TOPICAL REVIEW

Robust climate change research: a review on multi-model analysis

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Abstract

Significant differences in key results across the various climate models and integrated assessment models (IAMs) represent a critical challenge to reliable scientific findings and the robust design of climate policies, which leads to an enormous amount of attention and the urgent call for a multi-model study. In this paper, we develop an integrated literature–survey framework by combining the typical content analysis with a simple statistical analysis to systematically examine the developing trends of IAM-based multi-model studies and explore the model-robust climate policy findings; we also conduct an extended analysis to identify the role of a multi-model approach in global warming and other global change research by employing co-citation network analysis. The results reveal that multi-model comparison and ensemble are effective methods to explore reliable scientific findings and yield robust policy conclusions. The current multi-model studies are sparse as a whole, especially for IAM-based climate economic and policy research; future multi-model works, at both the global and regional levels, are therefore promising. We observe that the developed countries (the EU and the US) dominate the current multi-model study, which could be proved by the number of primary IAMs developed, frequency of models adopted, and number of works published. Addressing the risks of global warming relies on reliable scientific research and robust climate policy design, particularly for the developing large emitters, which heavily depends on consistent efforts toward primary model development and comprehensive cooperation with state-of-the-art model teams all over the world.

1. Introduction

Given the worsening of global warming, climate change has attracted increasing attention from academia, industry, and branches of government (Vardy et al 2017), which sufficiently reflects the growing demands of all circles of the community on substantial scientific research and decision-making on climate change. In effect, scientific studies on climate change are the cornerstones of policy making and involve several key aspects: scientific basis, facts and evidences of climate change, climate impacts and adaptation, and climate change mitigation (IPCC, 2014). Generally, mitigation and adaptation are the two core channels to cope with climate change risks; these two topics, therefore, have become the main focuses of current climate change research. For mitigation, the general interests include analysis of emission trajectories, assessment of mitigation costs, design of specific policies, and options of available low-carbon technologies. (Edenhofer et al 2010, Tavoni et al 2014, Anthoff et al 2016); When considering adaptation, the research problem focuses on the evaluation of the adaptation effect, analysis of adaptation costs, exploration of accessible adaptation, and potential interactions between mitigation and adaptation (Duan et al 2017, Enríquez-de-Salamanca et al 2017).

From the perspective of methodology, the majority of extant climate policy studies are based on integrated assessment models (IAMs), which uniquely feature an examination of the complex interactions among the macro economy, energy, and climate systems (Popp 2004, Tol 2006, Sassi et al 2010). These interactions play crucial roles in the development of future climate change policy (Hope 2005, Van Vuuren et al 2011, Duan et al 2014). First found in the 1970s,
IAMs gained rapid development—except for the most famous DICE model developed by William Nordhaus (Nordhaus, 1979), there are many other IAMs, such as PAGE (Hope et al 1993) and MERGE (Manne et al 1995). By 2002, the number of widely adopted IAMs was greater than 50 (Van der Sluijs 2002). IAMs are typical top-down (TD) models, and earlier versions of these models simply and roughly consider the possible relations between economy and climate systems (Hope 2005). With the advances in modeling technology, recent IAMs have become sufficiently well developed to cover most of the climate-related response systems and variables, including natural carbon cycles, land use emissions, non-carbon emissions, local air pollution cycles, and detailed interactive feedbacks between climate and economic systems (Bouwman et al 2006, Van Vuuren et al 2011, Crost and Traeger 2014, Duan et al 2017).

There are remarkable differences in geographic scales, regional divisions, options of initial year, and time coverage, for example, across various IAMs. DICE, ENTICE, E3METL, and DEMETER are representatives of one sector (single-region) IAMs (Nordhaus 1992, Van der Zwaan et al 2002, Popp 2004, Duan et al 2013), while RICE, WITCH, and GCAM divide the world into 12, 13, and 32 regions, respectively (Nordhaus and Yang 1996, Bosetti et al 2006, Kim et al 2006, Wise and Calvin 2011). Even for the same category of IAMs, (one-sector models or multi-regional models), there is still significant discrepancies in the future projections of population and economic growth, availability assumptions of energy technologies, sets of exogenous technological advancement, and options of climate policy portfolio. For example, regarding economic growth projections, the global economy gains an eye-catching growth for the coming 50 years in DICE (Nordhaus and Szołc 2013), followed by RICE and E3METL (Nordhaus and Yang 1996, Duan et al 2015). WITCH is relatively gloomy about the world’s future economic growth (Bosello and De Cian 2014). To be specific, the baseline gross world product in WITCH by the end of this century is only 40% of that in DICE (Duan et al 2017).

Such differences in model settings, parameter estimations, and value assumptions of key variables may lead to notable differences in conclusions across various IAMs, even for the same policy problem. With regard to the widely discussed problem—examining the optimal climate policy (carbon tax) paths given the 2-degree warming-limit threshold, conclusions drew by GCAM, DICE, and WITCH reveal that the optimal endogenous paths of a carbon tax are monotonously increasing, but the tax level in 2100 will be about USD 310 per ton of carbon ($/tC) under GCAM (Thomson et al 2011), versus 914 $/tC under DICE (Nordhaus 2010), which is approximately consistent with that under WITCH (Bosetti et al 2011). Interestingly, Grimaud et al (2011) indicated that the optimal path of a carbon tax may not be monotonously increasing, but ‘hump-shaped,’ peaking at around 2050 with the level of 30 $/tC (figure 1). Their finding of a non-increasing carbon tax path is further supported by the simulation of the REMIND model (Leimbach et al 2010, Bertram et al 2015).

Considering the possible discrepancies in findings across different IAMs given the same targeted problem, exploring the underlying rules behind the differences and getting the model-robust conclusions, which should be indispensable for the government to make scientific and reliable policies, is crucial (Srinivasan et al 2017). Multi-model comparison (MMC) followed by RICE and E3METL (Nordhaus and Yang 1996, Duan et al 2015). WITCH is relatively gloomy about the world’s future economic growth (Bosello and De Cian 2014). To be specific, the baseline gross world product in WITCH by the end of this century is only 40% of that in DICE (Duan et al 2017).

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was born under such a background. This method has even led to a new tendency of climate change research, and became one of the main supportive methodologies for Group I, II and III reports of the Intergovernmental Panel on Climate Change’s (IPCC’s) fifth assessment report (AR5) (Hof et al 2012, Kriegler et al 2017).

The developed countries had established official organization early in 1979, that is, an energy modeling forum (EMF) to coordinate the differences in model results and improve policy making; however, in approximately 2010, MMC analysis became a trendy and leading method in studies of robust climate policy (Azar et al 2010, Edenhofer et al 2010). Since then, many MMC exercises and projects have been launched throughout the developed regions, including Fondazione Eni Enrico Mattei (FEEM)-dominated low climate impact scenarios and the implications of required tight emissions control strategies, EMF series, Pacific Northwest National Laboratory (PNNL)-led Asian modeling exercise, Potsdam Institute for Climate Impact Research (PIK)-developed roadmaps towards sustainable energy futures, and assessment of climate change mitigation pathways and evaluation of the robustness of mitigation cost estimates.

However, no systematic review study has been conducted on MMC, as far as we know; and we are basically unclear about the status of MMC method development and applications, the centralized research topics, as well as the evolutionary networks of model cooperation. We therefore contribute to the existing literature in two aspects: the first is to summarize and analyze the extant IAM-based multi-model studies, capture the current literature gaps, explore some promising directions for future research, and serve as a robust and reliable resource for making science-based policy to address climate change. Meanwhile, multi-model approaches, especially for multi-model ensemble technology, play significant roles in projected changes in climate extremes, meteorology dynamics, and atmospheric physics (Lopez-Franca et al 2016, Romero et al 2017), predictive control in decarbonization engineering (Xu et al 2017), as well as assessment of air quality trends, water resources, and other global change issues (Colette et al 2011, Rao et al 2016, Myhre et al 2017, Mouratiadou et al 2018). Therefore, the second task of this review is to provide an extended analysis on multi-model ensemble projections and other multi-model-based global change issues, attempting to explore the growth trends of relevant publication and citations, identify the influential institutions in this field, and analyze the potential cooperation networks across institutions. Through this extended analysis, we expect to inform the roles of multi-model approach in the entire area of global change (beyond pure global warming), verify the findings concluded in climate change and policy studies, and provide important insights into future knowledge domains of multi-model analysis.

The remainder of this work is organized as follows. Section 2 briefly introduces the survey method we adopt. Section 3 comprises the results summary and in-depth analysis. In section 4, we perform a simple statistical analysis on the involved primary IAMs and their geographic distributions. Section 5 shows an extended study on multi-model approach by employing co-citation network and cluster analysis. The last section concludes.

2. Methodology

By following the typical literature review method of qualitative content analysis combined with a descriptive quantitative statistics, as well as simple scientometric approach (De Chazal and Rounsevell 2009, Brink et al 2016, Mao et al 2018), we developed an integrated framework to fulfill the intended tasks of this work.

Before conducting the IAM-based MMC analysis, we define key review topics, i.e. (1) analysis of the pathways of emission reductions under given climate targets, (2) energy technological deployment and policy cost assessment, (3) consistency between climate policies and energy security, (4) regional climate problems and other global change topics. This heavily relies on the long-term accumulation of related research experiences and an accurate grasp and understanding of the advances. We then collected publication data by search for keywords and topics, such as ‘MMC’, ‘integrated assessment model’, ‘climate change’, ‘carbon emissions’, and ‘energy technologies’, etc., in the ISI Web of Science Core Collection, which proves to be the most leading literature database worldwide, covering more than 12 000 of high impact peer-reviewed journals and over 160 000 conference proceedings. By searching for ‘MMC’, filtering out and refining records closely according to the four review topics, we could get around 22 publications from 2000–2017, which supports our main-body analysis on IAM-based MMC studies.

Descriptive statistical method is used to identify the hottest IAMs worldwide by examining the frequencies of models adopted in MMC studies, explore the geographic distributions of such model stars, and summarize the underlying research trends of MMC analysis. Finally, to analyze the roles of multi-model approach in climate change research, we extend the retrieving keywords and topics to cover ‘multi-model ensemble projections’ and ‘multi-model study on global change’, which results in 290 eligible publication records in the ISI web of Science database. We then employ co-citation analysis, network analysis, and clusters analysis to explore the cooperation networks of influenced institutions and research priorities of clusters based on the latest visualization platform CiteSpaceII (Wei et al 2015, Yu and Xu 2017). Co-citation analysis helps to examine frequently co-cited
publications, authors and journals and explore the cooperation networks of influenced institutions and universities; a node in co-citation network therefore denotes an article, author, keyword or institution, and a link between two nodes represents the two items are being co-cited by another item. The content and technical roadmap of this work is portrayed in figure 2.

3. Main results and analysis

3.1. Analysis of the pathways of emission reductions

Causal relations exist between the options of greenhouse gases (GHGs) emission paths and achievement of climate policy goals; essentially, the reach of a given warming target should not be governed by the emissions of some year or certain time point, but be contingent on short- and mid-term emission trajectories and budgets (Van Vuuren et al 2011, Rogelj et al 2016, Millar et al 2017). Stern (2015) argued that the most reasonable path for us to realize the 2°C warming-limit goal (with a probability of over 50%) is to decrease global GHG emissions early in 2013 by a magnitude that shrinks rapidly from 50 giga tons of carbon equivalents (GtCeq) to 35 GtCeq in 2030 and further to 20 GtCeq in 2050. The global GHGs emission budget in 2050 projected by Stern (2015) is consistent with the upper bound of emissions control defined by Van Vuuren et al (2011), which implies that the world’s total GHG emissions in 2050 should be reduced by 40%–80%, with a baseline from 2000, to maintain the average temperature rise below 2 °C. The IPCC’s AR5 on climate change gives up to 116 emission pathways, after consideration of multiple uncertainties in realizing the 2-degree warming-rise goal.

The analysis of emission paths responds to specific climate goals. The most common and unanimous goal is to limit the global average rise of temperature to below 2 °C (with respect to the pre-industrial level).

Azar et al (2010) developed an MMC framework by considering the IMAGE-TIMER, MESSAGE, and GET8 models. They argued that the achievement of the 2-degree warming-limit goal is greatly equivalent to stabilizing the atmospheric GHG concentration at 450 ppmv with a probability of 40%-90%, also equivalent to reaching the 400 ppmv target of concentration stabilization with a probability of 20%–70%. What was certain was that reaching the 2 °C goal requires that gross GHG emissions approach to zero by the end of this century, regardless of which concentration-stabilizing goal it specifically responds to (Azar et al 2006, Meinshausen et al 2006).

Rogelj et al (2015) further indicated that if we plan to realize the 2 °C target over a probability of 66%, the total emissions should be reduced to zero from 2060–2070. Then, the emissions must remain negative. By further extending the size of the considered IAM set of Azar et al (2010), Van der Zwaan et al (2013) argued that the intended national determined contribution (INDC) tasks committed in the Paris Agreement are insufficient to ensure the realization of the global 2-degree warming-limit goal, which may require the emissions to be negative throughout the latter half of this century; fortunately, the scientific community is gradually reaching a consensus on this point (Fawcett et al 2015, Rogelj et al 2016, Jackson et al 2017). Achievement of the 2-degree goal heavily depends on effective efforts and full participation of all countries, which is likely to be model-robust across all the targeted IAMs (Blanford et al 2014).

Different emission trajectories imply different emission budgets. For example, to stabilize the GHG concentration at 450 ppmv, the cumulative emissions during the entire 21st century should not exceed 1500 GtCO2eq, despite that 70% of this budget would have

Please see table B1 in appendix B for more information on the IAMs involved in this survey.
been consumed before 2030 (Friedlingstein et al. 2014). Hence, controlling GHG emissions in the short term is crucial to reach the given climate goal, particularly when we do not consider the other carbon dioxide removal (CDR) technologies, such as bio-energy with carbon capture and storage (BECCS), and that this has been proven to be model robust through Eom et al. (2015)’s MMC analysis. To explicitly examine the roles of emission budgets and paths in reaching the 2-degree warming-rise target, we organize a cross-study comparison (table 1).

Hence, the fulfillment of INDC targets in the Paris Agreement is far from sufficient for us to keep the global average warming-rise below 2 °C relative to the pre-industrial level. In spite of different possible emission pathways (with the average mitigation ratio in 2050 ranging from 43%–97% relative to 2000), achievement of the 2-degree goal requires full participation of all parties and zero emissions by the end of this century. Additionally, if short-term efforts in GHGs emission control are not effective and beyond-expected, then CDR technologies or negative emission technologies (NETs) may be indispensible to realize the 2 °C temperature-limit goal.

### 3.2. Energy technology inventory and policy cost assessment

Apart from the timing of emission controls, the evolutions of emission trajectories are driven more by the deployment and options of low-carbon energy technologies, which greatly affects the evaluation of policy costs under the given climate goals at gross and marginal levels (Luderer et al. 2013, Wilkerson et al. 2015).

Calvin et al. (2012) considered the energy technology deployment in Asia across regions and models, and they found that with respect to mitigation, most models emphasize the dominant roles of low-carbon technologies and minor roles of CCS. Van der Zwaan et al. (2013) built an MMC framework by considering GCAM, IMAGE, MESSAGE, TIAM-ECN, and WITCH models together and analyzed the possible technological diffusion paths correspond to the 2-degree warming-rise threshold. The results reveal that the annual additional capacity deployment intensity of global photovoltaic (PV) solar in 2030 must match the current capacity scale of coal plants to achieve the given climate goal, and this capacity intensity should increase exponentially until 2050. Bosetti et al. (2015) demonstrates that the development and cost fluctuations of nuclear power technology play more formidable roles than the other green energy technologies in affecting the future emission paths; therefore, it positively suggests developing new and safer generations of nuclear technology to manage the increasing risks of climate change. Notably, any single clean technology is not enough to determine the evolutions of emission paths and address the climate change problem. The availability and accessibility of technological portfolios are fundamental to achieve the 2-degree climate target (Kriegler et al. 2014).

To date, the global average temperature has risen by approximately 0.93 °C, relative to the pre-industrial level (Met Office 2015), which implies that the window to realize the common 2-degree
warming-limit goal is rapidly closing (Otto et al 2015). In this circumstance, the development of CDR and NETs, especially CCS technologies, becomes the key to realizing the 2 °C warming-control target (Jones et al 2016, Greenblatt et al 2017). The roles of these technologies are, therefore, at the center of MMC studies (Jackson et al 2017). Azar et al (2010) conducted an MMC study by employing the IMAGE-TIMER, MESSAGE, and GET models and emphasized that the inclusion of NETs significantly reinforces the effect of emission control and reduces the relative policy costs —to a large extent. Nevertheless, they suggested the government and public should not be so optimistic and dependent on the development of NETs that the positive efforts in emission controls are delayed or neglected; especially in the short term, as the development of NETs encounters a greater number of uncertain challenges than conventional non-fossil energy technologies, like wind and solar power.

Despite the crucial roles of BECCS and the other renewables, the underlying influences of NETs and nuclear power on achieving the global 2-degree warming-limit target may not be the most remarkable if seen from the perspective of policy cost, which should be largely determined by the developing performance of biomass energy, and this is likely to be model-robust (Edenhofer et al 2010). As aforementioned, achieving the 2-degree temperature rise target is strictly contingent on the positive short-term (before 2030) efforts in emissions reduction, and the period 2030–2050 is widely considered as an important stage for promoting the development of low-carbon technologies. If those crucial periods were missed, we would have to place all our hope on the NETs, which will make us rather passive in hedging against the coming risks of climate change (Eom et al 2015). More MMC studies on this topic are summarized in table 2.

Policy costs directly rely on the given climate targets; however, they are highly sensitive to the options of energy technologies and technology portfolios (McCollum et al 2014). Climate policy in this context mainly refers to carbon pricing, and the corresponding cost means both the level of carbon tax (social cost of carbon, SCC) and gross domestic product (GDP) loss associated with carbon abatement. Edenhofer et al (2010) established an MMC analysis framework by considering a series of IAMs, that is, E3MG, MERGE, REMIND, POLES, and TIMER, and concluded that the total policy cost accounts for approximately 2.5% of the cumulative GDP for achieving the 400 ppmv concentration-stabilizing goal, versus 0.8% for the 500 ppmv concentration stabilization goal. Van der Zwaan et al (2013) made an MMC analysis on policy costs. They obtained a model-robust conclusion that the cumulative cost from 2010–2050 is up to USD 50 trillion (Tri$) to reach the 2-degree climate goal (in constant 2005 prices), despite significant differences in technology inventory and cost consumptions across various IAMs.

Considering the full availability of all energy technologies, Eom et al (2015) evaluated the cumulative policy cost for stabilizing the atmospheric GHG concentration at 450 ppmv to be 13.5 Tri$ (2005 price); when moving the concentration limit to 550 ppmv, the corresponding cost falls to 6.3 Tri$. Based on the DNE21+, GCAM, MERGE, and WITCH models, Aldy et al (2016) argued that the average SCC is about 57 $/(tCO2)-eq (2015 price), given the Paris agreement targets and this value is estimated to be only 40% of that under the 2-degree warming-limit goal. Additionally, Jewell et al (2016) compared the policy cost under the US’s energy independence target with that under the INDC target. They indicated that the policy costs for reaching these two policy targets are roughly the same; however, they should be remarkably lower than the corresponding costs for achieving the global warming-rise goal of 2 °C warming-rise goal, and this is in agreement with the relative finding in Tavoni et al (2014). Furthermore, climate metrics, like global warming potentials and global temperature change potential, may also play a significant role in the mitigation strategies and policy costs (Harmsen et al 2016).

Despite the great emphasis on the significant roles of CDR or negative emissions technologies in achieving the global 2 °C warming-limit goal, the aforementioned research also indicates that the policy makers should not be over-optimistic to the deployment and performance of such technologies. On one hand, the development of CDR or NETs encounters more uncertainties on potentials, costs and technological progress, as compared to that of low-carbon technologies and renewables, like hydropower, nuclear, biomass, wind and PV solar, which proves to be expanded rapidly in recent years and more realistic to cope with global warming. On the other hand, too much dependence on NETs actually supports the attitude of ‘wait-to-see’ and may lead the effective short-term efforts in emission control to be delayed or neglected; if such crucial periods of emission reduction were missed, we will be rather passive in response to the possible climate damage risks.

Policy cost assessment is one of research centers of IAM-based multi-model analysis. The assessed policy costs vary significantly across different models under the given climate goals, which could be largely explained by the differences in model assumption, parameter setting and technology inventory. The model-robust finding is that the cumulative cost to attain the 2-degree warming-rise target would become remarkably higher if no effective short-term efforts in emissions mitigation were made, and this cost might be several folds of that to fulfill the tasks of INDC in the Paris Agreement.

3.3. Relationships between climate policy and energy security

The implementation of climate policies greatly mitigates advert climate damages and brings significant
Table 2. MMC studies: roles of energy technological options in emission controls and achievement of climate targets.

| Models involved | Technology included | Problems focused |
|-----------------|---------------------|-----------------|
| Aldy et al (2016) | DNE21+, GCAM, MERGE, WITCH | No specific focus | Evaluated the SCC and gross policy costs associated with the INDC tasks and 2 °C warming-rise limit |
| Bosetti et al (2015) | GCAM, WITCH, MARKAL-US | Nuclear, Solar, Biofuels, CCS, etc | Explored the possible impacts of technological deployment and cost uncertainties on evolutions of emission paths |
| Edenhofer et al (2010) | E3MG, MERGE, REMIND, POLES, TIMER | Nuclear, Biomass, Biomass with CCS, Fossil with CCS | Assessed the technical feasibility and the resulting policy costs for reaching the given climate policy targets |
| Eom et al (2015) | IMACLIM, DNE21+, REMIND, IMAGE, MERGE-ETL, MESSAGE, POLES, GCAM, WITCH | CCS, Renewables, Biofuels, Nuclear, Efficiency | Analyzed the effects of short-term less-than-optimal policies on climate goals, also focused on the roles of technological development and energy decarbonization |
| Jewell et al (2016) | MESSAGE, IMAGE, TIAM-ECN, REMIND, WITCH | Crude oil, natural gas, coal, biomass, biofuels, hydrogen | Estimated the possible co-benefits of energy security arising from the implementation of climate policies |
| Krieger et al (2014) | GCAM, FARM, MERGE, Phoenix, EC-IAM, IMAGE, TIAM-WORLD, IMACLIM, MESSAGE, POLES, REMIND, DNE21+, AIM-End use, GCAM-IIM, BET, WITCH, GRAPE, ENV-Linkages | Energy efficiency, CCS, nuclear, wind power, Solar, biomass | Investigated the roles of technological development and possible portfolios in long-term evolutions of emission trajectories, and made a MMC analysis on potential policy costs (macro-economic loss) for stabilizing the atmospheric GHGs concentration at 450 and 550 ppmv |
| McCollum et al (2014) | BET, GCAM, POLES, MERGE, REMIND, WITCH, TIAM-WORLD, MESSAGE, IMAGE, IMACLIM, GRAPE, EC-IAM | Coal, oil, natural gas, CCS | Examined the effects of price fluctuations of fossil fuels and resource constraints on evolutions of global energy system, and discussed the interactions between climate policies and energy security, given the 2 °C warming-limit target |
| Van der Zwaan et al (2013) | IMAGE, MESSAGE, GCAM, TIAM-ECN, WITCH | Fossil fuels, coal-ccs, gas-ccs, biomass-ccs, nuclear, biomass, solar, wind, hydrogen | Studied the technological diffusion patterns under the 2 °C warming-rise threshold, and the required deployment capacities of low-carbon alternatives for reaching this goal |
| Wilkerson et al (2015) | EPPA, GCAM, MERGE | Fossil fuels, gas-ccs, oil, solar, biomass, biomass-ccs, hydro, wind, nuclear, geothermal | Considered the possible roles of carbon pricing in energy restructuring of the US, special emphasis were put on the sensitivities of energy technical system to carbon pricing |

co-benefits to energy security, including the reduction of energy trade volume and improvement of energy intensity (Jewell et al 2013, 2014, von Stechow et al 2015). These co-benefits will decrease the economic costs resulting from climate policies (McCollum et al 2011, 2015). Early in 2006, Michael Grubb and his group had found a high consistency between the UK’s low-carbon goal and diversification target of power system. They emphasized that implementation of low-carbon policies would remarkably enhance the diversity of the power supply (Grubb et al 2006). Hence, the potential relations between climate policy and energy security have attracted considerable attention in MMC studies.

McCollum et al (2014) examined the possible influences of fossil resource endowment and climate policies on energy security by employing one dozen typical IAMs (table 2). The results demonstrate that the positive effects of mitigation policies on energy security are mainly revealed in the short term, including the reduction in energy trade volume and increase in energy diversity. The potential role of energy efficiency enhancement in improving energy security in the context of climate change remains an open question for further exploration. Based on five typical IAMs, that is, MESSAGE, IMAGE, REMIND, WITCH, and TIAM-ECN, Jewell et al (2016) developed an MMC analysis framework to discuss the interactions between climate policy and energy security. They stressed that the consistency between climate policy and energy security is likely to be unidirectional. For example, effective mitigation brings a considerable reduction in energy imports; conversely, proactive control of energy imports plays a neglecting role in emission reductions and deployment of non-fossil energy technologies. Thus, there might be hardly any
co-benefits of climate policies for the advocates of non-climate energy policy to support the pursuit of ambitious energy independence targets, despite this logic could help win over public support. Cherp et al (2016) organized a simple MMC analysis using WITCH and REMIND. They also found the positive effects of climate policies on energy security in the metrics of energy trades and energy diversity, particularly in the first half of this century. Implementation of mitigation policies significantly reduces the dependence of the energy supply and trades on conventional fossil fuels and GDP growth.

From the review analysis aforementioned, it is an emerging and promising direction to discuss the consistency between climate policies and energy security. In this context, energy security does not simply mean supply of oil from the conventional perspective; the metrics of energy security cover energy trades (especially imports), energy expenditures, and energy diversity of primary energy system, power and transportation systems. The multi-model analysis indicate an unidirectional consistency between climate policy and energy security, i.e. climate policies do bring significant co-benefits to energy security, on the contrary, policies of energy security play a neglectable role in addressing climate change, particularly at the global scale. Driven in large part by increasingly concern about both climate change and energy security, the studies on this topic is expected to keep expanding in the coming years, especially on the national level.

3.4. Regional studies and other global change issues
3.4.1. Regional MMC studies
Climate change is a typical global issue, and the majority of the extant IAMs and their MMC studies are on a global scale (Tavoni et al 2014), as we have surveyed. The problem of climate change also features significant regional attributes. First, there are remarkable cross-regional differences in geographic locations, climate vulnerabilities, and adaptation capacities, which leads to a variation in climate damage across countries (Parry 2009, Stern, 2015). The co-benefits of climate policies in different regions may also vary significantly (Jewell et al 2014, von Stechow et al 2015).

Second, the achievement of global climate targets definitively relies on the region-divided climate efforts on emission constraints, and policy designs; therefore, these are crucial to the fulfillment of the global emission control cap (Wende et al 2012).

A few MMC studies have focused on regional climate policy issues (table 5), and the countries involved were limited to the US, China, India, Brazil, and Mexico. Additionally, the discussed topics narrowly focused on several aspects, such as the roles of INDC-based climate policies in GHGs mitigation and technological development, consistency between climate policy and energy security, effects of mitigation mechanism options on emission controls, and policy cost estimation of regional mitigation. Hence, creating robust climate policy at the regional level urgently requires additional MMC studies that cover a greater number of countries and a broader range of topics.

3.4.2. Multi-model studies on other global change issues
Robust policy design is not only crucial for tackling the climate change problem, but for overcoming other global change problems, like local air pollution, ecological devolution, and disorders of water resource distribution (Arnell et al 2016), which yields the requirements of the current multi-model study. Furthermore, an MMC analysis framework could also be employed to discuss the mechanism design of stable climate alliance in combination with the non-cooperative game theory, and analyze the impacts of free-riding behaviors on the stability of the climate alliance (Arnell et al 2016, Lessmann et al 2015). Although many of the models involved in these studies may not purely be IAMs, most importantly, all reflect the significance of the MMC or ensemble method for obtaining reliable scientific findings and making robust climate policies (Palosuo et al 2012, Vetter et al 2015, Xu et al 2017, Mouratiadou et al 2018).

To be specific, Rao et al (2016) established an MMC framework by including seven typical IAMs, that is, TM5-FASST, AIM/CGE, GCAM, IMAGE, MESSAGE, REMIND, and WITCH. They confirmed the positive effects of climate policies on improving local air pollution. This positive effect includes a 40% reduction of the crowd exposed to particulate matters pollution. Further, they found that the uncertainties associated with market failure in emission externalities could be largely offset by emission controls and the policy portfolios of technological incentives. By using three typical IAMs, i.e. GCAM, IMAGE and MESSAGE, Smith et al (2016) studied the similarities and differences in future aerosol emissions at the sectoral level, and traced the differences to specific characteristics of reference case, assumptions on technology deployment and emission controls.

Palosuo et al (2012) estimated the soil carbon stock by adopting five soil-only models (Q, ROMUL, RothC, SoilCO2/RothC, Yasso07) and reported the possible sources of the results’ differences and uncertainties. Schmitz et al (2013) discussed the issues of agricultural land use under climate change by using a set of global agro-economic models: four partial equilibrium and six general equilibrium models, and they emphasized that the most remarkable uncertainties in model results are related to differences in the costs or substitution elasticities of land expansion, assumptions on bio-energy demand, and the endogenous productivity responses. Rosenzweig et al (2014) also assessed the possible agricultural risks of climate change for major crops across seven global gridded crop models, five global climate models. By incorporating the HBV, SWIM, and VIC models, Vetter et al (2015) discussed the possible influences of climate
change on river discharge under four RCPs. They argued that the sources of their results’ uncertainties vary as the targeted basin changes. Based on four energy economic models, Srinivasan et al. (2017) considered India’s water consumption and withdrawals problems resulting from the transformation of the power system under its committed carbon intensity goal. The results reveal that development of wind and PV solar helps to reduce water consumption, whereas deployment of nuclear and hydropower has the opposite effect. Overall, the increase of water withdrawals associated with the development of power technologies could be greatly offset by adopting water-saving cooling technologies. Iverson et al. (2017) investigated the statistical relations among key attributes for 30 species in the eastern US by using typical species distribution models. They stressed the importance of robust policy assessment on the roles of climate change in species’ evolution.

Actually, as compared to the application in the field of climate economics and policy analysis, the development and adoption of multi-model approach started earlier in forecasting climate extremes, assessing air quality, nexus between climate change and

### Table 3. Summary of regional MMC studies.

| Numbers | Models adopted | Regions | Main findings |
|---------|----------------|---------|---------------|
| Calvin et al (2012) | GCAM-IM, AIM-Enduse, DNE21+, EPPA, GCAM, GEM-E3, GRAPE, MERGE, POLES-IPTS, MESSAGE, Nepal-MARKAL, Phoenix, REMIND, WITCH, IMAGE, etc | Asia | Emission pathways under carbon constrains vary significantly across regions and models, and the aggregate regional carbon emissions are not sensitive to changes in urbanization trends, but sensitive to variations in energy intensity and income; stringency of local climate strategies varies more across regions than models |
| Chen et al (2016) | IPAC, GCAM, REMIND, WITCH | China | The future course of action for China to cope with the risks of climate change should transfer to macro-economic transformation, technological innovation and energy decarbonization |
| Jewell et al (2013) | GCAM, IMAGE, MESSAGE, REMIND, WITCH, TIAM-ECN | The US, India, the EU | The enforcement of climate policies leads to reductions of energy imports and resource extraction, and increase of energy diversity |
| Johansson et al (2015) | FAIR, TIMER, DART, CEEPA, China MARKAL, MARKAL-India, IEG-CGE, | China, India | There are significant differences in the effects of climate policies, what is model-robust is that China’s cumulative emission reduction before 2050 will far larger than that of India |
| Kober et al (2016) | TIAM-ECN, POLES, TIAM-WORLD, GCAM | Latin America | Climate policy will lead to a increase of investment in low-carbon technologies, like solar, wind and CCS; the annual additional investment scale of Latin America would reach 21 billion US dollars in 2050 for realizing the 2-degree warming-limit goal |
| Lucena et al (2016) | EPPA, GCAM, Phoenix, TIAM-ECN, POLES, MESSAGE-Brazil | Brazil | Low-level carbon tax and less-strict emission constraints play rather limited role in reducing emissions; the main contributor of mitigation is the remarkable deployment of biomass, wind power and CCS, in addition to direct decrease of fossil fuels demand |
| Veysey et al (2016) | GCAM, TIAM-ECN, IMAGE, Phoenix, POLES, EPPA | Mexico | The reach of Mexico’s domestic mitigation goals with acceptable costs heavily relies on the decarbonization of transportation and power systems, and flexible options of energy portfolio |
| Wilkerson et al (2015) | EPPA, GCAM, MERGE | The US | Carbon pricing significantly affects the timing of carbon peaking, and extent of this impact depends on the specific policy design and evolutions of energy technological system |
| Zhang et al (2015) | LEAP, WITCH, C-GEM, EPPA, MARKAL, Haiku, GAINS-MESSAGE, MERGE, GAINS, etc | China | The literature remains sparse on assessing the underlying co-benefits arising from climate policies, and future research emphasis should be put on policy integrated effects, energy restructuring and multiple uncertainties |
water sources, and examining the possible influences of surface ozone and other global change risks (Colette et al 2011, Langner et al 2012, Myhre et al 2017). To further explore the roles of multi-model framework (including IAMs, other climate models, atmospheric dynamic models, and meteorology models, etc) in the entire field of climate change, we will conduct an extended in-depth analysis on the multi-model studies, involving development trends, priorities of research focus, and institution cooperation networks in the later section 5.

4. Trends of IAMs’ development and research

To further explore the possible gaps of MMC studies in the fields of integrated modeling and climate policy analysis, we conduct a simple statistical analysis on the IAMs involved in this survey. If taking no account of the related literature on other global change issues, we get 22 MMC studies in total, involving 48 primary and secondary IAMs; the frequency of the model adopted is 167 (figure 3)\(^9\). As observed in figure 3, a GCAM developed by the PNRL, the TIMES integrated assessment model (TIAM) and a WITCH built by FEEM are the most widely used ‘model stars,’ with their probability of adoption accounting for 10.2%, 9.0% and 8.4%, respectively.

To be specific, GCAM features its comprehensiveness, especially the detailed descriptions on the agricultural and land use sectors, whereas TIAM and WITCH are characterized by its relative rich technical details and the flexible mechanisms of mitigation and adaptation. These are followed by REMIND, IMAGE, MARKAL, MERGE, and MESSAGE, which have been, correspondingly, developed by the PIK, the Netherlands Environmental Assessment Agency (PBL), Brookhaven National Laboratory (BNL) and Nuclear Research Center (KFA), Allan S Manne at Stanford University, and the International Institute of Applied System Analysis (IIASA); they are all adopted by 9–10 times. Furthermore, the typical TD general equilibrium models, like POLES and EPPA, are also widely used in the extant MMC studies. The other famous IAMs, such as Phoenix, TIMER, DNE+21, and GAINS, have been used four in the reviewed MMC studies. The remaining 29 IAMs, like RICE, E3MG, and WorldScan, are referred to as one-time-used models.

Additionally, we analyze geographical distributions of the adopted IAMs (figure 4). The EU’s model research strength is the strongest by both metrics of number of the developed IAMs and the frequency of use of these models. Specifically, there are four IAMs in the Netherlands: IMAGE, WorldScan, STACO, and TIMER; four IAMs in Germany: MARKAL, REMIND, EC-IAM, and DART; and two in Austria (GAINS and MESSAGE) and the UK (E3MG and FUND). Moreover, the typical frequently adopted IAMs: WITCH and TIAM, were also built or developed in Europe. IAMs’ research level of the US closely follows the EU. Several ‘model stars,’ such as GCAM and MERGE, originated in the US, and there are many other representative IAMs in this country, including one of the earlier IMAs, RICE, famous general equilibrium models, EPPA and Phoenix. Seen from the Asia, Japan performs much better than the other countries in the strength of IAM research, with four IAMs developed: DNE21+, BET, AIM-Enduse, and GRAPE. China and India are typical followers in the field of IAM research, and the majority of the IAMs used in these two countries are derived and secondary, including China’s GAINS-AIM and China MARKAL (Chen 2005, Dong et al 2015) and India’s MARKAL-India and GCAM-IIM (Shukla 1997, Shukla and Chaturvedi 2012). China has made great strides in integrated models’ development and research during the past decade, especially in the area of single-sector IAMs and computable general equilibrium models (Jiang et al 2010, Duan et al 2013, Chen et al 2016). We only consider the IAMs adopted in the MMC studies in this statistical analysis, while taking no account of many other famous IAMs, like DICE, DEMETER, and E3METL (Nordhaus 1992, Nordhaus and Boyer 1999, Gerlagh and Van der Zwaan, 2002, Duan et al 2013, 2015), which are typical one-sector models and seldom adopted in current MMC studies.

5. Extended analysis on multi-model global change studies

To further explore the roles of multi-model approach in addressing global change issues and echo the findings summarized from simple statistical analysis in section 4, we provide an extended analysis in this section. The extension involves two aspects: first, we extend the main keyword combinations from ‘MMC’, ‘climate economics’, ‘energy technology’, and ‘policy assessment’ to cover ‘multi-model ensemble’, ‘projection’, ‘predictive control’, and ‘environmental and global change’ when retrieving in ISI web of Science database, this leads to 290 refinement records between 1998–2018, of which 109 publications are related to ‘multi-model ensemble’, 21 for ‘water resource...
change’, 11 for ‘energy and climate engineering’, and more than 120 for other ‘atmospheric, geographic and environmental change’; because a large proportion of articles are interdisciplinary, the numbers summed here for each category should overlap. Second, we use co-citation and clusters analysis to examine the influenced institution networks and research priorities of topic clusters based on CiteSpaceII platform.

5.1. Analysis on citation growth and publication distribution

Seen from figure 5, we could find that multi-model study seems to be a late starter in the field of climate change, and the first publication appears in 2002; it gradually becomes prevalent only in recent 5 years with the increasing voice of robust scientific and policy findings, and the total amount of publications is still limited. The multi-model study raises great concern in the field of climate change. For example, there is only 10 relevant publications in 2008, while the total citations of such works reaches 166; when moving to 2017, the numbers of publications increase to 42, and the citations exponentially grows to 1400.

Table 4 summarizes the information of top-15 highly published journals of multi-model studies and the geographic distribution of the corresponding
publications. The top-3 leading journals are in the areas of climate, atmospheric chemistry and climatology, which reflects the fact that climate economics and policy studies may be far from dominant in the field of climate change. As for IAM-based climate economic and policy issues, Energy Economics, Energy Policy and Energy Journal are the most frequent and influenced journals. Seen from the geographic distribution of publications (columns 4-5 in table 4), Europe performs as the center of multi-model climate research, especially for Germany, the UK, Italy and the Netherlands; and the US leads the study of multi-model analysis at the country level. This is largely in line with the findings obtained through survey on IAM-based MMC research (section 4), and what is different is that China becomes one of countries that publish the most in the field of extended multi-model global change studies.

5.2. Influenced institution analysis
As for IAM-based climate economic and policy research, PNNL, ECN, FEEM are the most influenced institutions, followed by PIK, PBL and IIASA (section 4); the situation changes when extending the multi-model methodology to investigate the global meteorology, climatology, atmospheric physics and chemistry, water resources and other environmental change issues. As shown in figure 6, the most influential institution is Max Planck Institute for Meteorology (MPI-M), as an early starter\(^\text{11}\), MPI-M has published 20 articles in the field of multi-model analysis; National Center for Atmospheric Research (NCAR), Utrecht University and PIK also play leading roles in multi-model climate studies, each with 19 publications affiliated. The institutions that are active in IAM-based multi-model research, such as IIASA, PNNL and PBL, still shine in the extended climate study of multi-model approach. As compared to China’s weak performance in multi-model climate economic and policy studies due to lack of influential primary IAM model, Chinese Academy of Sciences (CAS) rises to the top-5 institutions in the extended climate change research, whose number of publications reaches 18. Through refining the network we could further explore that most of the institutions in the US and Europe closely cooperate with each other, especially among MPI-M, NCAR and Utrecht University; on the contrary, cooperation is scarcely happened between CAS and other institutions, which should be a dominant obstacle for the long-term growth of institution influence.

5.3. Research clusters in multi-model global change area
Figure 7 depicts the visualization of research clusters in extended multi-model research area. It is easy to observe that the colors of the clusters do change over time, which implies that the research priorities of multi-model study are time-varying. Clusters labels are extracted and refined from titles, abstracts and keywords of the retrieved publications (Yu and Xu 2017). Cluster #0 and Cluster #1 are relatively old ones, and Cluster #4, Cluster #5 and Cluster #6 are fresh ones. This means that earlier multi-model research focuses more on multi-model ensemble approach in theory and global warming pattern in application; attentions on IPCC scenarios have long been attracted, from B1, B2, A1B and A2 scenarios in the special report on emissions scenarios to the shared socioeconomic pathways (SSPs) in the fourth assessment report (AR4) and updated SSP scenarios in AR5. In recent years, great interest of the researchers in the multi-model study area has been moving to IAM-based multi-model assessment and comparison, and consistency between climate change and energy transition and security. Besides, the coupled model intercomparison

\(^{11}\) The color bar on the top of the chart changes from dark to light, denoting the year of publications from early to late between 1998-2018.
projects act as one of formidable platforms to conduct multi-model global change studies, particularly at the regional scale, such as east Asia and southeast Asia.

6. Conclusions and discussions

Driven by the urgent needs of reliable scientific findings and robust policy-making, multi-model analysis, especially IAM-based MMC, has been paid considerable attentions in forecast of climate extremes, assessment of climate change risks, analysis of emission paths, and mechanism design of mitigation and adaptation (Tavoni et al 2014, Srinivasan et al 2017, Zhang et al 2015). On this basis, we conducted a survey on the extant multi-model studies in this work, to systematically examine the research status of the multi-model method, conclude the model-robust findings, and explore the possible gaps for future steps.
6.1. Lessons learned from the existing IAM-based MMC research

First, MMC is a more effective approach for us to find the rules behind discrepant model results and produce model-robust policy conclusions, compared with the conventional single-model method. Although these findings are still relatively robust to the chosen sets of IAMs, they are undoubtedly crucial to making robust policy. To be specific, we observed several model-robust findings based on the existing MMC research:

- Achievement of the 2-degree warming-limit goal requires a positive effort and full participation of all emitters worldwide;
- Effective and beyond-expected emission reductions in the short term (before 2030) may be indispensable for reaching the warming-rise goal of 2 °C, especially when the development of the performance of CDR methods and NETs are not promising;
- Rapid development of crucial renewables, like wind and PV solar power, and typical CDR technologies, such as CCS and BECCS, are a reliable technical guarantee for limiting the rise in temperature within the given 2 °C threshold;
- Completely fulfilling the tasks committed in the INDC plans is far from enough to assure the realization of the 2-degree temperature-limit goal, and the policy cost under the INDC tasks is much lower than that under the given global threshold target.
- The implementation of climate policy does bring co-benefits to energy security and local air quality, at least at the global scale.

Second, MMC analysis helps us determine the sources of results’ uncertainty, which contributes to model updating and simulation improvement. Through our survey we summarize several key sources of the model and result uncertainties, including the differences in model structures (BU or TD), estimation of key parameters (e.g. substitution elasticities between production inputs, substitution capabilities between energy technologies), projections on future economic and population growth, availability and options of technology portfolios, and assumptions on the pure time preference and discount rates. Generally, projections on future economic and population growth are fundamental and comprehensive factors that closely relate to almost all climate policy research (Gillingham et al 2015, Kriegler et al 2017). If we focus on assessing the likelihood of reaching the 2-degree warming-rise target, the assumptions about the timing of emission reductions and technical feasibility perform more crucial (Chen et al 2016). However, if the concern is to evaluate the policy costs or benefits associated with some given climate goals, the values of the pure time preference and discount rates should be paid considerable attention (Hof et al 2012, Duan et al 2017).
Third, the existing IAM-based MMC research has focused on a limited number of topics, with the majority restrained to the global scale. Despite a growing level of academic interest in MMC analysis, our review of the literature found only 22 articles, which could not be enough to fulfill the enormous requirements for making robust climate policy. Specifically, the extant body of MMC research confines its concerns to emission path analysis under the given climate goals, policy cost assessment, deployment of clean technologies, and consistency between climate policy and energy security and, by contrast, pays dramatically less attention to many other critical issues, such as the effects of variety of market-oriented tools (e.g. carbon tax, energy resource tax, emission trading scheme) on emission reductions and technological development, roles of multiple uncertainties on economy growth, technology availability, energy efficiency enhancement, timing of tipping points, and climate sensitivity in the realization of the global warming-rise target, impacts of optimal adaptation on avoiding climate damages, and potential interactions between mitigation and adaptation in managing the risks of global warming (Enríquez-de-Salamanca et al. 2017, Parry 2009).

Furthermore, there remains, for now, a scarcity of MMC research that focuses on regional climate policy issues, despite the equivalent importance and growing needs for robust policy making at the regional scale (Wende et al. 2012). Thus, there is an urgency to conduct more region-level MMC analysis on climate-related problems, particularly focusing on the largest emitters, such China, the US and India.

Fourth, through simple statistical analysis, we observe that the US and EU dominate the current state-of-the-art IAM research by metrics of the number of developed IAMs and the frequency with which these models are used. From the perspective of model adoption frequency, the most widely used IAMs are GCAM, TIAM and WITCH, followed by REMIND, IMAGE, MARKAL, MESSAGE, and MERGE. These IAMs include both economy-dominated TD models and technology-driven BU types, but the only characteristic they have in common is that they better bridge the modeling logics of TD and BU, and can analyze the underlying roles of energy and climate policies in emission controls.

Seen from the geographic distribution of IAMs, the majority of the primary models are overwhelmingly built and developed in the US and Europe. Many famous IAM teams are in the US, such as those at Stanford University, the Massachusetts Institute of Technology (MIT), and PNNL. The PIK in Germany, ECN, and PBL in the Netherlands play a formidable role in the advanced modeling strength of Europe. Despite the several primary IAMs developed in Japan, most MMC studies in Asia are supported by secondary IAMs, which implies that the Asian countries, including the largest emitters, China and India, may act more as followers in global integrated modeling research.

6.2. Main findings obtained through the extended multi-model analysis

Through retrieving and refining records in the ISI Web of Science database via ‘multi-model’ and ‘climate change’ related topics and keywords, we find 290 publications in total, which implies that there is considerable potential for multi-model frameworks to develop in the field of global climate change. Despite the limited amount of multi-model studies, the influences of such publications are significant. Specifically, there are only 42 relevant publications in 2017, while the total citations of such works reach 1400; and the cumulative citations from 1998 to 2018 for the whole 290 publications are 8350.

The top-3 leading journals that multi-model study published are in the areas of climate, atmospheric chemistry and climatology, which implies the fact that climate economics and policy studies may be far from dominant in the field of climate change. As for IAM-based climate economic and policy issues, Energy Economics, Energy Policy and Energy Journal are the most influenced journals. The geographic distribution of publications supports the findings obtained from the previous IAM-based MMC analysis, i.e. Europe and the US are centers of the multi-model climate change research.

Co-citation network analysis indicates that the Max Planck Institute for Meteorology (MPI-M), NCAR and Utrecht University are the most influenced institutions in multi-model study; further, as rare representatives in Asia, CAS also shines in this field. However, there are frequent and close cooperation among MPI-M, NCAR and Utrecht University, while relatively scarce cooperation is found between CAS and other institutions. Clusters analysis tells that the research priorities of multi-model study are changing over time, as a whole, from multi-model ensemble approach in theory and global warming pattern in application to IAM-based multi-model assessment and comparison, as well as nexus between climate change and energy transition.

6.3. Insights for future multi-model study

It is expected that multi-model methodology may play an increasingly important role in climate change research, not only in the specific IPCC special report on the impacts of a global warming of 1.5 °C and the related GHG emission pathways and the forthcoming sixth assessment report (AR6) (Hulme 2016), but many conventional climate policy and global change issues at both the global and regional levels (Vardy et al. 2017). There are several key challenges to future multi-model research. First, making a concerted effort to develop primary IAMs based on specific conditions,
especially for the emerging emitters, like China and India, which is the premise for these countries to conduct further region-level MMC studies. Although the majority of the extant IAMs built in the EU and US separately consider these representative emitters in their geographic divisions, the modeling basis (e.g. data availability and accessibility, accuracy of parameter estimation, projections on growth of economy, and energy demand) could not be more sufficient and reliable as the natives (Duan et al 2017). Besides, given the great importance of robust sector-scale findings to macro-scale climate policy making, it should be promising to develop problem-oriented and sector-scale integrated models and conduct corresponding MMC policy studies.

Second, building stable and enhanced cross-country, cross-team collaborative networks before developing an effective multi-model analysis framework is crucial, which is notably challengeable if we plan to incorporate additional model teams (Gillingham et al 2015). A greater number of virtuous and incentive mechanisms must be well developed to spur the research interests of all the participants, reduce uncertainty in model outcomes, and explore the effective way to communicate those model projection uncertainties between different model teams, and between scientists and policy makers, especially if we reach a consensus across all stakeholders.

Third, how to choose the competent model from the intended model sets to successfully fulfill the research tasks is another key challenge. In addition to the wills of the modelers, applicability of such models to specific targeted problems is also a crucial consideration of model options, including solidifying model structures, data availability at the micro level, and solving feasibility, especially for IAM-based MMC frameworks and non-IAM multi-model ensemble analysis (Tavoni et al 2014, Zhang et al 2015, Lopez-Franca et al 2016, Romero et al 2017).

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Appendix A. Abbreviations for model names
Table A1. Full names of model abbreviations.

| Abbreviations | Model full names |
|---------------|------------------|
| IMAGE         | Integrated Model to Assess the Global Environment |
| GCAM          | Global Change Assessment Model |
| TIMER         | The Targets IMage Energy Regional simulation model |
| TIMES         | The Integrated MARKAL-EFOM System |
| MESSAGE       | Model for Energy Supply Strategy Alternatives and their General Environmental impacts |
| REMIND        | RRegional Model of INvestments and Development |
| TIAM-ECN      | The TIMES Integrated Assessment Model |
| WITCH         | The World Induced Technical Change Hybrid model |
| E3METL        | Energy-Economy-Environmental Model with Endogenous Technological change by employing Logistic curves |
| DICE          | Dynamic Integrated Climate Economic model |
| FUND          | The climate Framework for Uncertainty, Negotiation and Distribution |
| RICE          | Regional Integrated Climate Economic model |
| MAGICC        | Model for the Assessment of Greenhouse gas Induced Climate Change |
| MERGE         | Model for Estimating the Regional and Global Effects of greenhouse gas reductions |
| PAGE          | The Policy Analysis of the Greenhouse Effect model |
| EPPA          | The Economic Projection & Policy Analysis model |
| DNE21+        | Dynamic New Earth 21 (DNE21) model |
| ENV-Linkages  | A recursive-dynamic neo-classical general equilibrium model inter-linked across several macro-economic sectors and regions |
| POLES         | Prospective Outlook on Long-term Energy Systems |
| E3MG          | Energy-Environment-Economy Model of the Globe |
| FAIR          | The Factor Analysis of Information Risk model |
| MARKAL        | The MARKet ALlocation model |
| DART          | Dynamic Applied Regional Trade model |
| CEEPA         | The China Energy and Environmental Policy Analysis model |
| IEG-CGE       | Institute of Economic Growth-Computable General Equilibrium model |
| IAMCLIM-R     | A multi-sector multi-region dynamic-reursive growth model |
| IPAC          | Integrated Policy Assessment model for China |
| DEMETER       | DE-carbonisation Model with Endogenous Technologies for Emission Reduction |
| STACO         | The STAbility of CO2lutions model |
| CWS           | The CLIMNEG World Simulation model |
| MICA          | Model of International Climate Agreements model |
| AIM           | Asia-Pacific Integrated Model |
| BET           | Basic Energy systems, Economy, Environment, and End-use Technology model |
| EC-IAM        | European Commission Integrated Assessment Model |
| FARM          | Farm Aquaculture Resource Management model |
| IGSM          | The MIT Integrated Global Systems Model |
| GAINS         | The Greenhouse gas-Air pollution Interactions and Synergies model |
| GET           | Global Energy Transition model |
| GRAPE         | Global Relationship Assessment to Protect the Environment |
| WorldScan     | WORLD model for SScenario ANalysis |
| GEM-E3        | General Equilibrium Model for Economy-Energy-Environment |
| LEAP          | Long-range Energy Alternatives Planning model |
| TM5-FASST     | Tracer Model 5-Fast Scenario Screening Tool model |

Note: The full names of model abbreviations are not found for ENV-Linkages and IAMCLIM.

Appendix B. Supplementary information on IAMs involved in this survey
### Summary of IAMs Information

| Model name     | Model type                        | Geographical region | Affiliation                  | Sources                        |
|----------------|-----------------------------------|---------------------|------------------------------|-------------------------------|
| IMAGE          | Dynamic, process oriented model   | Global, 32 regions  | EU-Netherlands (PBL)         | Bouwman et al (2006)          |
| GCAM           | Dynamic-recursive partial equilibrium | Global, 32 regions | US (PNNL/JGCRI)              | Kim et al (2006)              |
| TIMER          | System dynamics simulation model  | Spatially-0.5 × 0.5 grid | EU-Netherlands (PBL)         | Van Vuuren et al (2011)       |
| MESSAGE        | Systems engineering optimal LP    | Global, 11 regions  | EU-Austria (IIASA)           | Messner and Strubegger (1995) |
| REMIND         | Optimal economic growth model     | Global, 11 regions  | EU-Germany (PIK)             | Leimbach et al (2010)         |
| TIAM-ECN       | Linear optimization model         | Global, 15 regions  | EU-Netherlands (ECN)         | Rosler et al (2011)           |
| WITCH          | Optimal economic growth model     | Global, 13 region-free | EU-Italy (FEEM)              | Rossetti et al (2006)         |
| E3METL         | Aggregate optimal growth model    | Global, one sector  | China (CAS)                  | Duan et al (2013)             |
| DICE07         | Updated version of DICE           | Global, one sector  | US (Yale U)                  | Nordhaus (2008)               |
| DICE2013R      | Updated version of DICE           | Global, one sector  | US (Yale U)                  | Nordhaus and Sotorc (2013)    |
| FUND 2.8+      | Aggregate optimal growth model    | Global, 16 regions  | UK                           | Tol (2006)                    |
| GCAM-IIM       | Dynamic-recursive partial equilibrium | Global, 32 regions | India (IIM)                  | Shukla and Chaturvedi (2012)  |
| MAGICC4        | Simple climate model              | Global, 12 region-free | EU (Stanford U)             | Wigley (1993)                 |
| MERGE          | Aggregate optimal growth model    | Global, 8 regions   | EU-UK                        | Manne et al (1995)            |
| PAGE2002       | Aggregate optimal growth model    | Global, 16 regions  | US (MIT)                     | Hope (2006)                   |
| EPDA           | Computable general equilibrium    | Global, 54 regions  | Japan (RIE)                  | Babiker (2005)                |
| DNE21+         | Line programing model             | Global, 50 regions-free | EU Commission               | Akimoto (2010)                |
| POLES          | Market equilibrium model          | Global, 20 regions  | EU-UK                        | EC (1996)                     |
| E3MG           | Econometric simulation model      | Global, 12 regions  | EU-Netherlands (PBL)         | Köhler et al (2006)           |
| FAIR           | Aggregated Climate policy model   | Global, 27 regions  | US                           | Den Elzen and Lucas (2005)    |
| MARKAL-US      | Energy system model               | Global, 12 regions  | EU-Netherlands (PBL)         | Fishbone and Abilock (1981)   |
| DART           | Computable general equilibrium    | Global, 12 regions  | OECD                         | Klepper et al (2003)          |
| ENV-Linkages   | Computable general equilibrium    | Global, 12 regions  | Affiliation                  | Burniaux and Chateau (2008)   |
| Model name     | Model type                        | Geographical region |                              | Sources                       |
| CEEPA          | Computable general equilibrium    | China              | China (BIT)                  | Liang et al (2007)            |
| China MARKAL   | Energy system model               | China              | China (Tsinghua)             | Chen (2005)                   |
| IEG-CGE        | Computable general equilibrium    | India              | India (IEG)                  | Paltsev et al (2012)          |
| MARKAL-India   | Energy system model               | India              | India (IIM-A)                | Shukla (1997)                 |
| IAMCLIM-R      | Computable general equilibrium    | Global, 12 regions  | EU-China (CIRED)             | Sassi et al (2010)            |
| IPAC           | Recursive-dynamic partial equilibrium | Global, 9 regions  | China (NDC-ERI)              | Jiang et al (2010)            |
| Phoenix        | Computable general equilibrium    | Global, 24 regions  | US (PSU/BU)                  | Fisher-Vanden et al (2012)    |
| STACO          | Combined game-theoretic and IA    | Global, 12 regions  | EU-Netherlands               | Nagashima et al (2009)        |
| RICE           | Modified version of RICE          | Global, 6 regions   | EU-Belgium                   | Nordhaus and Yang (1996)      |
| CWS            | Aggregated RICE model             | Global, 6 regions   | EU-Germany (PIK)             | Eckelmans and Tolkens (2003)  |
| MICA           | Extended RICE model               | Global, 11 regions  | EU-Germany (PIK)             | Lessmann et al (2009)         |
Table B1. (Continued.)

| Model name | Model type | Geographical region | Affiliation | Sources |
|------------|------------|---------------------|-------------|---------|
| AIM-Enduse | Partial equilibrium | Global, 32 regions | Japan (NIES) | Akashi et al (2014) |
| BET        | General equilibrium | Global, 32 regions | Japan | Yamamoto et al (2014) |
| EC-IAM     | Computable general equilibrium | Global, 11 regions | EU-Germany (PIK) | Kriegler et al (2014) |
| FARM       | Computable general equilibrium | Global, 15 regions | US | Rose et al (2015) |
| IGSN       | Computable general equilibrium | Global, 16 regions | US | Prinn et al (2011) |
| GAINS      | Optimization model | Global, 47 regions | EU-Austria (IIASA) | Wagner et al (2007) |
| GET        | Liner programming model | Global, 11 regions | EU-Sweden | Azar et al (2003) |
| GRAPE      | General equilibrium model | Global | Japan (IAE) | Kurosawa (2006) |
| WorldScan  | Computable general equilibrium | Global, 16 regions | EU-Netherlands (PBL) | Johannes and Corjan (2014) |

Note: 1. FUND is first developed by Richard Tol, now is co-developed by David Anthoff and Richard Tol, as the model web states, FUND has no institutional home, here we define it by the affiliation of its chief developer, Richard Tol (www.fund-model.org).
2. The model affiliations shown in this table may not be accurate home of the models; we define them in terms of affiliations of the leading developer.
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References
Akashi O, Hanaoka T, Masui T and Kainuma M 2014 Halving global GHG emissions by 2050 without depending on nuclear and CCS Clim. Change 123 611–22
Akinoto K 2010 Estimates of GHG emission reduction potential by country, sector and cost Energy Policy 38 3384–93
Aldy J et al 2016 Economic tools to promote transparency and comparability in the Paris Agreement Nat. Clim. Change 6 1000–6
Anthoff D, Estrada F and Tol R S J 2016 Shutting down the thermohaline circulation Am. Econ. Rev.: Papers Proc. 106 602–6
Arnell N et al 2016 The impact of climate change across the globe: a multi-sectoral assessment Clim. Change 134 157–74
Azar C, Lindgren K and Andersson A 2003 Global energy scenarios meeting stringent CO2 constraints: Cost-effective fuel choices in the transportation sector Energy Policy 31 961–76
Azar C, Lindgren K, Larson E and Mollersten K 2006 Carbon capture and storage from fossil fuels and biomass: costs and potential role in stabilizing the atmosphere Clim. Change 74 47–79
Azar C et al 2010 The feasibility of low CO2 concentration targets and the role of bio-energy with carbon capture and storage (BECCS) Clim. Change 100 195–202
Bahker M 2005 The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4 MIT Joint Program on the Science and Policy of Global Change, Report Massachusetts Institute of Technology, Cambridge, MA (https://globalchange.mit.edu/publication/14578)
Bertram C et al 2015 Complementing carbon prices with technology policies to keep climate targets within reach Nat. Clim. Change 5 235–9
Blanford G J, Kriegler E and Tavoni M 2014 Harmonization versus fragmentation: overview of climate policy scenarios in EMF27 Clim. Change 123 383–96
Bosello F and De Cian E 2014 Documentation on the development of the AIM hybrid model Environ. Modelling Assess. 11 1157–78
Chen W 2005 The costs of mitigating carbon emissions in China: findings from China MARKAL-MACRO modeling Energy Policy 33 885–96
Chen W Y, Yin X and Zhang H J 2016 Towards low carbon development in China: a comparison of national and global models Clim. Change 136 95–108
Cherp A, Jewell J, Vinichenko V, Bauer N and de Cian E 2016 Global energy security under different climate policies, GDP growth rates and fossil resource availabilities Clim. Change 136 63–94
Colette A et al 2011 Air quality trends in Europe over the past decade: a first multi-model assessment Atmós. Chem. Phys. 11 11657–78
Crosby B and Traeger C P 2014 Optimal CO2 mitigation under damage risk valuation Nat. Clim. Change 4 631–6
De Chaillu J and Rounsevell M D A 2009 Land-use and climate change within assessments of biodiversity change: A review Glob. Environ. Change 19 306–15
Den Elzen M G J and Lucas P I 2005 The FAIR model: a tool to analyse environmental and costs implications of regimes of future commitments Environ. Modeling Assess. 10 115–34
Dong H et al 2015 Pursuing air pollutant co-benefits of CO2 mitigation in China: a provincial leveled analysis Appl. Energy 144 165–74
Duan H B, Fan Y and Zhu L 2013 What’s the most cost-effective policy of CO2 targeted reduction: an application of aggregated economic technological model with CCS Appl. Energy 112 866–75
Duan H B, Zhang G P, Wang S Y and Fan Y 2017 Balancing China’s climate damage risk against emission control costs Mitigation Adaptation Strateg. Glob. Change 22 387–403
Duan H B, Zhu L and Fan Y 2014 Review on the integrated assessment model of energy-environment-economy for the global change J. Syst. Eng. 29 852–68 (http://cnki.com.cn/Article/CFIDTotal-XTGC2014060104.htm)
Duan H B, Zhu L and Fan Y 2015 Modeling the evolutionary paths of multiple carbon-free energy technologies with policy incentives Environ. Modeling Assess. 20 55–69
Edenhofer O et al 2010 The Economics of local stabilization: model comparison of mitigation strategies and costs Energy J. 31 11–48
Enriquez-de-Salamanca Á, Díaz-Sierra R, Martín-Aranda R M and Santos M J 2017 Environmental impacts of climate change adaptation Environ. Impact Assess. Rev. 64 87–96
Eom J et al 2015 The impact of near-term climate policy choices on technology and emission transition pathways Technol. Forecast. Soc. Change 90 73–88
European Commission (EC) 1996 POLES 2.2. European Commission DG XII EUR 17358 EN (https://ec.europa.eu/jrc/en/energy/poles)
Eyckmans J and Talke K 2003 Simulating coalitioanally stable burden sharing agreements for the climate change problem Resour. Energy Econ. 25 299–327
Fawcett A et al 2015 Can Paris pledges avert severe climate change Science 350 1168–9
Fishbone L G and Abilock H 1981 Markal, a linear-programming model for energy systems analysis: technical description of the BNL version Int. J. Energy Res. 5 353–75
Fisher-Vanden K, Schu K, Sue Wing L and Calvin K 2012 Decomposing the impact of alternative technology sets on future carbon emissions growth Asia Modeling Exercise: Exploring Role Asia Mitigating Clim. Change 34 359–65
Friedlingstein P et al 2014 Persistent growth of CO2 emissions and implications for reaching climate targets Nat. Geosci. 7 709–15
Gerlagh R and Van der Zwaan B C 2002 Endogenous technological change in climate change modeling Energy Econ. 24 1–19
Gillingham K, Nordhaus W, Anthoff D, Blanford G, Bosetti G, Christensen P, McLean H, Reilly J and Sorens P 2015 Modeling uncertainty in climate change: a multi-model comparison Joint Program Report Series Report 290 Yale University, New Haven, CT p 47 (www.nber.org/papers/w21637)
von Stechow C et al 2015 Integrating global climate change mitigation goals with other sustainability objectives: A Syntheses Annu. Rev. Environ. Resour. 40 363–94
Wagner F, Amann M and Schoepo W 2007 The GAINS optimization module as of 1 February 2007 IIASA Interim Report IR-07-004 International Institute for Applied Systems Analysis (IIAS) (http://pure.iiasa.ac.at/8451)
Wei F, Grubesic T H and Bishop B W 2015 Exploring the GIS knowledge domain using CiteSpace Prof. Geogr. 67 374–84
Wende W, Bond A, Bobylev N and Stratmann L 2012 Climate change mitigation and adaptation in strategic environmental assessment Environ. Impact Assess. Rev. 32 88–93
Wigley T M L 1993 Balancing the carbon budget. implications for projections of future carbon dioxide concentration changes Tellus B 45B 409–25
Wilkinson J T, Leibowitz B, D, Turner D D and Weyant J P 2015 Comparison of integrated assessment models: carbon price impacts on US energy Energy Policy 76 18–31
Wise M and Calvin K 2011 GCAM 3.0 agriculture and land use: technical description of modeling approach (Pacific Northwest National Laboratory PNNL, No. 20971)
Xu W D, Zhang J F and Zhang R D 2017 Application of multi-model switching predictive functional control on the temperature system of an electric heating furnace ISA Trans. 68 287–92
Yamamoto H, Sugiyama M and Tsutsui J 2014 Role of end-use technologies in long-term GHG reduction scenarios developed with the BET model Clim. Change 123 583–96
Yu D J and Xu C 2017 Mapping research on carbon emissions trading: a co-citation analysis Renew. Sustain. Energy Rev. 74 1314–22
Zhang S H, Worrell E and Crijns-Graus W 2015 Synergy of air pollutants and greenhouse gas emissions of Chinese industries: a critical assessment of energy models Energy 93 2436–50