-way soft link
This study	Energy system model	Two-way soft link iteratively exchanging information on detailed economies and energy systems

2. Materials and methods

2.1. Overview

We developed a new integrated modeling framework that incorporates MESSAGEix-GLOBIOM, an intertemporal energy system

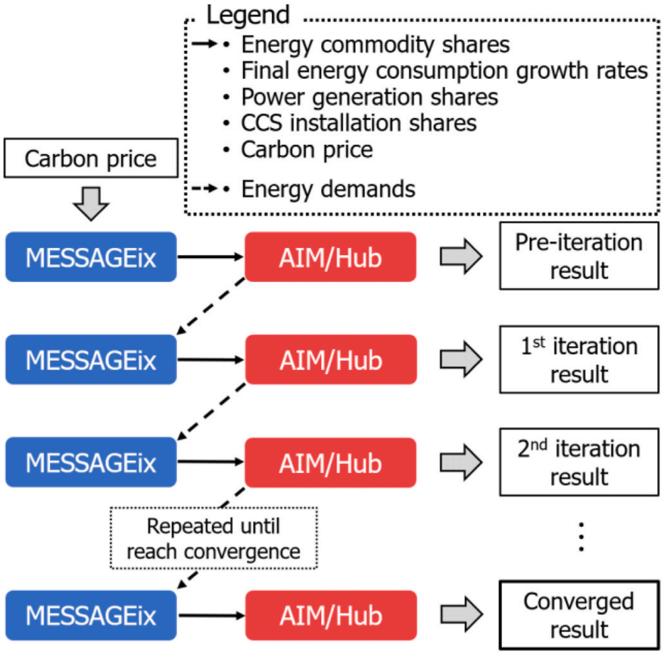

Fig. 1. Overview of the method used to integrate the two models.

model, and AIM/Hub, a recursive-dynamic multi sectoral CGE model. Fig. 1 shows the integration of the two models. In this framework, these models were integrated by introducing the results from each model into the other model. First, MESSAGEix-GLOBIOM calculated the baseline, with no reduction in GHG emissions or mitigation scenario, where the emissions were constrained only by the carbon price trajectory described later. Subsequently, the MESSAGEix-GLOBIOM results for the energy system were imported to AIM/Hub, and the same scenario was calculated. Then, the energy demand results were introduced into MESSAGEix-GLOBIOM and the calculation was performed again. This iteration of data exchange was repeated until the results of both models were consistent based on the data convergence criterion described later. In the mitigation scenario, the calculations were executed by imposing a consistent carbon price path to both models. An alternative approach would be to implement the mitigation scenarios to impose an emissions constraint. The approach adopted here was selected for two reasons. First, for AIM/Hub, energy system related variables were forced to those of the MESSAGEix-GLOBIOM output, which enabled a feasible solution with an emissions constraint. Second, the imposition of a carbon price would enable the model response to be clearly obtained.

After the model integration, we analyzed the result of the integrated model. Fig. 2 shows the flow for analyzing the results. The integrated model and its standalone counterparts, i.e., the AIM/Hub and MESSAGEix-GLOBIOM models, were used to compute a shared baseline scenario and mitigation scenario, with a subsequent comparison of the results. In addition, we calculated diagnostic indicators to understand the model behavior proposed by Kriegler et al. [31] and Harmsen et al. [32] with the output of the three models. The timeframe of this study was from 2020 to 2050. This could have been extended to 2100 but, because we intended to inspect the details of each model output in depth, it was limited to the mid-century.

2.2. Models

We utilized AIM/Hub, as a CGE based IAM [3] and MESSAGEix-GLOBIOM as an energy system model [10,11]. The two models have played significant roles in climate change mitigation studies and both were used in the quantification of representative concentration pathways (RCPs) and shared socio-economic pathways (SSPs) [33,34]. These models are written in the general algebraic modeling system (GAMS) and we also conducted our model integration with GAMS. AIM/Hub has been widely used to estimate mitigation scenarios [19] and analyze the social impacts of GHG reduction measures [9]. The model is described as a mixed complementarity problem (MCP), and equilibrium solutions are obtained every year until 2050, with 2005 as the base year. The model includes 43 industrial, government, household, and investment sectors. In the household sector, a certain proportion of the income from labor and capital is allocated to consumption. A linear expenditure system function determines the expenditure on each commodity. The rest of the income is placed in investments or savings. The saving proportion is endogenously determined to balance saving and investment, and the capital formation for each good is determined by a fixed coefficient. Each industrial sector has its own capital stock, and the sector's capital stock is subject to annual investment and capital depletion of 4% per year. The production function is represented by multi-nested constant elasticity substitution (CES) functions and the production sectors maximize their profits based on the function. In the energy transformation sectors, the output coefficients against energy and value added are fixed to deal appropriately with energy conversion efficiency. The energy goods consumption is determined by the CES function for total energy and the logit function for energy carrier selection, which partly considers the heterogeneity of goods. Computable general equilibrium models are generally calibrated using a social accounting matrix. AIM/Hub was calibrated to a 2005 baseyear using the Global Trade Analysis Project (GTAP) database [35]. In addition, to estimate energy consumption and GHG emissions more accurately, the 2007 to 2015 period has been selected for calibration using the Energy Balance Table [36].

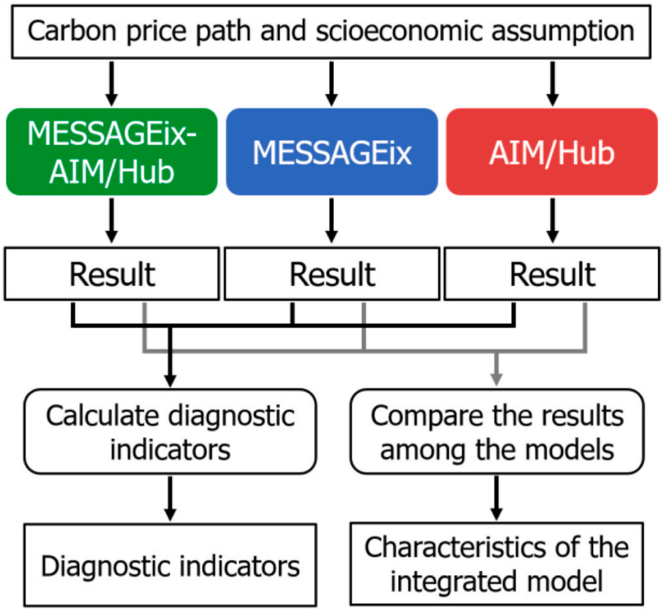

Fig. 2. Flow for analyzing integrated model results.

MESSAGEix-GLOBIOM is a linear programming energy engineering model that uses an intertemporal optimization solution framework to minimize the total discounted energy system cost, subject to technical and scenario-specific constraints [9,10]. The model includes 49 technologies for final energy consumption in the transportation, building, and industrial sectors. In addition, the model also includes 54 specific conversion technologies to produce electricity, heat, liquid, gaseous fuels, and hydrogen. As with AIM/Hub, the model sets assumptions about energy demand and costs in the base year based on the International Energy Agency (IEA) energy balance table. MESSAGEix-GLOBIOM can be integrated with a single sector economic model called MACRO to provide estimates that consider the economic losses associated with emissions reductions or climate policy more broadly as a default model setting. However, MACRO is a macroeconomic model that maximizes the utility of a single representative producer-consumer with a limited goods classification, which reduces the need for detailed economic information. The land use model GLOBIOM [37,38] provides MESSAGEix-GLOBIOM with information on land use and its implications, including the availability and cost of bioenergy, and availability and cost of emission mitigation on land. To reduce computational costs, MESSAGE iteratively queries a GLOBIOM emulator, which provides an approximation of land-use outcomes during the optimization process. To simplify notation, because the link between AIM/Hub and MESSAGEix-GLOBIOM is focused on the energy system, we referred to it as MESSAGEix in this study, despite the continued use of the GLOBIOM emulator in the model. MESSAGEix was integrated with AIM/Hub to develop MESSAGEix-AIM/Hub.

For comparison, we also calculated scenarios with MESSAGEix integrated with MACRO (MESSAGEix-GLOBIOM) and with the standalone AIM/Hub to identify how the original model results differed from those of MESSAGEix-AIM/Hub.

2.3. Exchanged data

This section describes the variables exchanged between the models. From MESSAGEix, the growth rate of final energy consumption by sector, the share of final energy consumption by sector and energy commodity, the share of electricity generation by energy source, and the share of Carbon Capture and Storage (CCS) installation rates of each technology (e.g., coal-fired power plants) were fed into AIM/Hub. MESSAGEix includes about 49 specific technologies for final energy consumption. These 49 technologies are classified into seven energy carriers in the sectors of industry, buildings, and transportation, and then introduced into AIM/Hub. Additionally, MESSAGEix considers 33 power generation technologies. These technological representations are much more detailed than those of AIM/Hub and we aggregated them into 10 relatively coarse technologies. They were then given directly to AIM/Hub as the technological shares of power generation. The CCS related variables were also taken from MESSAGEix and translated into the share of CCS installation in each technology, enabling us to obtain the w/and w/o CCS ratio. The final energy source and its share of energy carriers, and the share of power generation from MESSAGEix were input into AIM/Hub and treated as a constraint. The parameters of autonomous energy efficiency improvement (AEEI), preferences for energy carriers, for final energy consumption, and the power generation share, which were originally assumed to be exogenous parameters in the standalone AIM/Hub model, were endogenized in its integrated framework. From the AIM/Hub model, the growth rate of energy demand by sector was introduced into MESSAGEix. Because the AIM/Hub model calculates energy demand for 25 different sectors, they were aggregated into the industrial, domestic transportation, international transportation, and building sectors and the growth rate of energy demand by sector from 2015 was introduced into MESSAGEix. This allows the energy demand, which is exogenously specified in MESSAGEix, to be calculated endogenously in the integrated framework. Specific data processing methods and the mapping between technologies and sectors are described in the Supplementary Information.

It is difficult to match perfectly the energy system results of MESSAGEix and AIM/Hub due to the disparities in the information utilized for calibration, variation in regional definitions, the extent of sectors covered, and the differences in model structure. To align the results of the two models, a data exchange was conducted utilizing the growth rates and shares of final energy consumption, energy demand, energy commodities, power generation, and CCS (See Supplementary information). This exchange of data enabled the matching of changes in the energy system structure and the size and magnitude of the economic impacts between the two models, while allowing for slight deviations in the absolute values of the variables. To prevent the two models failing to converge or having their results influenced by significant changes resulting from data exchange, we used the shares and growth rates, with the maximum rate of change of the variables used in data exchange compared to the previous data exchange set to 10%. Consequently, the results of the two models gradually approached each other.

2.4. Convergence criteria

To identify differences in the two models with respect to the energy system and energy demand through data exchange, we focused on several indicators that represented the differences of these two models. We use a Taxicab- or 1-norm vector as a quantitative measure.

$$||\boldsymbol{x}||_1 = \sum\nolimits_i |x_i|,$$

where x is the vector of the model's decision variables for all periods. As a convergence measure, we normalized the 1-norm as shown below. Specifically, the final energy consumption growth rate, final energy share, power generation share, and total energy demand growth rate were considered. We aggregated the native model results into the appropriate regional, sectoral, energy sources or technological classification that were comparable between two models. The regions and sectors were classified into seven regions (Pacific OECD, Asia, Europe, the former Soviet Union, Middle East and Africa, North America, and South America) and three sectors (industry, transportation, and buildings), respectively. We compared the results for every five-year period starting from 2020 to 2050.

1) Growth rate of the final energy consumption and energy demand

To quantify the difference in the growth rate of final energy consumption and energy demand, Xgr_dif_v was defined as in Equation (1):

$$Xgr\_dif_v = \frac{\sum\limits_{y\in Y}\sum\limits_{r\in R}\sum\limits_{s\in S1}\left|Xgr_{v,\text{"}MESSAGE\text{"},y,r,s} - Xgr_{v,\text{"}AIMHub\text{"},y,r,s}\right|}{\sum\limits_{y\in Y}\sum\limits_{r\in R}\sum\limits_{s\in S1}\left|Xgr_{v,\text{"}MESSAGE\text{"},y,r,s} + Xgr_{v,\text{"}AIMHub\text{"},y,r,s}\right|/2} \tag{1}$$

where $Xgr_{v,m,y,r,s}$ is the relative ratio of the variable v (final energy consumption or energy demand) in year y in region r and sector s calculated by model m to that of 2015, $S1$ is a set of three sectors, R is the set of seven regions, and Y is the set of years covered by the calculation from 2020 to 2050.

2) Share of final energy consumption and power generation

To quantify the differences in the final energy composition and power generation share, we defined the indicator Xsh_dif_v as in equation (2):

$$Xsh\_dif_v = \frac{\sum\limits_{y\in Y}\sum\limits_{r\in R}\sum\limits_{s\in S2}\sum\limits_{c\in C}\left| Xsh_{v,\text{"}MESSAGEix\text{"},y,r,s,c} - Xsh_{\text{"AIM/Hub"},y,r,s,c} \right|}{\sum\limits_{y\in Y}\sum\limits_{r\in R}\sum\limits_{s\in S2}\sum\limits_{c\in C}\left| Xsh_{v,\text{"}MESSAGEix\text{"},y,r,s,c} + Xsh_{\text{"AIM/Hub"},y,r,s,c} \right|/2} \tag{2}$$

where, $Xsh_{v,m,y,r,s,c}$ is the share of energy good c in year y in region r and sector s calculated in model m, $S2$ is the set of three sectors plus the power generation sector, and C is the set of energy goods used in sector s.

2.5. Model diagnostic indicators

Factors such as the design of IAMs, the setting of renewable energy and abatement technology potentials and costs, the resolution of technological representations and economic sectors, the method of dynamization, and the scope covered by the model (i.e., general equilibrium vs. partial equilibrium) also vary across IAMs, leading to variations even under the same climate targets (e.g., common carbon budgets). To understand the model behavior, diagnostic indicators for IAMs have been developed and comparisons have been made between IAMs and between model versions. Kriegler et al. [31] proposed diagnostic indicators to identify the differences associated with model versions and among models, and Harmsen et al. [32] improved the indicators to assess IAM behavior systematically and routinely: relative abatement Index; *RAI*, emission reduction type index; *ERT*, transformation index; *TI*, fossil fuel reduction; *FFR*, cost per abatement value; *CAV*. We applied the same method to compare three types of model results, namely, the newly developed integrated model, the MESSAGEix, and AIM/Hub. They were computed using Equation (3) through (9), where P is the set of four energy supply methods (fossil fuel, nuclear, biomass, and renewable energy excluding biomass) and $Mitigation\ Cost_y$ refer to the change in GDP compared to the baseline:

$$RAI_y = \frac{CO2\ Ene\&Ind_{y,\text{"}Baseline\text{"}} - CO2\ Ene\&Ind_{y,\text{"}Policy\text{"}}}{CO2\ Ene\&Ind_{y,\text{"}Baseline\text{"}}} \tag{3}$$

$$CIred_y = \frac{Cabon\ Intensity_{y,\text{"}Baseline\text{"}} - Cabon\ Intensity_{y,\text{"}Policy\text{"}}}{Cabon\ Intensity_{y,\text{"}Baseline\text{"}}} \tag{4}$$

$$EIred_y = \frac{Energy\ Intensity_{y,\text{"}Baseline\text{"}} - Energy\ Intensity_{y,\text{"}Policy\text{"}}}{Energy\ Intensity_{y,\text{"}Baseline\text{"}}} \tag{5}$$

$$ERT_y = \frac{CIred_y}{CIred_y + EIred_y} \tag{6}$$

$$TI_y = \sum_{p\in P}\left|PrimaryEnergyShare_{y,p} - PrimaryEnergyShare_{\text{"}2020\text{"},p}\right| \tag{7}$$

$$FFR_y = \frac{Primary\ Energy_{\text{“2020”,”}fossil\text{”}} - Primary\ Energy_{y,\text{”}fossil\text{”}}}{Primary\ Energy_{\text{“2020”,”}fossil\text{”}}} \tag{8}$$

$$CAV_y = \frac{Mitigation\ Costs_y}{GHG\ Reduction_y * Carbon\ Price_y} \tag{9}$$

2.6. Scenarios

We calculated a baseline scenario and a mitigation scenario with constraints on GHG emissions for the entire world. In both scenarios, socioeconomic assumptions, including population and economic growth, were set based on the SSP2, the middle-of-the-road socioeconomic projection in the Shared Socioeconomic Pathways scenario [39]. The baseline scenario assumed no climate mitigation policies; therefore, there is no carbon price throughout the calculation period. The mitigation scenario was based on one of the scenarios proposed by Kriegler et al. [31] and Harmsen et al. [32]. In the mitigation scenario, we used a common global carbon price starting in 2020. The carbon price grew by 5% annually to reach $80/t-CO$_2$ in 2040 (Fig. 3). The mitigation scenario imposed this carbon price on both models before the data exchange occurred.

3. Results

This section presents the results of the newly-developed model alongside the outcomes from the standalone models for comparison. The newly-developed model was designated as MESSAGEix-AIM/Hub, while the standalone models shown for comparison were denoted as MESSAGEix and AIM/Hub. MESSAGEix calculates optimized results every five years. Hence, in this chapter, all model results are presented at 5-year intervals.

3.1. Carbon dioxide emission and energy system

In this section, we report the results for carbon dioxide emissions and energy systems as a result of the integrated model and how they changed in relation to the results of the standalone MESSAGEix and AIM/Hub models. Additionally, we verified the results of the indicator to check the convergence of data exchange.

In the baseline scenario, MESSAGEix-AIM/Hub and MESSAGEix showed a difference in carbon dioxide emissions throughout the period. For the current or historical periods, the discrepancies were caused by the differences in the calibration methodology of MESSAGEix and AIM/Hub, while both models used the IEA energy database. In the future scenarios the differences were mainly due to the changes in preference for electricity and technological development, which were exogenously determined. The carbon dioxide emission pathways in the mitigation scenarios from all models were consistent with the range of existing scenarios taken from the AR6 scenario database [40] that limited the temperature rise to well below 2 °C (Fig. 4, panel b). There were minor differences between MESSAGEix-AIM/Hub and MESSAGEix.

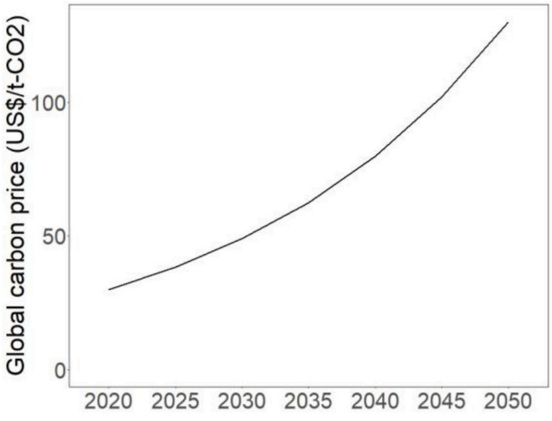

Fig. 3. Carbon price.

Compared to the standalone AIM/Hub model, MESSAGEix-AIM/Hub included an earlier emission reduction resulting in a cumulative carbon dioxide emissions reduction of 98 Gt-CO$_2$. This result reflected the fact that MESSAGEix-AIM/Hub was developed by integrating an intertemporal energy system model. Emission reduction rates in 2050 were calculated to be 61% (MESSAGEix-AIM/Hub), 66% (AIM/Hub model), and 65% (MESSAGEix model), respectively (Fig. 4, panel a). Regarding the sector-wise carbon dioxide emissions, MESSAGEix-AIM/Hub calculated reduction rates of 15.2% in the transportation sector, 11.7% in the industrial sector, and 2.0% in the building sector compared to the total carbon dioxide emission in the baseline. Conversely, AIM/Hub calculated reductions of 10.9% in the transportation sector, 19.8% in the industrial sector, and 3.8% in the building sector. MESSAGEix-AIM/Hub produced larger reductions in the transportation sector, while in the industry and building sectors, they produced a smaller reduction than AIM/Hub.

The total final energy consumption in 2050 for the baseline scenario was 573 EJ/year (AIM/Hub model), 581 EJ/year (MESSAGEix model), and 569 EJ/year (MESSAGEix-AIM/Hub model), respectively. In the mitigation scenario, the total final energy consumption in 2050 was 437 EJ/year (AIM/Hub model), 413 EJ/year (MESSAGEix), and 428 EJ/year (MESSAGEix- AIM/Hub), respectively. For the energy mixes of the total final energy consumption, MESSAGEix and MESSAGEix-AIM/Hub produced similar shares, whereas AIM/Hub exhibited higher electricity and less gas fuel consumption compared to the two models (Fig. 5, panel a). For the electrification rate of each sector, MESSAGEix-AIM/Hub and MESSAGEix produced similar values in all sectors. Compared to the AIM/Hub model, MESSAGEix-AIM/Hub indicated a higher electrification rate in the transportation sector but a lower rate in the industrial

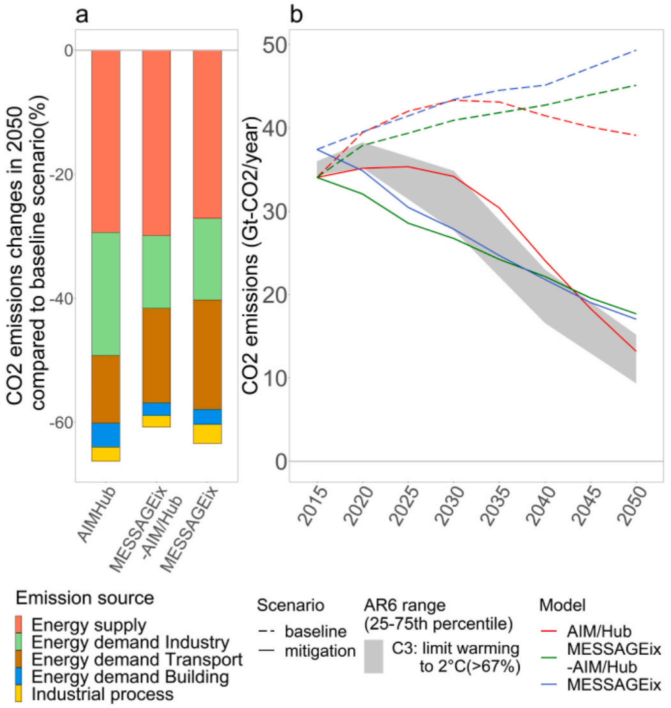

Fig. 4. Global carbon dioxide emissions. The line in panel a shows the carbon dioxide emissions from fossil fuels and industrial process for each model, and the shaded areas represent the 25th to 75th percentiles for scenarios that limit the temperature increase to less than 2 °C reported in IPCC AR6 [40]. Panel b shows the change ratios of carbon dioxide emissions in the mitigation scenarios relative to the baseline scenario for each sector in 2050.

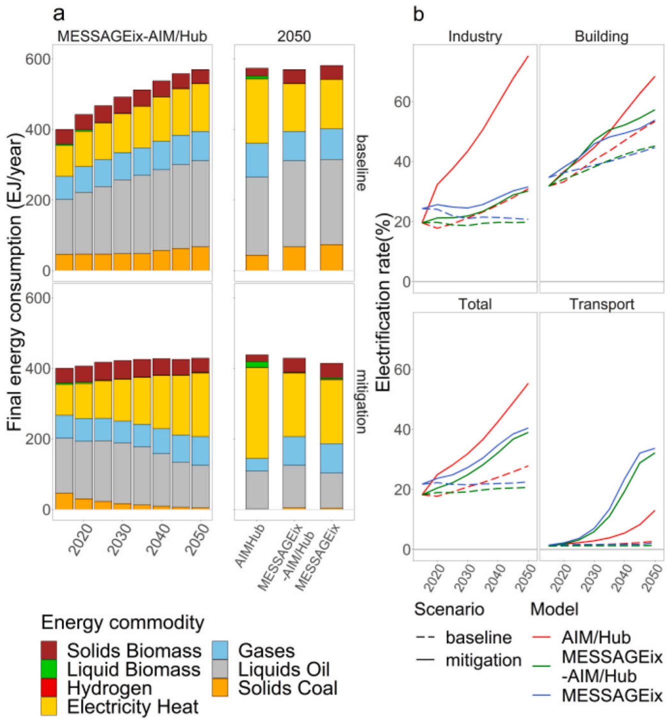

Fig. 5. World final energy consumption. Panel a shows the final energy consumption of each energy commodity. The left panel shows the MESSAGEix-AIM/Hub results and the right panel is the final energy consumption in 2050 calculated by three models. Panel b shows the electrification rate for each sector.

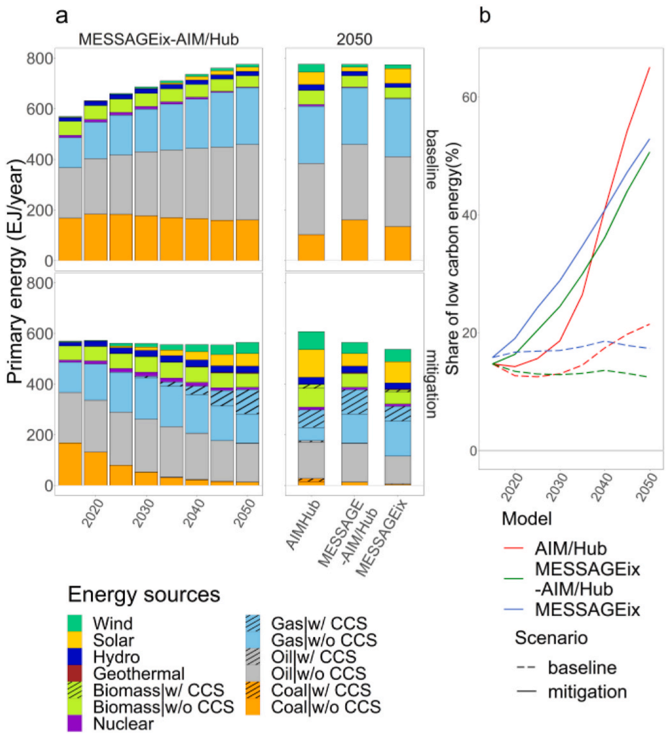

Fig. 6. Primary energy supply. Panel a shows the global primary energy supply by energy sources. The left panel shows the MESSAGEix-AIM/Hub result and the right panel shows the primary energy supply in 2050 calculated by the three models. Panel b shows the low-carbon energy supply rate.

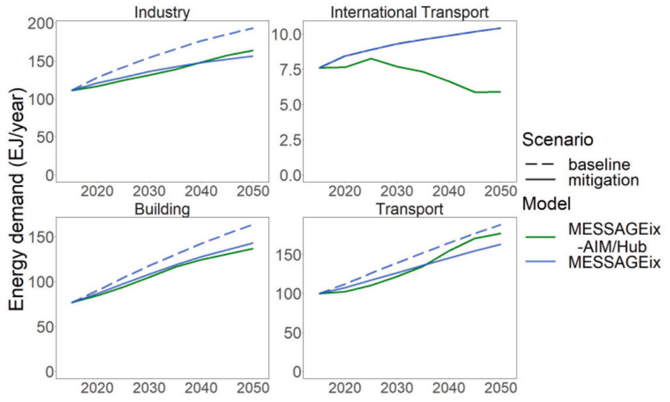

Fig. 7. Energy demand in each sector. Dashed lines show the baseline scenario, which was the default setting of MESSAGEix. Solid lines show the mitigation scenario calculated by MESSAGEix-AIM/Hub and MESSAGEix.

sector (Fig. 5, panel b). Comparing the regional results of MESSAGEix-AIM/Hub with those of AIM/Hub (Fig. S5), the electrification rate was low in all regions excluding North America, which was in line with the global trend.

Due to differences in the energy conversion efficiencies assumed by each model, as well as differences in the final energy mix and consumption, each model estimated different energy supplies even for the same scenario design. In the baseline scenario, the total energy supply in 2050 was 776 EJ/year (AIM/Hub model), 773 EJ/year (MESSAGEix model), and 775 EJ/year (MESSAGEix-AIM/Hub), respectively. Under the mitigation scenario, the total primary energy supply for each model was 607 EJ/year (AIM/Hub), 537 EJ/year (MESSAGEix), and 564 EJ/year (MESSAGEix-AIM/Hub) in 2050 (Fig. 6, Panel a). In the mitigation scenario, AIM/Hub indicated that the supply from low-carbon energy was lower until 2030, unlike the other two models. After 2030, the supply from low-carbon energy sources substantially increased (Fig. 6, Panel b). MESSAGEix-AIM/Hub acquired a long-term view by integrating MESSAGEix and presented a gradual increase in supply from low-carbon energy, as compared to AIM/Hub. Additionally, MESSAGEix-AIM/Hub predicted more oil would be used in the mitigation scenario than MESSAGEix because of the higher energy demand in the transport sector.

MESSAGEix and MESSAGEix-AIM/Hub estimated the changes in energy demand using MACRO and AIM/Hub, respectively. Comparing the energy demand results in the mitigation scenario, the integrated model showed slightly higher energy demand in the industry and transport sectors than in MESSAGEix because these sectors have high energy intensity, and the industrial structure was changed due to emission constraints. A clear difference between the two models was observed in the international and domestic transport sectors (Fig. 7). It is important to note that international shipping transport in MESSAGEix was not included in the demand response of MACRO and, therefore, remained unaltered in the mitigation scenario while MESSAGEix-AIM/Hub showed a significant decrease in energy demand due to a decrease in the international demand for fossil fuels.

Here we present the results of the indicator for confirming convergence explained in section 2.4. Prior to the data exchange, the indicator was 0.998 for the baseline scenario and 1.016 for the mitigation scenario which implied that there were large discrepancies. The data exchange reduced the difference between the two models rapidly and, after 10 data exchanges, the indicator became 0.068 for the baseline scenario and 0.066 for the mitigation scenario, which could be interpreted as being well converged (Fig. 8). The difference between the 9th and 10th results was less than 5%. From these results, the 10th result was deemed the result of the model developed in this study. Among the four indicators, the indicator for the share of final energy consumption showed a relatively slow decline in the difference, indicating that minor

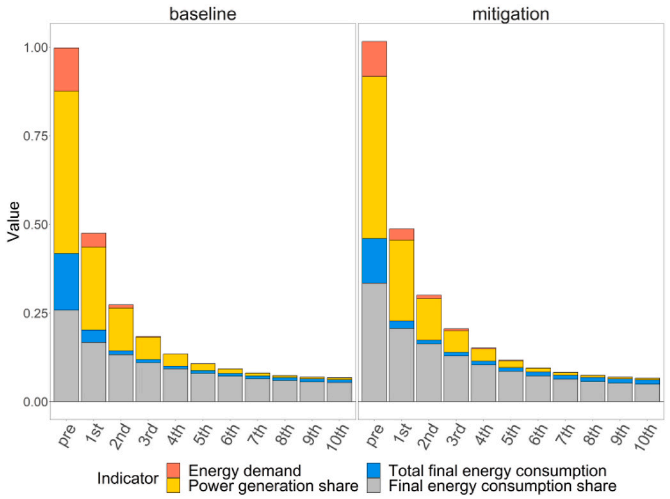

Fig. 8. Indicators for confirming convergence. On the x-axis, "pre" indicates the result obtained by calculating the indicator based on the results calculated before data exchange. The others show the results calculated based on the results after each of the data exchanges.

variations between the models remained even after 10 data exchanges. The values of the indicators for power generation share and energy demand decreased rapidly with data exchange. To confirm the convergence between the two models, we checked the final energy consumption, power generation share, and energy demand estimated by the two models during the 10 data exchanges. Focusing on the global results for final energy consumption, we found a slight difference between the two models in the transport and industry sectors even after 10 data exchanges (Fig. S1). Focusing on the sector and regional results, we can see the differences in some regions and sectors (Fig. S2). The two models had little differences in power generation share and energy demand (Fig. S3 and Fig. S4).

3.2. Economic indicators

In this section, we report the economic indicators that cannot be calculated by MESSAGEix alone, highlighting one of the benefits of integrating multiple models.

The MESSAGEix-AIM/Hub results showed that an emissions reduction led to a GDP loss of 3.5% in 2050. The MESSAGEix-AIM/Hub results were intermediate between the losses obtained from AIM/Hub and MESSAGEix (Fig. 9, panel a). The MESSAGEix-AIM/Hub model and the AIM/Hub model calculate the economic impact using the AIM/Hub model. Therefore, the reason why the MESSAGEix-AIM/Hub model calculated less GDP loss than the AIM/Hub model is mainly due to the difference in the method of selecting energy goods and power generation methods. Focusing on the results in each sector, MESSAGEix-AIM/Hub showed a decline in value added in agriculture, services, and pulp and paper, but an increase in energy extraction and conversion, iron and steel, chemicals, non-ferrous metals, and non-metallic minerals, most of which were associated with relatively high emissions. When compared with AIM/Hub, MESSAGEix-AIM/Hub showed a higher value added in all sectors except the energy sector (Fig. 9, panel b). At a regional level, the MESSAGEix-AIM/Hub results had similar trends to the global scale results for Asia and North America and Pacific OECD but varied for other regions. In contrast to the global trend, the Middle East and Africa and South America showed a decrease in value added in the energy-related sector. Comparing the MESSAGEix-AIM/Hub results with those of AIM/Hub revealed significant differences, especially in South America and Asia. Furthermore, and contrary to the global trend, the Europe and North America regions demonstrated a higher value added in the energy-related sector (Fig. S7).

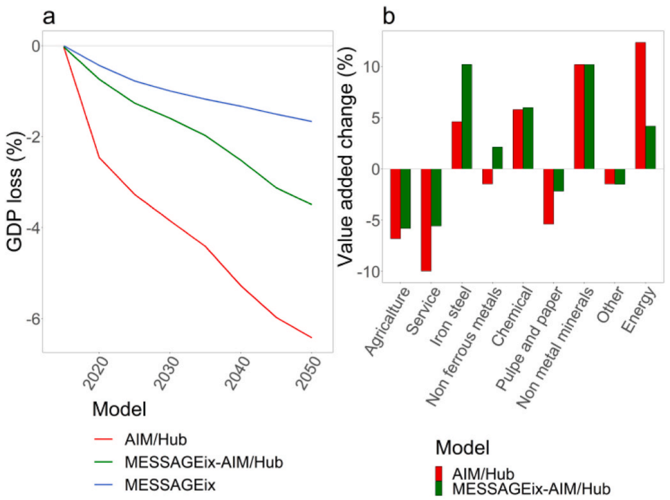

Fig. 9. Global economic impact of emission reductions. Panel a shows the changes in GDP compared to the baseline calculated by the three models. Panel b shows the changes in value added in each sector in 2050 compared to the baseline calculated by AIM/Hub and MESSAGEix-AIM/Hub.

Emission reductions led to a loss in household consumption. AIM/Hub calculated a loss of 8.5%, and MESSAGEix-AIM/Hub projected a loss of 4.5% in 2050 (Fig. 10, panel a). Both models showed increases in the prices of crops, biomass, electricity, and hydrogen of over 10% due to emission reductions. Comparing the results of MESSAGEix-AIM/Hub with those of AIM/Hub, electricity prices were higher, while the prices of other goods were lower (Fig. 10, panel b). MESSAGEix-AIM/Hub showed a decrease in the household consumption of goods other than electricity and hydrogen due to emission reductions. Additionally, compared to AIM/Hub, the consumption of energy goods derived from biomass and fossil fuels decreased, while the consumption of other goods increased (Fig. 10, panel c).

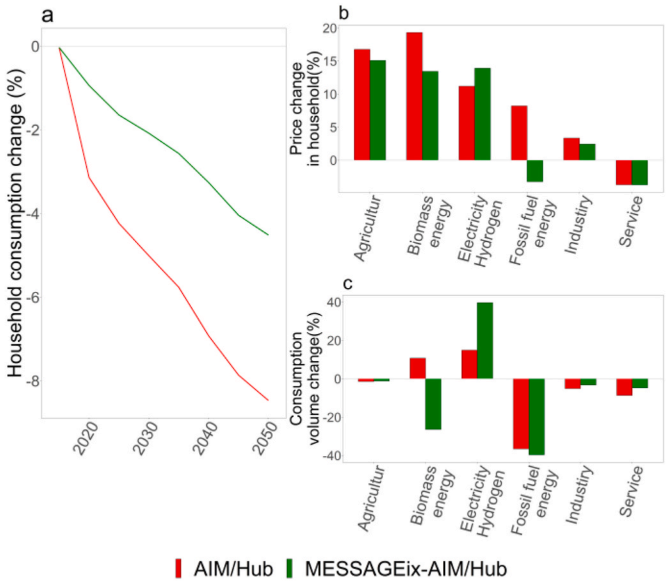

Fig. 10. Changes in household consumption due to emission reductions. Panel a shows the changes in household consumption compared to the baseline calculated by MESSAGEix-AIM/Hub and AIM/Hub. Panel b shows the price changes for each household good in 2050 compared to the baseline. Panel c shows the changes in household consumption volume for each household good in 2050 compared to the baseline.

3.3. Diagnostic indicators

We present the diagnostic indicators outlined in section 2.5 for each of the three models. The *RAI* results were largely consistent with those of the other two models. The *CAV* and *ERT* outcomes for MESSAGEix-AIM/Hub fell within the range of the AIM/Hub and MESSAGEix values. For *FFR* and *TI*, the results were comparable to those of MESSAGEix, but the results between AIM/Hub and MESSAGEix were not comparable (Fig. 11). These indicators showed that, compared to AIM/Hub, MESSAGEix-AIM/Hub had the following characteristics.

1. higher contribution of demand-side emission reductions
2. lower change in the composition of the primary energy supply
3. lower fossil fuel abatement rates
4. lower abatement costs

The *CAV* and *ERT* of MESSAGEix-AIM/Hub were intermediate between those of AIM/Hub and MESSAGEix, which was to be expected. However, the other indicators (*FFR*, *TI*, *RAI*) were smaller than those of both models. The reason for the aforementioned indicators yielding values outside the range of the two models was attributed to differences in the efficiency of conversion from the primary energy supply to the final energy consumption in the whole economy, and in the methods used to calculate the impact of mitigation on energy demand across the two models. Due to the disparities in energy conversion efficiency, MESSAGEix-AIM/Hub estimated a different primary energy supply value, compared to that of the MESSAGEix model, even when perfectly aligned with MESSAGEix for the final energy consumption. This discrepancy resulted in differing *FFR* and *TI* values. The variation in the methods used to estimate energy demand was another factor contributing to the different outcomes for each sector. MACRO, which is conventionally integrated with MESSAGEix, receives the energy system costs as an input as well as the additional abatement costs projected by MESSAGEix and determines the saving, investment, and consumption to maximize the utility function of a single representative producer-consumer in each world region. In our integrated model, AIM/Hub estimated the impact of policy based on the equilibrium in the whole economy considering multiple economic sectors and agencies. This feature allowed the ripple effects of industrial structural changes on energy demand to be considered when meeting the emission target. As a result, MESSAGEix-AIM/Hub produced higher energy demand values than MESSAGEix in both the industrial and transport sectors, which are difficult areas for emission reduction. The strong demand for liquid fuel and high-temperature heat in these sectors leads to continued fossil fuel usage and a lower reduction rate of carbon dioxide in the mitigation scenario. Consequently, the calculated *RAI*, *TI*, and *FFR* values were outside the range of the two models.

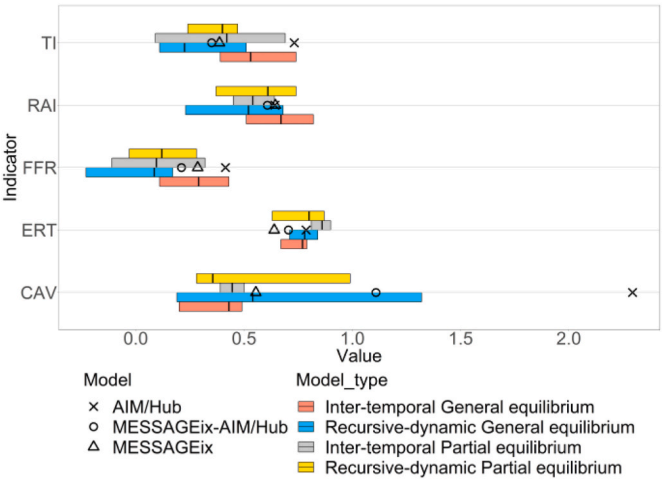

Fig. 11. Diagnostic indicators. Points shows the results of the three models. Bars shows the range of results from Harmsen et al. (2021) for each model type.

4. Discussion

This section is divided into two parts. The first part discusses the energy system and its economic implications in the mitigation scenarios, to show the benefit of model integration. In the second part, we discuss the convergence criteria and the limitation of the proposed method for integrating two models.

4.1. The energy system and its economic implications

The model developed in this study constitutes a departure from the conventional methodology employed by the traditional CGE model, as it draws on the energy system model to inform its calculations. MESSAGEix-AIM/Hub estimations of an energy system resemble those of MESSAGEix. The AIM/Hub selection of energy goods is based on the CES and the logit function, whereas MESSAGEix selects technologies to minimize energy system costs. These contrasting energy selection approaches reflect divergent assumptions. AIM/Hub assumes a selection method that considers the heterogeneity of goods and consumers and projects future scenarios as an extension of the current condition. Conversely, MESSAGEix shows the results of executing the most efficient emission reduction plan considering the detailed energy supply and demand technologies with a long-term perspective. Moreover, disparities in the representation of the economic sectors affect the estimation of the economic impacts due to mitigation policy, with MESSAGEix and MESSAGEix-AIM/Hub estimating different results for the changes in energy demand. Additionally, the difference in the representation of international transportation between MACRO and AIM/Hub is another factor indicating different energy demand changes. In addition to direct emissions, the use of fossil fuels in fossil fuel-importing countries also generates emissions due to international transportation. When countries that import fossil fuels replace fossil fuels with renewable energy, these direct and indirect emissions can be reduced simultaneously. The international transport representation allows MESSAGEix-AIM/Hub to capture the effects of renewable energy substitution more accurately in fossil fuel-importing countries. These variations in energy demand also affect the results of energy system estimates, with MESSAGEix-AIM/Hub also estimating slightly different results from the MESSAGEix estimates. Comparing the specific mitigation measures estimated by MESSAGEix-AIM/Hub and AIM/Hub, the AIM/Hub approach was to rely on electrification even in sectors with low abatement efficiencies from energy goods conversion. This required more electricity and resulted in extra emission reduction costs. In MESSAGEix-AIM/Hub, the sectors with the highest abatement efficiencies from energy switching were prioritized to switch energy goods in a less expensive way, thus consuming less electricity and resulting in less cost to the energy system. This resulted in smaller GDP losses due to emission reductions compared to the AIM/Hub outcomes.

Because MESSAGEix-AIM/Hub includes a CGE model that considers multiple sectors and commodities, it is possible to analyze the factors behind the differences in economic impacts. MESSAGEix-AIM/Hub calculated a smaller value added in the energy sector than did AIM/Hub at the global scale. As mentioned above, MESSAGEix-AIM/Hub suppressed the additional costs to the energy sector compared with AIM/Hub due to the differences in mitigation measures. This resulted in smaller changes in value added in the energy sector i.e., fewer production factor inputs. Instead of a decrease in energy factor inputs in the energy sector, production factor inputs in other sectors increased, resulting in suppressed GDP losses. A region-wise comparison of MESSAGEix-AIM/Hub and AIM/Hub showed that in all regions GDP losses were reduced due to mitigation measures in MESSAGEix-AIM/Hub. However, the different regions had different ways of controlling

GDP losses. In Asia and the Pacific OECD, the sectoral economic impact of emission reductions followed the global trend. In North America, Europe, the former Soviet Union, and the Middle East and Africa, MESSAGEix-AIM/Hub calculated a higher value added in energy-related sectors from emission reductions than did AIM/Hub. In these regions electrification of the transportation sector reduced emissions and increased the electricity demand, whereas in regions where fossil fuel reductions were skewed toward coal, natural gas and oil extraction/utilization increased. For the Middle East and Africa, and the former Soviet Union, one reason for the decrease in GDP loss is that resources that were not utilized in AIM/Hub were used in a scenario calculated by MESSAGEix-AIM/Hub. For North America and Europe, more electrification of the transportation sector and less investment in the industrial sector reduce emission reduction costs. The GDP losses decreased because reduced production factors were input into the other sectors. Despite these regional differences, the GDP losses estimated by MESSAGEix-AIM/Hub were still smaller than those of AIM/Hub in all regions.

4.2. *Proposed method to integrate the two models*

The indicator for confirming convergence showed the percentage difference between the two models relative to their average values. The result obtained after ten iterations was adopted as the result of the integrated model because this indicator had a sufficiently small value, and because the difference from the previous iteration value was less than 5%, therefore further repetition of the data exchange would not significantly improve the indicator. Focusing on each component of the indicator, it was apparent that small differences remained in the growth rate and share of final energy consumption even after 10 data exchanges. However, as noted above, the results of MESSAGEix-AIM/Hub mostly reflected the characteristics of MESSAGEix with respect to the energy system. Hence, the differences between the models in the energy system shown by the indicator were considered to be small enough to serve the purpose of model integration. When the methodology proposed by this study was applied to other models, a convergence could be determined based on the value of 0.068 for this indicator.

After the data exchange, the two models converged well. However, for the final energy consumption the discrepancies still remained in absolute terms. The reason for this was that the base year was not perfectly consistent between the models, especially when focusing on the regional and sectoral scale. In terms of the energy systems, differences also arose for the energy supply side, which was primarily because the study did not exchange technological information, such as the energy conversion efficiency in the energy transformation sectors. The differences could be further reduced by reconciling the base year information and exchanging the technological information, as mentioned above. However, in the process of integrating the energy system and CGE models, it was impossible to achieve a perfect agreement due to differences in the representation of energy-related technologies and sectors in the two models, and there needs to be a compromise at some point. One of the advantages of the method proposed in this study is that it allowed for some degree of difference, while still obtaining the consistency between the two models that was necessary for model integration.

Although the two models coupled in this study were both calibrated using the IEA energy balance tables, they did not fully converge due to the differences in the base year. It is important to match the information in the base year, to apply the method proposed by this study to other models, and it would be difficult to apply the method to models with different base year information.

5. Conclusion

This study developed a new method for integrating global scale CGE and energy system models, and demonstrated a new model that captured the strengths of both models by integrating MESSAGEix and AIM/Hub. The proposed method integrated the two models by exchanging the energy system and energy demand until convergence, which was quantified using indicators measuring the difference between the two models. As a result of integrating MESSAGEix and AIM/Hub, the index showing the difference between the two models was calculated to be less than 0.068, confirming that the two models estimated a consistent scenario.

Table 4 summarizes the characteristics of the models integrated in this study and the conclusions about the methods of integration developed in this study. Comparing the diagnostic indicators calculated for the newly-developed MESSAGEix-AIM/Hub with those of AIM/Hub, MESSAGEix-AIM/Hub was characterized by a higher contribution of demand-side reductions to emission reductions, a lesser alteration in primary energy supply composition, lower fossil fuel abatement rates, and lower abatement costs. The analysis using the output from the CGE model showed that the lower abatement costs were the result of a shift in the sectors targeted for investment in emission reductions from the energy supply sector to the transportation and industrial sectors by considering changes in energy demand and supply technology over the long-term. Lower abatement costs suppressed the change in value added in the energy sector, i.e., production factor inputs decreased. Instead of a decrease in factor inputs in the energy sector, factor inputs in other sectors increased, thus reducing GDP losses. This indicates that the method applied in this study has successfully developed a new model that incorporates the strengths of both models.

Model integration will become even more critical in the future as various problems caused by climate change emerge and various emission reduction technologies are developed. For the method for integrating global scale CGE and energy system models, in addition to modifications to both models, the main task is the creation of maps for energy and sectors. Creating these maps requires significant effort, but once completed, these models can be re-combined with only minor updates to the mapping in case of updates to both models. If the coupled model is operated continuously, it will be worth the development effort.

The method developed by this study was designed to apply to other models. It would be useful for the further application of the integrated model to climate change mitigation studies. However, as a limitation of the method proposed in this study, the two models will not converge when this method is applied to two models with different base year information. It is essential to match the base year information to apply this method to other models. Applying this method to models with different base year information would require additional work to match the base year information.

CRediT authorship contribution statement

Osamu Nishiura: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Volker Krey:** Resources, Software, Supervision, Writing – review & editing, Methodology. **Oliver Fricko:** Resources, Software, Supervision, Writing – review & editing, Methodology. **Bas van Ruijven:** Resources, Software, Supervision, Writing – review & editing. **Shinichiro Fujimori:** Conceptualization, Funding acquisition, Resources, Software, Supervision, Writing – review & editing, Methodology.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Osamu Nishiura reports financial support was provided by International Institute for Applied Systems Analysis. Shinichiro Fujimori reports financial support was provided by Environmental Restoration and Conservation Agency. Shinichiro Fujimori reports financial support was

Table 4
Research summary.

Characteristics of MESSAGEix-AIM/Hub compared to AIM/Hub
Higher contribution of demand-side reductions to emission reductions
Lesser alteration in primary energy supply composition and lower fossil fuel abatement rates
Reduced GDP losses due to reduced additional factor inputs in the energy sector for mitigation measures
Conclusions on the model integration methodology developed in this study
The integration methodology developed in this study is classified as a two-way soft link.
The integrated model allowed a detailed analysis of the economic impact of mitigation measures.
The results of the integrated models mainly reflected the characteristics of the corresponding energy system model concerning the energy system.
When applying the methodology developed in this study, the base year information must be similar between the two models.

provided by Sumitomo Electric Industries, Ltd.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2024.131039.

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