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Integration of a computable general equilibrium model with an energy system model: Application of the AIM global model

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ABSTRACT

An integrated assessment model AIM (Asia-Pacific Integrated Model) has been used climate change mitigation studies and the core of AIM is a computable general equilibrium model, AIM/Hub. However, the energy representation in the AIM/Hub is abstract and to overcome that shortcoming, this study integrated AIM/Hub with the energy system model AIM/Technology. First, we assessed how the new integrated model differ from the original standalone AIM/Hub. Second, we conducted the exchange of model outputs iteratively and evaluated how the model results converged. Comparing previous and corresponding iteration, the data points with discrepancies greater than 5% at the third iteration were only 5 variables which were minor variables from the full energy system point of view. The macroeconomic implications of climate change mitigation differ between the standalone AIM/Hub and the new integrated model, and however, there was no systematic discrepancies. Overall, the new model is valid for exploring energy-economic scenarios.

1. Introduction

Integrated assessment models (IAMs) have played vital roles in studies of long-term climate change, particularly climate change mitigation. Scenarios simulated using IAMs are widely employed in Intergovernmental Panel on Climate Change reports across Working Groups (IPCC, 2021; Pörtner et al., 2022; Shukla et al., 2022), as well as in impactful international reports such as the Emissions Gap Report (United Nations Environment Programme, 2022) and the sixth Global Environment Outlook (United Nations Environment Programme, 2019). These scenarios help to elucidate the possible greenhouse gas (GHG) and air pollutant emissions pathways over the next few decades or century, as well as the main inputs for physical science model simulations (O'Neill et al., 2016) (e.g., general circulation models) using downscaled emissions (Gidden et al., 2018) and land-use (Hurtt et al., 2020), and impact assessments related to climate change. IAMs typically consider human systems that drive emissions, such as energy systems, economies, agriculture, and land use. At the same time, models have differing degrees of detail in the representation of each component, which depend on the primary model objectives, the main principles of the model, and the model type (Baumstark et al., 2021; Calvin et al., 2019; Huppmann et al., 2019; Stehfest et al., 2014).

The Asia-Pacific Integrated Model (AIM) is an IAM originally developed around 1990 (Matsuoka et al., 1995). AIM has actively and continuously contributed to enriching scientific knowledge associated with global and national climate change mitigation strategies (Hasegawa et al., 2016; Mittal et al., 2016; Siagian et al., 2017; Silva Herran and Fujimori, 2021; Thanh Tu et al., 2016). One such activity is participating in model inter-comparison projects of IAMs or agricultural economic models to obtain robust insights or address uncertainty (Fujimori et al., 2019a; Hasegawa et al., 2018, 2021; Luderer et al., 2018; McCollum et al., 2018; Nelson et al., 2014; Riahi et al., 2021). Another vital contribution of IAMs to climate change research is providing climate community scenarios (Fujimori et al., 2017; Masui et al., 2011; Nakicenovic et al., 2000). The AIM approach is a modular method that consists of multiple models that exchange inputs and outputs with each other, which has typically been accomplished through one-way coupling or emulation of model outputs (Fujimori et al., 2020;

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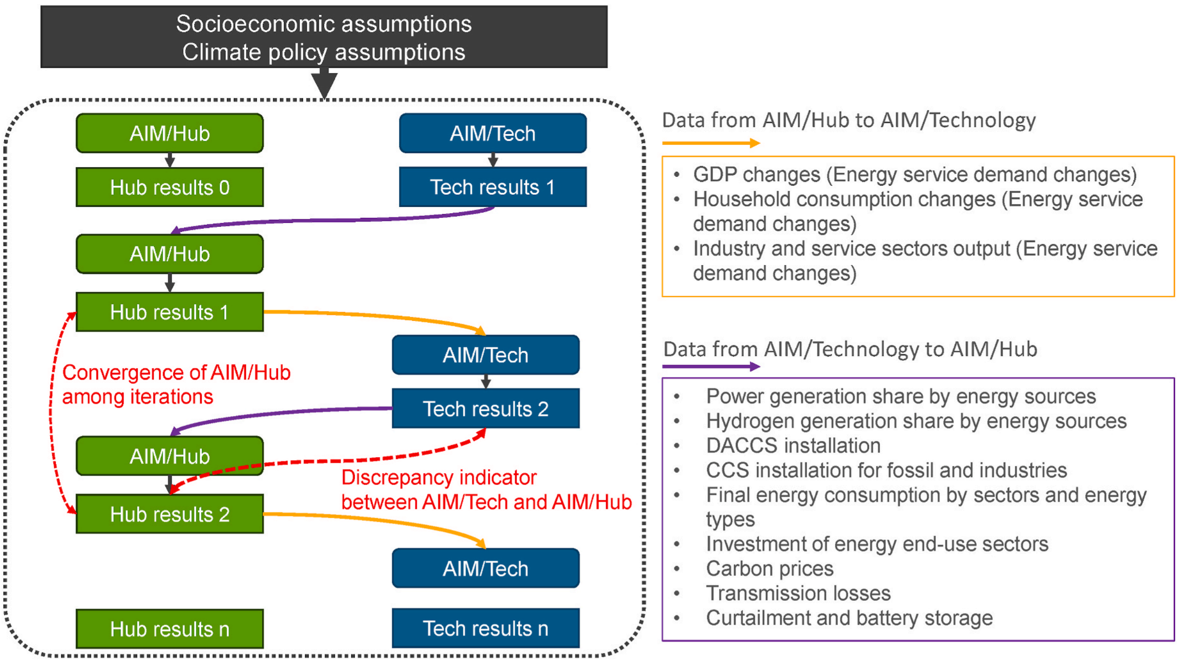

Fig. 1. Overall framework of the models' interactions.

Hasegawa et al., 2017; Takakura et al., 2021); Supplementary Fig. 1 illustrates the AIM framework. Over the past two decades, most scientific contributions generated using AIM have directly or indirectly involved the global computable general equilibrium (CGE) model AIM/Hub (formerly named AIM/CGE), which is the core model of the AIM framework. As a multi-sectoral and multi-regional CGE model, AIM/Hub has two advantages. First, economic responses to shocks, such as climate policies, including carbon pricing, emissions targets, and climate change impacts, are represented in detail. This advantage allows sectoral adjustment effects, and goods and service price changes in response to shocks to be simulated at finer resolution. Second, because the entire economic system is represented, this model treats energy, agriculture, and other sector behaviors consistently. Meanwhile, relative to other IAMs with more detailed representations of the energy system (such as MESSAGE-ix (Huppmann et al., 2019), GCAM (Calvin et al., 2019), and TIAM (Anandarajah et al., 2011)), the model's capability to derive technological implications is limited, which is the fundamental disadvantage of AIM/Hub.

Several attempts have been made to improve the representation of energy systems in CGE models and overcome this shortcoming of CGE models other than the AIM. The methods of improvement can be classified into two types. The first approach is to include a more detailed or realistic representation of the energy systems within CGE models. In the past, global CGE models were unable to represent the power sector with fine technological resolution, and several attempts were made to disaggregate the power sector (Böhringer and Rutherford, 2008, 2009; Jacoby et al., 2006). The second approach is coupling with external model information, typically through incorporating the outputs of energy system models (Lanzi et al., 2012; Vandyck et al., 2016; Waisman et al., 2012). Alternatively, a similar approach, namely coupling the sectoral models to the CGE models, can improve energy system representation (Zhang et al., 2018). The literature cited above includes global model studies; however, more examples of both approaches can be found in national or regional model studies (Abrell and Rausch, 2016; Andersen et al., 2019; Arndt et al., 2016; Drouet et al., 2005; Fujimori et al., 2019b; Helgesen and Tomasgard, 2018; Krook-Riekkola et al., 2017; Rodrigues and Linares, 2014; Tapia-Ahumada et al., 2015). The latter approach, which incorporates energy system model information into the CGE model, has a great advantage of consistently including an energy system model along with the CGE model. However, while studies have reported integrating the information from energy system model outputs into CGE models, descriptions of the methodological differences related to coupling and convergence of the iterative procedure have not been detailed, hampering understanding of the models' behavior. Moreover, representation of new technologies such as hydrogen and direct air capture (DAC) are not well reflected, although such technologies could be vital factors in climate change mitigation studies.

Against this background and with consideration of recent energy system model developments, such as AIM/Technology in the AIM global modeling framework (Oshiro and Fujimori, 2022; Oshiro et al., 2023), we developed a new modeling platform that integrates a global CGE model (AIM/Hub) with a global energy system model (AIM/Technology) using an iterative procedure to exchange model outputs. The objectives of this paper are to describe the integration of these two models, assess the behavior of the original two models and the newly developed model, and report the convergence conditions of the iterative procedure. We also identify potential future research topics that can exploit the newly developed framework.

2. Methods

2.1. Overall model integration procedure

We integrated AIM/Hub (CGE model) and AIM/Technology (energy system model) within the AIM modeling framework as shown Supplementary Fig. 1. The principle of this methodology is based on the assumption that energy-related simulation and model outputs made by the energy system model are more reliable than by the economic model since energy supply and demand are technologically represented in detail in the energy system model. Accordingly, we feed the energy system model outputs into AIM/Hub exogenously by endogenizing the existing parameters, allowing AIM/Hub to mimic the behavior of AIM/Technology. The details of this methodology will be explained later. In contrast, macroeconomic changes computed by AIM/Hub are fed into AIM/Technology, which changes energy service demand. The original AIM/Technology model uses exogenous inputs of energy service demand; therefore, This input does not alter the original model formula of AIM/Technology but rather changes the input parameters of AIM/

Table 1
How AIM/Technology information is used in AIM/Hub.

Information type	Method
Shares of power generation technologies	The share of power generation for each technology is exogenously forced into the model. Here, logit function parameters determining each technology's share are endogenized. The share parameter is originally exogenous parameter and therefore new variables to represent logit share parameters are introduced in the corresponding equation.
Shares of hydrogen generation technologies	The share of hydrogen generation for each technology is exogenously forced into the model. Here, logit function parameters determining each technology's share are endogenized. The share parameter is originally an exogenous parameter, and therefore, new variables to represent logit share parameters are introduced in the corresponding equation.
Final energy consumption by sector and energy carrier type	The logit function determines the share of energy carrier consumption in the industrial, transport, commercial, and residential sectors. These shares are exogenously forced, and the logit share parameters are endogenized. The share parameter is originally an exogenous parameter, and therefore, new variables to represent logit share parameters are introduced in the corresponding equation. For the total energy consumption by sectors, they are also exogenously forced as exogenous parameters. To realize that Autonomous Energy Efficiency Improvement (AEEI) parameters, which are initially exogenous parameters, are endogenized to match the total energy consumption with AIM/Technology outputs. Here, new variables to represent AEEI are introduced in the corresponding equation.
Investment in energy end-use sectors	To decarbonize its energy consumption, energy end-use equipment requires additional investment costs for energy efficiency improvement or switching energy carriers (e.g., electrification). This investment induces additional capital requirements in each sector, which are fed into the model as exogenous inputs. The capital input parameter in the CES function, which determines the value added, labor inputs, and capital inputs, is endogenized. We consider additional capital investment in the mitigation scenarios relative to the baseline scenario because some energy end-use equipment in AIM/Technology considers only relative energy efficiency improvement and differences in capital cost, and also because identifying the absolute investment volume associated solely with energy consumption is difficult for many manufacturing facilities.
CCS installation	CCS installation rates for thermal power plants and industrial processes (steel and cement production) are exogenously input. CCS installation in terms of CO_2 volume, which AIM/Technology provides, is translated into CCS installation ratios for thermal power plants and industrial process emissions. For example, the percentage of CCS installation in gas-fired thermal power plants is directly fed into the model, as AIM/Hub initially determines the CCS installation rates based on carbon prices.
Curtailment and battery storage	Ratios of curtailment and battery storage to variable renewable energy sources are directly fed into AIM/Hub. We replaced the equation determining curtailment and battery storage with these parameters.
Transmission losses	Transmission loss rates can be treated as exogenous parameters for the original stand-alone AIM/Hub; thus, these parameters are directly adjusted using AIM/Technology outputs.
Carbon prices	Carbon prices are treated as exogenous parameters for the original stand-alone AIM/Hub.
DACCS installation	DACCS is determined from carbon price in the original stand-alone AIM/Hub. We deactivate this function and force the DACCS volume exogenously.

Technology. The exchange of model outputs is conducted iteratively (Fig. 1). Section 2.2 provides more details about this procedure.

In the present study, we employed this procedure for baseline and mitigation scenarios, which are roughly equivalent to scenarios with and without climate change mitigation actions, respectively.

2.2. Models

2.2.1. AIM/Hub

AIM/Hub is a 1-year-step recursive-type dynamic general equilibrium model that covers all regions globally. AIM/Hub includes 17 regions and 58 industrial classifications (see Supplementary Table 1 and Supplementary Table 2 for the regional classifications and Supplementary Table 3). The energy supply technologies are disaggregated to finer resolution for appropriate assessment of the energy system. Multiple crop and livestock sectors are explicitly represented to appropriately consider bioenergy and land use (Fujimori et al., 2014). Production sectors are assumed to maximize profits through multi-nested constant elasticity substitution (CES) functions and input prices. Input energy and the value added for the energy transformation sector are treated as fixed coefficients of the output representing the energy conversion efficiency of the energy transformation sector. Power generation values associated with several energy sources are combined using a logit function because it ensures energy balance, unlike the CES function. As reported previously, curtailment and battery storage are represented within this model using a simplified exponential function for the share of variable renewable energy, with parameter values based on a previous study (Dai et al., 2016a). A linear expenditure system function describes household expenditures on each commodity type, for which the adopted parameters are recursively updated based on income elasticity assumptions (Hasegawa et al., 2015). Logit selection determines land use (Fujimori et al., 2014). DAC combined with carbon capture and storage (CCS) is represented by the assumption that an industry that provides DAC + CCS (DACCS) service for each government has a Leontief production function, and the technological parameters are obtained from previous research (Keith et al., 2018); for more details, see Fujimori et al.. AIM/Hub includes representations of the major GHGs and air pollutants, which have been described previously (Fujimori et al., 2017) and are not directly related to this study.

The base year of AIM/Hub is 2005. Because recent energy information is used as available, the model results regarding energy supply and consumption generally follow the International Energy Agency (IEA) World Energy Balances until 2019 (International Energy Agency, 2020). The same methodology is used for this historical calibration as for model integration with an energy system model, in which the final energy, transport energy share, and power energy technological share are exogenously provided. At the same time, corresponding parameters in the production function and household consumption are endogenized (Fujimori et al., 2019b). We selected the year 2019 to exclude the effects of the unique events of the COVID-19 pandemic and the Ukraine–Russia conflict.

Regarding the data for AIM/Hub, the Global Trade Analysis Project (GTAP) (Dimaranan, 2006) and World Energy Balances (International Energy Agency, 2013a, 2013b) are used as the basis for the social accounting matrix. The data have been reconciled with other available data, such as national accounting statistics (United Nations, 2013). The

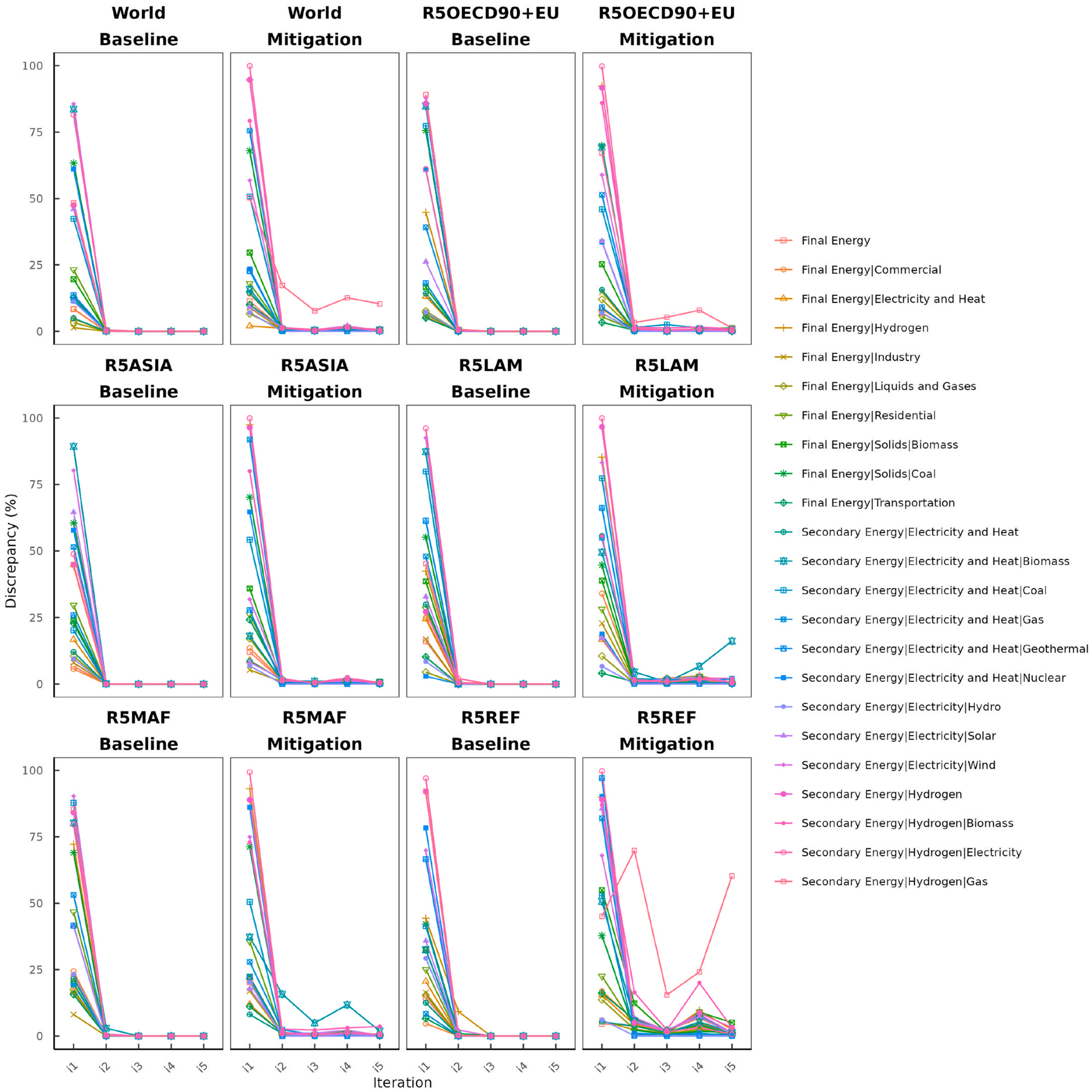

Fig. 2. Convergence indicator (*ConvInd*) representing the difference between the previous iteration and target iteration from AIM/Hub. The horizontal axis indicates the iteration; for example, "i1" is the comparison of iterations 0 and 1. The first and third columns show the baseline scenario, and the second and fourth columns illustrate mitigation scenarios. Panels show the global total and five aggregated regions (R5***).

concept behind the reconciliation method has been described previously (Fujimori and Matsuoka, 2011). GHG and air-pollutant emissions are calibrated using the EDGAR dataset ver. 4.2 (EC-JRC/PBL, 2012). For land-use and agricultural sectors, agricultural statistics (Food and Agriculture Organization of the United Nations, 2013), land-use representative concentration pathway data (Hurtt et al., 2011), and GTAP data (Avetisyan et al., 2011) are used as physical data. Agricultural consumption is converted into caloric intake using a conversion factor derived from agricultural statistics (Food and Agriculture Organization of the United Nations, 2013). Data on solar and wind, as energy resource potentials, are from previous studies (Dai et al., 2016b; Silva Herran et al., 2016) and calculated using high-spatial-resolution data (0.5 arc-minute or approximately 1 km at the equator). Fossil-fuel resources are from a previous study (Rogner, 1997). Although this is relatively old information, the newer information(Bauer et al., 2016; Rogner et al., 2012) did not change so much on the energy system outcomes of the model. Techno-economic information related to energy supply facilities, such as capital and operation costs, is based on information available in 2020, including the IEA World Energy Outlook (International Energy Agency, 2019).

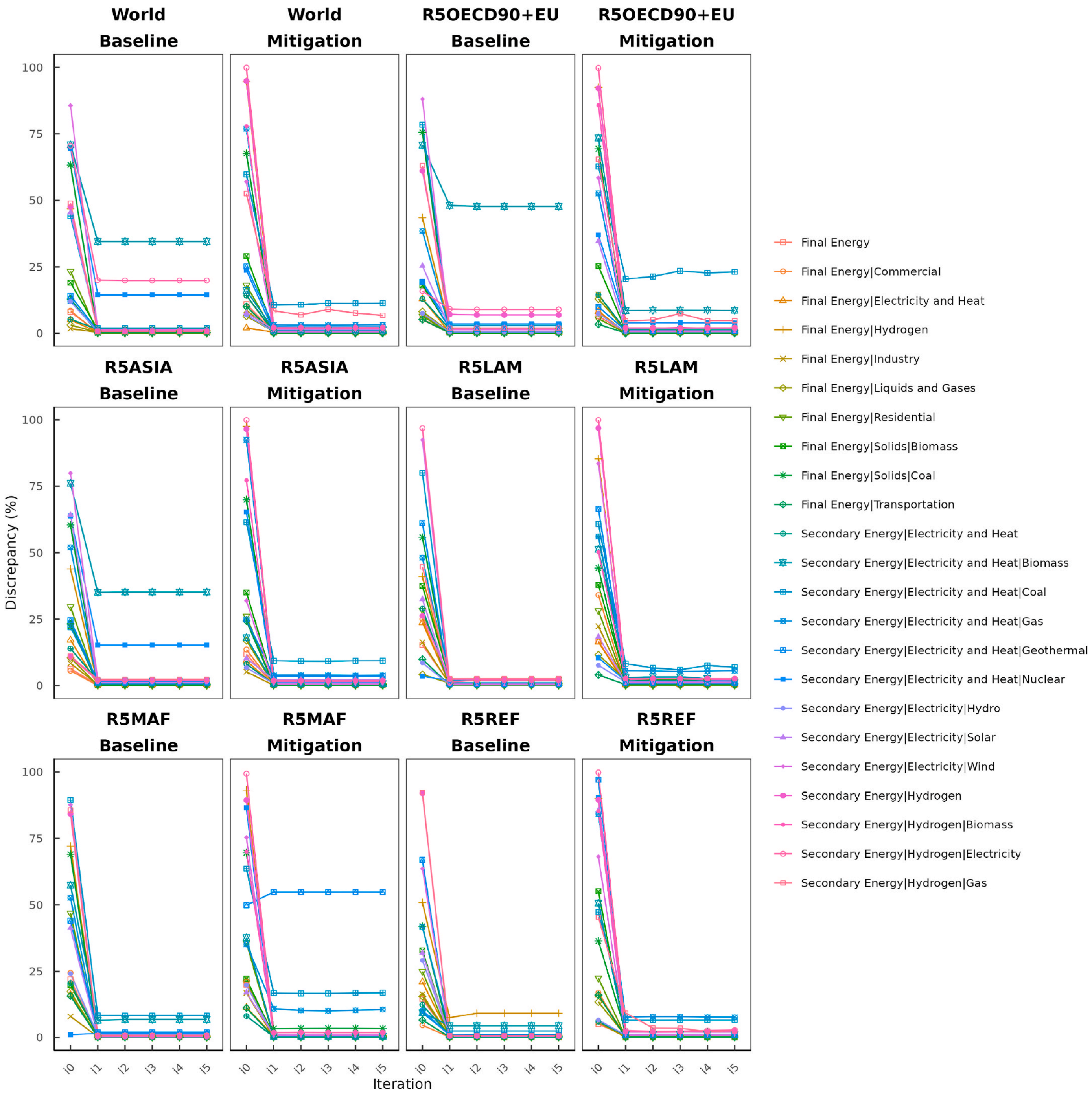

Fig. 3. Model differences (*DiscInd*) by iteration. The first and third columns show the baseline scenario, and the second and fourth columns illustrate mitigation scenarios. Panels show the global total and five aggregated regions (R5***).

2.2.2. AIM/Technology

AIM/Technology is a bottom-up global energy system model that determines energy supply, demand, and CO2 emissions from energy sectors using linear programming to minimize the total energy system cost consisting of capital investment and operation & management cost. The model is classified as a recursive dynamic model that solves every year (Oshiro and Fujimori, 2022). The details of this model, including its mathematical equations and parameter assumptions for energy technologies, are summarized in the model description document (Oshiro, 2021). AIM/Technology models multiple energy technologies across multiple energy supply and demand sectors. Energy demand sectors include the industry, buildings, and transport sectors, which are disaggregated into various industrial products, energy services in buildings, and transport modes. Energy extraction from biomass and fossil fuels, as well as energy transformation processes such as electricity, heat, and hydrogen, are represented in the energy supply sectors.

The exogenous parameters include each technology’s energy efficiency and cost parameters, energy service demands, and associated constraints such as energy resource potentials. More information, including the source code of AIM/Technology, is provided in the code availability statement. Various energy technologies are modeled in AIM/Technology in each energy sector, with most techno-economic information available online (https://kenoshiro.github.io/AIM-Technology-doc). The power sector considers several energy sources,

Table 2
List of variables with discrepancies greater than 5% in the convergence indicator.

Scenario	Region	Var	Discrepancy at third iteration
Mitigation	World	Secondary Energy|Hydrogen|Gas	7%
Mitigation	R5OECD90+EU	Secondary Energy|Hydrogen|Gas	5%
Mitigation	R5MAF	Secondary Energy|Electricity and Heat|Biomass	16%
Mitigation	R5REF	Secondary Energy|Hydrogen|Gas	17%

including fossil fuels, renewables, and nuclear energy. This sector uses a dispatch module with 1-h temporal resolution on representative days for the integration of variable renewable energies, battery storage, and pumped hydro storage, which can be used as electricity storage options. In contrast, electrolysis can effectively use excess electricity output. Furthermore, battery electric vehicles and heat-pump water heaters can be operated as demand-response resources. AIM/Technology includes multiple hydrogen-based energy carriers. Hydrogen can be generated through the conversion of fossil fuels or biomass, as well as electrolysis. Regarding CCS, AIM/Technology considers carbon capture from large emission sources and DAC. Large emission sources include facilities for power and hydrogen generation, oil refining, bioenergy liquefaction, steel and cement production, and furnaces. For DAC, solvent-based DAC requiring large amounts of heat is modeled.

The efficiency and cost parameters of power generators are based on the IEA (IEA, 2019). The energy potential of dedicated energy crops and costs are based on estimates obtained from AIM/PLUM (Hasegawa et al., 2017; Wu et al., 2019). Wind and solar potentials, as well as their hourly generation profiles, are estimated based on climate, weather, and land information in 0.5° × 0.5° grid cells. Solar irradiance and wind speed data are obtained from the Modern-Era Retrospective analysis for Research and Applications Version 2 (MERRA-2) dataset (Global Modeling and Assimilation Office (GMAO), 2015a, 2015b). Climate data are converted into hourly power output and physical potentials for solar and wind power based on formulae and parameter settings obtained from the literature (Pfenninger and Staffell, 2016; Staffell and Pfenninger, 2016).

2.2.3. Information exchanged between models

To describe the overall model integration procedure, three major topics are described here, namely 1) the basic assumption and principle of this integration, 2) the overall iteration procedure and information exchanged between models, and 3) regional and sectoral mapping.

1) Basic assumption and principle of model integration

This model integration procedure is based on the assumption that the CGE model (AIM/Hub) accurately represents the economic response to the energy system changes, as overall economic market interactions, prices, and production factor allocations are considered. Similarly, the energy system model (AIM/Technology) is assumed to better represent the energy system due to its detailed technological resolution. To reflect this principle, AIM/Hub obtains energy system-related information from AIM/Technology by forcing it as exogenous constraints, and macroeconomic feedback data obtained from AIM/Hub provide exogenous inputs to the AIM/Technology simulation.

2) Overall iteration procedure and information exchanged

Both models are run for each step, and the results of each model are fed into the other (Fig. 1). We refer to the native model results as stand-alone results. The first iteration begins with AIM/Hub, which incorporates the stand-alone AIM/Technology outputs. Then, the second run of AIM/Technology is implemented using the outputs from the first iteration of AIM/Hub. We implemented five iteration steps and confirmed that the results converged well; the assessment results are discussed in section 3.

For input to AIM/Technology, macroeconomic changes such as gross domestic product (GDP) loss rates and consumption losses are obtained from AIM/Hub while considering income elasticity in the energy service demand projection. Income elasticity or equivalent information have been reported previously (Oshiro and Fujimori, 2022). The changes in macroeconomic indicators are translated into energy service demand change ratios for the mitigation scenarios relative to the baseline projection. For example, supposing that passenger car transport demand has an income elasticity of 0.5, and a mitigation scenario simulated by AIM/Hub exhibits a 5% GDP loss, then the passenger car transport demand drops to around 2.5% in the mitigation scenario.

On the AIM/Hub side, Table 1 lists the information obtained from AIM/Technology and fed into the model, and describes how each type of information is implemented. The basic approach is the same as that used in Japan's national model (Fujimori et al., 2019b).

3)Regional and sectoral mapping

AIM/Hub has coarser regional classifications than AIM/Technology (Supplementary Table 4), meaning that information from AIM/Technology can be aggregated into AIM/Hub. Conversely, AIM/Hub information cannot be directly used in AIM/Technology as absolute volume data, and we instead use change ratios of macroeconomic indicators, as noted above.

In terms of sectoral resolution, the detailed energy technology information for the energy supply side provided by AIM/Technology can be used as simple aggregated information in AIM/Hub. Treatment of the energy demand side differs from that of energy supply, for which AIM/Hub has a more detailed industrial sectoral resolution. Therefore, exogenous inputs of energy demand information are treated as the summation of multiple sectors, and endogenized variables for those sectors are uniformly altered. For example, machinery, chemistry, and other manufacturing sector parameters, e.g., Autonomous Energy Efficiency Improvement (AEEI), change at the same ratios in each region. Regarding energy service demand, AIM/Hub represents only the total energy consumption of individual sectors, rather than individual energy services. Therefore, the simple summation of energy consumption associated with individual energy services represented the AIM/Technology at a fine resolution can be used in AIM/Hub.

2.2.4. Scenarios

We developed two simple scenarios, designated as the baseline and mitigation scenarios. The latter scenario is implemented based on global total cumulative CO_2 budgets of 500 Gt from 2011 to 2100. All scenarios used Shared Socioeconomic Pathway 2 as the background socioeconomic assumption, which has been widely employed (O'Neill et al., 2017; Riahi et al., 2017), and we ran the model for baseline conditions by assuming no carbon price and energy and land-use systems projected from their historical trends.

2.2.5. Analysis of the simulation results

Two analytical aspects are addressed here, namely the condition of convergence across iterations and the discrepancies among stand-alone AIM/Hub, stand-alone AIM/Technology, and the integrated model. The two indicators used to assess those mean absolute errors are determined as follows:

Table 3
Discrepancies at the third iteration between AIM/Hub and AIM/Technology.

		Baseline						Mitigation					
		World	R5ASIA	R5OECD90+EU	R5REF	R5MAF	R5LAM	World	R5ASIA	R5OECD90+EU	R5REF	R5MAF	R5LAM
Final energy by carriers	Final Energy	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.01	0.00	0.01
	Final Energy|Electricity and Heat	0.00	0.00	0.00	0.01	0.01	0.01	0.00	0.00	0.00	0.01	0.01	0.00
	Final Energy|Liquids and Gases	0.00	0.00	0.01	0.00	0.00	0.01	0.01	0.00	0.01	0.01	0.00	0.02
	Final Energy|Solids|Coal	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.02	0.03	0.01
	Final Energy|Solids|Biomass	0.01	0.01	0.02	0.00	0.01	0.02	0.01	0.01	0.01	0.00	0.01	0.02
	Final Energy|Hydrogen	0.01	0.00	0.02	0.09	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00
Final energy by sectors	Final Energy|Industry	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
	Final Energy|Commercial	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Final Energy|Residential	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Final Energy|Transportation	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Electricity generation by energy sources	Secondary Energy|Electricity and Heat	0.01	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.01
	Secondary Energy|Electricity and Heat|Coal	0.02	0.02	0.03	0.02	0.08	0.01	0.11	0.09	0.23	0.07	0.17	0.06
	Secondary Energy|Electricity and Heat|Gas	0.01	0.01	0.01	0.01	0.01	0.01	0.03	0.04	0.02	0.08	0.10	0.05
	Secondary Energy|Electricity and Heat|Nuclear	0.14	0.15	0.04	0.01	0.01	0.02	0.01	0.01	0.04	0.01	0.01	0.02
	Secondary Energy|Electricity|Hydro	0.01	0.02	0.00	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.01
	Secondary Energy|Electricity|Solar	0.01	0.01	0.02	0.00	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01
	Secondary Energy|Electricity|Wind	0.01	0.02	0.01	0.01	0.00	0.01	0.00	0.01	0.01	0.01	0.01	0.01
	Secondary Energy|Electricity and Heat|Biomass	0.35	0.35	0.48	0.04	0.07	n.a.	0.01	0.01	0.09	0.01	0.00	0.03
	Secondary Energy|Electricity and Heat|Geothermal	0.01	0.01	0.02	0.01	0.02	0.01	0.02	0.04	0.01	0.01	0.55	0.01
Hydrogen generation by energy sources	Secondary Energy|Hydrogen	0.01	0.02	0.07	0.01	0.00	0.02	0.02	0.02	0.02	0.02	0.02	0.03
	Secondary Energy|Hydrogen|Gas	0.01	0.02	0.02	0.01	0.01	0.03	0.09	n.a.	0.07	0.03	n.a.	n.a.
	Secondary Energy|Hydrogen|Biomass	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0.02	0.02	0.02	0.02	0.02	0.03
	Secondary Energy|Hydrogen|Electricity	0.20	n.a.	0.09	n.a.	n.a.	0.02	0.02	0.02	0.02	0.02	0.02	0.03

$$ConvInd_{m,i,s,n} = \frac{\sum_t \left|X_{m,t,i,s,n} - X_{m,t,i,s,n-1}\right|}{\sum_t \left(\frac{X_{m,t,i,s,n}+X_{m,t,i,s,n-1}}{2}\right)} \quad (1)$$

$$DiscInd_{m,m',i,s,n} = \frac{\sum_t \left|X_{m,t,i,s,n} - X_{m',t,i,s,n}\right|}{\sum_t \left(\frac{X_{m,t,i,s,n}+X_{m',t,i,s,n}}{2}\right)} \quad (2)$$

where $ConvInd_{m,i,s,n}$ is the convergence indicator for model m, variable i, scenario s, and iteration number n and $DiscInd_{m,m',i,s,n}$ is the discrepancy indicator representing the differences between models m and m' for variable i, scenario s, and iteration number n. $X_{m,t,i,s,n}$ is the model output of model m, year t, variable i, scenario s, and iteration number n.

The basic principle of convergence assessment of the iteration is assessing differences between the model outputs of a given iteration and those of the previous iteration. The discrepancies of indicator values among models are similar to mean absolute errors. In terms of convergence, if the indicator is negligibly small and stable (e.g., less than 5% for several iterations), the iteration procedure could be interpreted as having converged. The threshold used to determine whether it has converged depends on the purpose of the study and characteristics of the variables. Furthermore, the selection of target variables also must be considered. For example, if a study focuses on a specific sector, such as the transport sector, the convergence of the variables related to the transport sector would need to be good, whereas the other sector's convergence requirements may not need to be so strict. In this study, our primary focus is better representing the energy transformation structure and final energy consumption in AIM/Hub; therefore, we primarily focus on secondary energy production and final energy consumption, as well as the compositions of those factors.

3. Results

3.1. Convergence

Overall, model convergence derived from the differences between previous iterations and the target iteration was good after the third iteration (Fig. 2 and Fig. 3). In the third iteration (i3 in Fig. 2), the AIM/Hub results generally converged in both scenarios. Notably, in the baseline scenario, all variables had differences smaller than 5%, indicating that the model converged well at the third iteration. A few exceptions were found in specific variables and regions in the mitigation scenario (Table 2). The data points (combination of scenarios, regions, and variables) with discrepancies greater than 5% at the third iteration were extracted. Most such variables were related to hydrogen, which is dominantly supplied by electrolysis in the mitigation scenarios, whereas hydrogen originating from gas or biomass showed low convergence. The share of biomass and gas hydrogen was initially small, less than 5%, and there could be some fluctuation among the iterations within small shares. However, it would indicate that this lack of convergence is not a fundamental issue for the overall energy system. (Supplementary Fig. 7, Supplementary Fig. 8, Supplementary Fig. 9, Supplementary Fig. 10).

3.2. Differences between AIM/Hub and AIM/Technology

The differences in the model outputs between AIM/Hub and AIM/Technology at the five iterations are shown in Table 3. Overall, minor differences occurred for most variables and mostly converged at third iteration (Fig. 3). More than 95% of the variables, 229 out of 240, had differences smaller than 10%; the exceptions to this are discussed in detail. For final energy consumption by sector and fuel type, all five regions and scenarios had differences less than 10%, indicative of good consistency. Meanwhile, some variables showed more significant differences in electricity or hydrogen generation by energy source. In

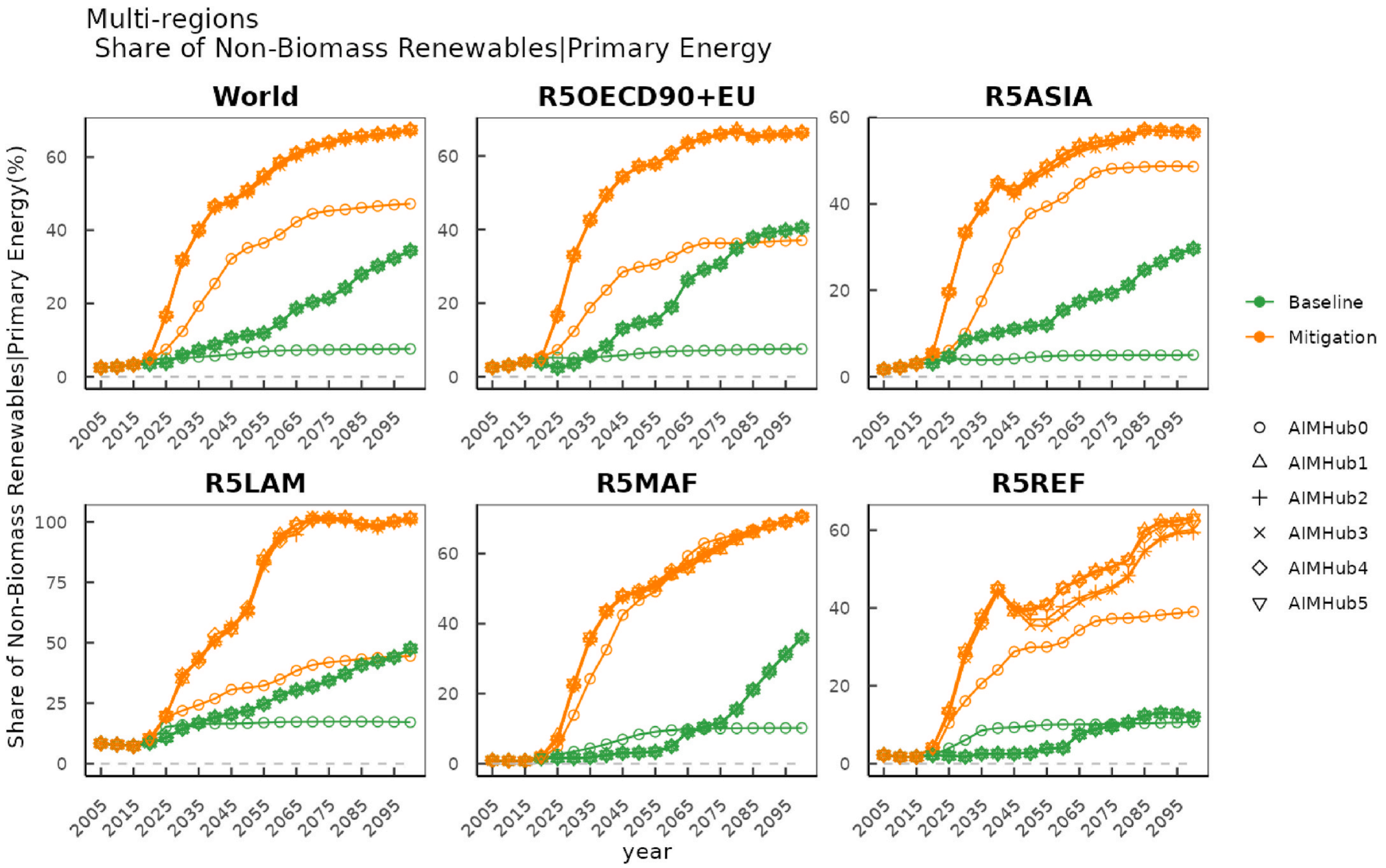

Fig. 4. Shares of non-biomass renewable energy in terms of electricity and heat generation in five aggregated regions and the global total in different iterations.

general, these relatively large discrepancies affected variables representing relatively small shares of electricity and hydrogen generation. For example, biomass and nuclear electricity had small shares and absolute volumes in the baseline scenarios (See Supplementary Fig. 4, Supplementary Fig. 5). Similarly, coal- and gas-fired electricity was phased out rapidly in the mitigation scenarios and consequently became small after 2030 (Supplementary Fig. 6). In the mitigation scenario, hydrogen was generated mainly through electrolysis. Thus, electrolysis-based hydrogen in the baseline scenario and hydrogen from natural gas in the mitigation scenario had small shares. Biomass hydrogen generation does not occur in the baseline scenario, and is assigned a value of N/A (Supplementary Fig. 7, Supplementary Fig. 8, Supplementary Fig. 9, Supplementary Fig. 10).

Based on convergence and model discrepancies at the fifth iteration, overall the models converged well, with AIM/Hub and AIM/Technology model simulating similar values. In addition to the individual indicators, similar results were obtained for the compositions of primary energy and power generation (Supplementary Fig. 11, Supplementary Fig. 12).

3.3. Main features of the energy-economic system

This section demonstrates how the results of the original AIM/Hub and integrated model differ to elucidate the system behaviors that are critical to climate change mitigation studies. For this assessment, the original and fifth-iteration AIM/Hub results are compared (designated AIMHub0 and AIMHub5, respectively). We present the share of non-biomass renewable power energy (representative of energy supply), electrification rate (representative of energy demand), mitigation cost, and electricity prices, which are critical variables for mitigation studies. The differences in other variables between these two models are provided in the supplementary data.

3.3.1. Share of non-biomass renewable energy

Fig. 4 presents the shares of non-biomass renewable energy sources (solar, wind, and hydro) in the total electricity and heat generation. The major difference occurred in the baseline scenario, where the original model (AIMHub0) was stable throughout the current century. In contrast, the integrated model (AIMHub5) indicated an increasing trend, with the world total reaching approximately 75% in 2100. This is a remarkable difference, and the original AIM/Hub (AIMHub0) tends to preserve the current condition. At the same time, the integrated model (AIMHub5), which relies on AIM/Technology, reacted to the cost condition changes which basically tend less cost in renewable energy than fossil-based energy consumption. This reactiveness to the cost and price condition changes is stronger in AIM/Technology which relies on cost minimization mechanism whereas original AIMHub model uses non-linear function responding moderately to the price condition changes. In contrast, the general time-series trend of mitigation scenarios was similar among models, with a trend of increasing dramatically in the near-term future until around 2030, when rapid emission reductions are required. This trend was similar in all regions. However, the speed of the increase and the maximum renewable share tended to be lower for AIM/Hub0 than the integrated model (AIMHub5).

3.3.2. Electrification rates

The global electrification rate of total final energy consumption tended to be smaller in the integrated model (AIMHub5) than in the original model (AIMHub0) for both scenarios (Fig. 5). However, this trend varied among regions. For example, regions R5OECD and R5LAM in the mitigation scenario had similar trends between these two models, whereas in the baseline scenario, the integrated model (AIMHub5) was higher than the original model (AIMHub0). R5ASIA and R5MAF exhibited trends similar to the world total, and appeared to be major drivers of the world total results. The major drivers of differences

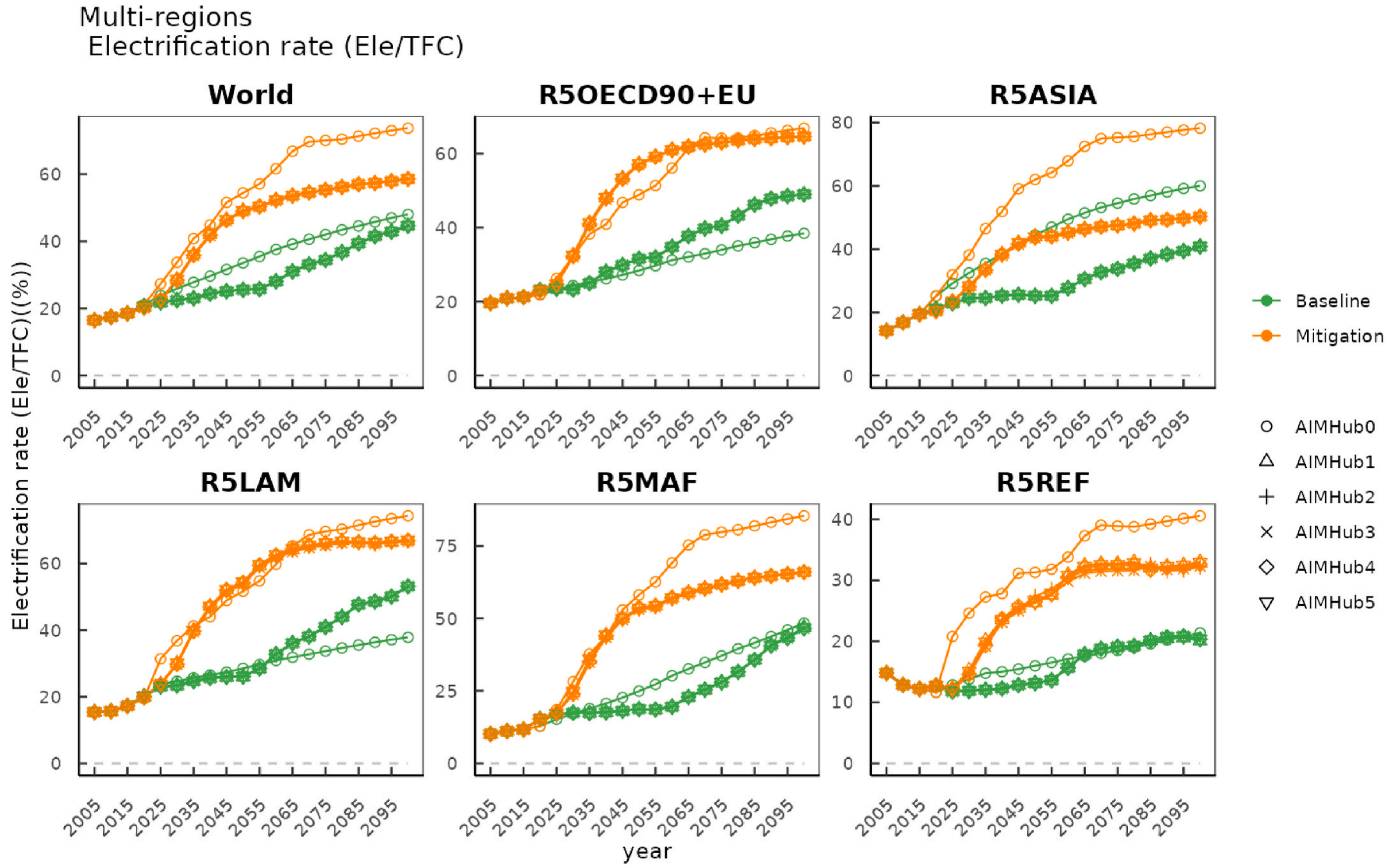

Fig. 5. Electrification rates in terms of total final energy demand in five aggregated regions and the global total (electricity consumption/total final energy consumption).

between these two models are their baseline electrification rates, which depend on the assumption of AEEI of the original AIM/Hub (AIMHub0) and the energy-consumption device penetration condition of AIM/Technology. Additional electrification was required in the mitigation scenarios, which is a typical characteristic in the literature and was observed with both models. However, the integrated model (AIMHub5) tends to be lower than the original model (AIMHub0). This is mainly due to the availability of hydrogen and flexibility of fuel shift in AIM/Technology.

3.3.3. *Economic aspects (macroeconomic responses and electricity price)*

The global total GDP loss rates associated with climate change mitigation sharply increase after the climate change mitigation starts responding to the emissions reduction constraints. Particularly, the former part of this century shows relatively higher because the speed of the increase in macroeconomic loss is faster than that in GDP growth. These trends can be found regardless of the choice of models. For the differences between the original and integrated models, global total value shows generally similar tendency (Fig. 6). However, this finding could be a coincidence, as regional results differed between the models. The R5OECD and R5ASIA regions were similar, while other regions had higher costs in AIMHub5 than AIMHub0. Moreover, the main drivers of those differences differed among regions. For R5REF, fossil fuel-related industries, for which capital efficiency is higher than other sectors, remain in the original model (AIMHub0), whereas fossil fuel usage decreases in the integrated model (AIMHub5). Consequently, AIMHub5 becomes more capital inefficient than AIMHub0, resulting in relatively higher macroeconomic losses. A similar response can also be found in R5MAF, which includes the Middle East and North Africa. These are consistent with the renewable energy share results that showed relatively larger renewable energy in AIMHub5, which implies that the volume of remaining fossil fuel is relatively low in AIMHub5 as mentioned above. In R5LAM, the mitigation scenarios include a large volume of hydrogen from renewable energy, mainly for export. This means additional capital for this hydrogen export is required. This would further induce the situation where the capital that can be used for the general domestic consumption sectors is taken by the hydrogen industry. Eventually, the GDP loss in AIMHub5 becomes larger than that in AIMHub0. Regarding the convergence of the GDP loss, most regions show good convergence among the iterations.

Among regions, the electricity price was similar in the baseline scenario, whereas the mitigation scenario showed different behavior (Fig. 7). The price tended to be lower in the integrated model (AIMHub5) than the original model (AIMHub0). This difference arises due to the AIM/Technology model mechanism of cost minimization, which allows for a rapid response of phasing out fossil fuel-fired power generation, whereas the original model (AIMHub0) retains fossil fuel-fired power to some extent, carrying a penalty in terms of carbon pricing.

4. Discussion

4.1. *Interpretation of convergence*

Overall, convergence is good in the third iteration, mainly due to the limited sensitivity of the macroeconomic feedback in AIM/Technology. The income elasticity of energy service demand is less than 1 and generally less than 0.2. While AIM/Technology considers macroeconomic losses at the third iteration, the magnitude of those changes is relatively minor. That minor change is fed into AIM/Hub at the third and later iterations. However, the macroeconomic response to such minor differences in the energy system diminishes with each run. Thus, the two models converge quite well at the third iteration.

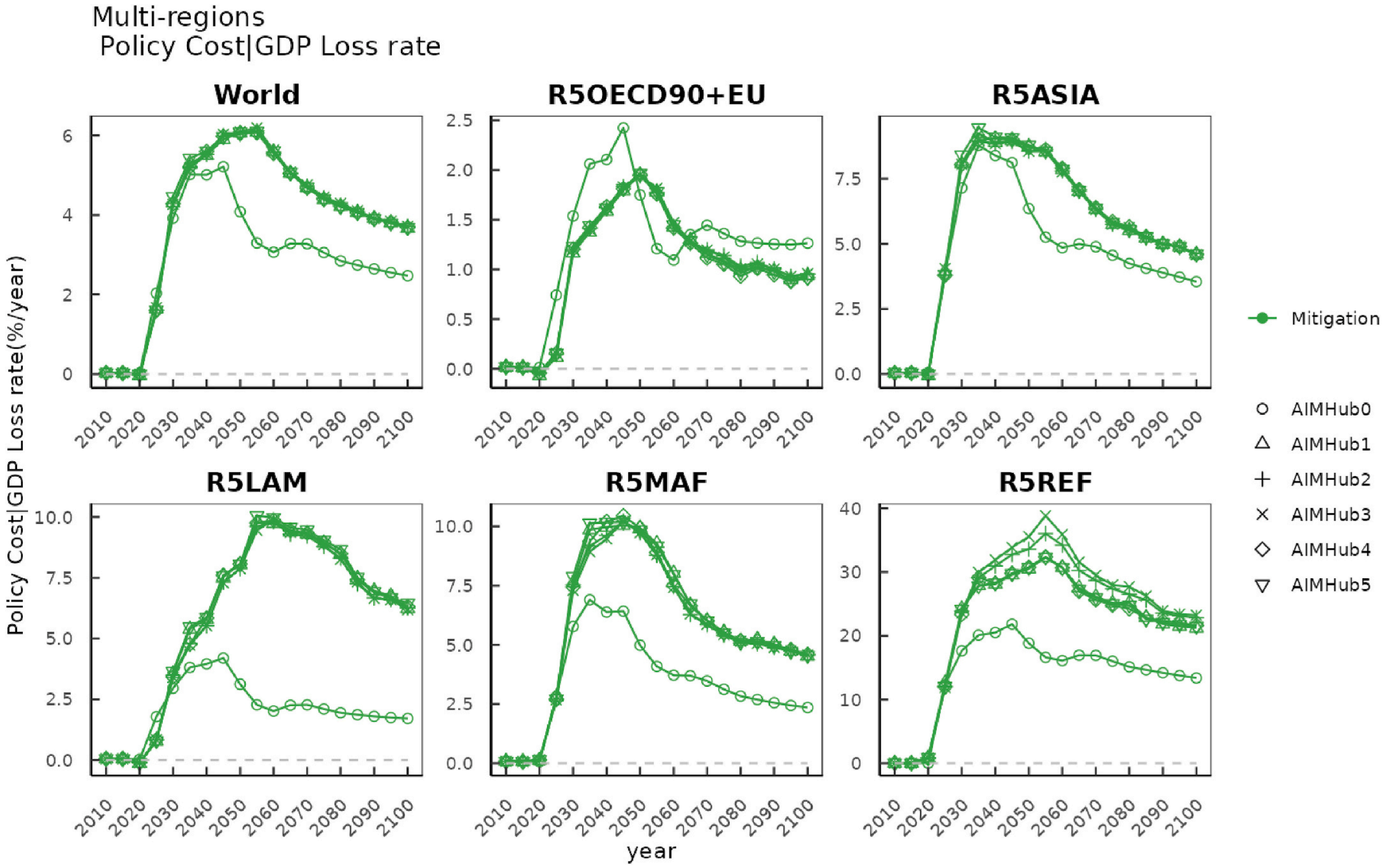

Fig. 6. GDP loss rates in five aggregated regions and the global total.

Additionally, most of the characteristics of AIM/Technology is well reflected at the first iteration indicating that if we would not consider the macroeconomic feedback in AIM/Technology, even one iteration would be sufficient. This would further imply that if the mitigation level is modest, the iteration can be finished at once or twice iteration.

One potential concern is that the trading behavior in AIM/Technology is sensitive under some conditions. For example, at specific carbon price conditions and in a particular year, one region could have the lowest hydrogen generation cost due to having the cheapest solar power, which can be exported to the rest of the world. That condition may change the following year. This situation could occur even with minor macroeconomic feedbacks, although we did not observe such results within our scenarios. Therefore, attention should be paid to such changes when the new model framework is applied.

4.2. Consistency between the two models

We confirmed that AIM/Hub and AIM/Technology generally agree. We mainly investigated relatively coarse regional results, and the same can be said for the native 17 regions of the AIM/Hub model. However, some exceptions exist, affecting mainly minor sectors from the viewpoint of the overall energy system. Therefore, if a model application requires detailed regional or sectoral information, a much closer data check and additional refinement are needed. For example, we could not harmonize all techno-economic information, such as the lifetime and capital costs of power generation; therefore, a study focused on the investment requirement of the power sector and its macroeconomic feedback would require more detailed harmonization of the techno-economic information related to power generation.

4.3. Difference between original AIM/Hub and the new integrated model, and advantages and disadvantages

We could not judge which model results are better quantitatively between the original AIM/Hub model and the new integrated model. The model performance is often assessed using the validation or comparison against the observations. For this case, there is no true value for the future scenarios that enable us to judge the model performance. Moreover, even if we compare with the limited historical period of a few years, such as from 2020 to 2022 (this is because the model integration starts from 2020), that neither helps nor guarantees the performance of future scenarios.

However, we can argue the advantages and disadvantages, qualitatively. One major advantage of using the integrated model is that energy system results have relatively detailed technological resolution and consider macroeconomic feedbacks, which may be valuable. The new integrated model can answer more detailed energy system-related questions than the original AIM/Hub model. The detailed assessment of technology and energy services is a great advantage that will allow the new model to advance research that simultaneously considers the details of economic sectoral behaviors and technologies. For example, the energy demand side of the AIM/Hub model does not explicitly distinguish changes in energy service and energy technologies, but that distinction is possible under this new framework. Hydrogen consumption is difficult to represent in the original AIM/Hub model, as future hydrogen demand should occur for specific energy services, such as steel furnaces and ships, which cannot be represented with a conventional CES function. Those technological details are well represented in the new framework. On the energy supply side, the power system adjustment function, which is needed when the variable renewable energy share is high due to implementation of gas-fired power, batteries, curtailment, and hydrogen, is complex and CGE models may be unable

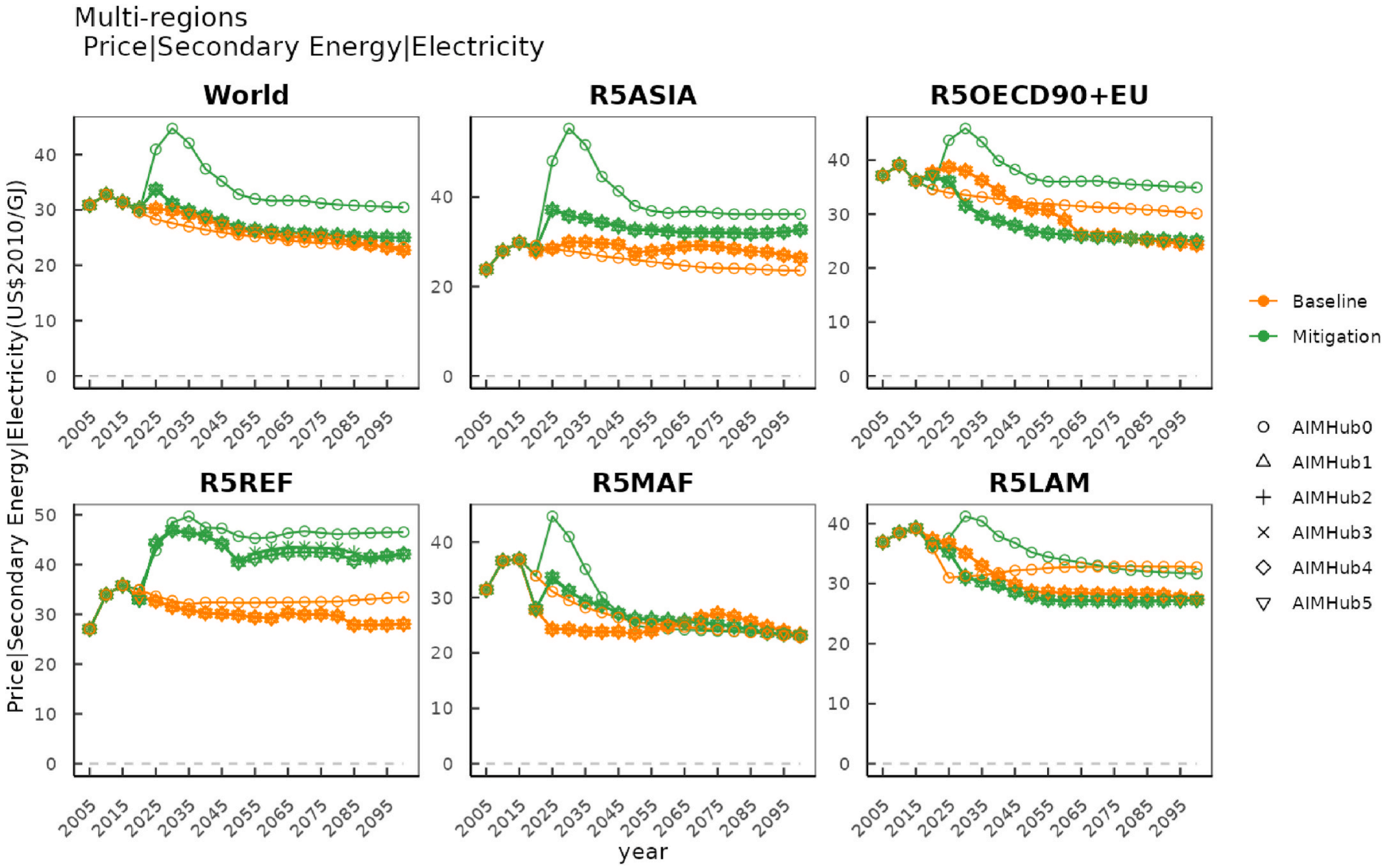

Fig. 7. Price of electricity in five aggregated regions and the global total.

to represent these technologies. However, the new model can easily consider changes in these technologies. Moreover, the speed of the shift to the renewable energy is faster than the original CGE model which has been reported in the results section is one of the advantages using the energy system model since CGE model might have been recognized as conservative model that has difficulties in radical changes in the energy system.

The main disadvantage of the new model framework is an increase in computational time and computational resource requirements. Iteration increases the time needed to obtain outcomes. We used a Xeon Gold 6326 processor (Intel, Santa Clara, CA, USA), and the computational time was around 1.5 days for five iterations. In most cases, the considerable benefits of the new model outweigh its costs.

5. Conclusions

We developed and assessed a new global AIM framework, integrating CGE (AIM/Hub) and energy system (AIM/Technology) models. This modeling framework has a great advantage enabling to have detailed representation both in energy system and economic system. The model outputs are well converged at five iterations. Moreover, the third-iteration results provide a good approximation of the final results. We also identified the extent to which variables differ between the integrated model and the original stand-alone models. The energy volume terms, such as energy supply by technology and energy consumption by sector and fuel type, are similar to those in stand-alone AIM/Technology. At the same time, the macroeconomic responses to climate change mitigation strategies differ from the original AIM/Hub as well as among regions. These differences in macroeconomic responses are primarily due to the model's assumptions related to energy-related investment and partly due to the differing primary mechanisms driving energy system changes between these two models (total system cost optimization versus non-linear equilibrium).

Finally, we suggest some future potential research topics based on this study, which can be interpreted as limitation of this study. First, while acknowledging that this framework is applicable, the assumptions for the treatment of investment should be investigated in greater depth, as those aspects are not well harmonized and could considerably influence climate policies. Second, we tested only one socioeconomic assumption, namely SSP2. However, extending this model to the other socioeconomic conditions may lead to different situations and thus may require more than five iterations. Third, regarding the interaction with land use, energy system behavior affects bioenergy and afforestation potential. However, in this study, we did not input this interaction into AIM/Technology. Considering this linkage would require integration of a gridded land-use model (AIM/PLUM), which should be addressed in the future.

Software availability

Software name: AIM/Hub, AIM/Technology and integration tool.
Developer: Shinichiro Fujimori, Ken Oshiro.
First year available: 2023.
Program language: GAMS, R and bash.
Cost: free.
Software requirement: GAMS (CONOPT, PATH and CPLEX), R.
Availability:

The AIM/Hub code is implemented in GAMS, whereas code management is done using shell script. The AIM/Hub 2.3.19 code is archived at Zenodo (https://doi.org/10.5281/zenodo.8368468). The technical model documentation is available from https://doi.org/10.5281/zenodo.8366820. The input data for the AIM/Hub is available from https://doi.org/10.5281/zenodo.8365324. The data includes the data which is purchased from third parties and therefore currently password protected.

The source code of AIM/Technology is available at https://github.com/KUAtmos/AIMTechnology_core, and the v2.1.1 code is archived at https://doi.org/10.5281/zenodo.8401421. The technical model documentation is available at https://kenoshiro.github.io/AIM-Technology-doc/. The input data for the AIM/Technology is available from (https://doi.org/10.5281/zenodo.8401547). The data includes the data which is purchased from third parties and therefore currently password protected.

The AIM/Hub and AIM/Technology integration tool is archived at Zenodo (https://doi.org/10.5281/zenodo.8368434). After downloading the integration tool, the user should make directory as "./Model" under the same directory and locate the AIM/Hub and AIM/Technology models into that directory. Within the directory of AIM/Hub which is named as AIMCGE, there is directory "data" and the input data for the AIM/Hub should be located under that directory.

The GAMS code, results, and requisite scripts to produce the figures shown in this paper are archived at Zenodo (https://doi.org/10.5281/zenodo.8312685).

CRediT authorship contribution statement

Shinichiro Fujimori: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Ken Oshiro:** Writing – review & editing, Software, Methodology. **Osamu Nishiura:** Software. **Tomoko Hasegawa:** Writing – review & editing. **Hiroto Shiraki:** Writing – review & editing.

Declaration of competing interest

There is no conflict of interest between the authors.

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.envsoft.2024.106087.

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