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Perspective of comprehensive and comprehensible multi-model energy and climate science in Europe

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Perspective of comprehensive and comprehensible multi-model energy and climate science in Europe

A. Nikas [a], A. Gambhir [b], E. Trutnevyte [c], K. Koasidis [a], H. Lund [d], J.Z. Thellufsen [d], D. Mayer [e], G. Zachmann [e], L.J. Miguel [f], N. Ferreras-Alonso [f, g], I. Sognnaes [h], G.P. Peters [h], E. Colombo [i], M. Howells [b, j], A. Hawkes [k], M. van den Broek [l], D.J. Van de Ven [m], M. Gonzalez-Eguino [m, n], A. Flamos [o], H. Doukas [a, *]

[a] School of Electrical & Computer Engineering, National Technical University of Athens, Athens, Greece
[b] Grantham Institute for Climate Change and the Environment, Imperial College London, London, United Kingdom
[c] Renewable Energy Systems, Institute for Environmental Sciences (ISE), Section of Earth and Environmental Sciences, University of Geneva, Geneva, Switzerland
[d] Department of Planning, Aalborg University, Aalborg, Denmark
[e] Bruegel, Brussels, Belgium
[f] Research Group on Energy, Economy and System Dynamics, University of Valladolid, Valladolid, Spain
[g] CARTIF Foundation, Valladolid, Spain
[h] CICERO Centre for International Climate and Environmental Research, Oslo, Norway
[i] Politecnico di Milano, Milan, Italy
[j] Loughborough University, Leicestershire, United Kingdom
[k] Department of Chemical Engineering, Imperial College London, London, United Kingdom
[l] IREES, Energy and Sustainability Research Institute Groningen, University of Groningen, Groningen, Netherlands
[m] Basque Centre for Climate Change (BC3), Leioa, Spain
[n] University of the Basque Country, Bilbao, Spain
[o] Technoeconomics of Energy Systems Laboratory (TEESlab), Department of Industrial Management & Technology, University of Piraeus (UNIPI), Piraeus, Greece

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ABSTRACT

Europe's capacity to explore the envisaged pathways that achieve its near- and long-term energy and climate objectives needs to be significantly enhanced. In this perspective, we discuss how this capacity is supported by energy and climate-economy models, and how international modelling teams are organised within structured communication channels and consortia as well as coordinate multi-model analyses to provide robust scientific evidence. Noting the lack of such a dedicated channel for the highly active yet currently fragmented European modelling landscape, we highlight the importance of transparency of modelling capabilities and processes, harmonisation of modelling parameters, disclosure of input and output datasets, interlinkages among models of different geographic granularity, and employment of models that transcend the highly harmonised core of tools used in model inter-comparisons. Finally, drawing from the COVID-19 pandemic, we discuss the need to expand the modelling comfort zone, by exploring extreme scenarios, disruptive innovations, and questions that transcend the energy and climate goals across the sustainability spectrum. A comprehensive and comprehensible multi-model framework offers a real example of "collective" science diplomacy, as an instrument to further support the ambitious goals of the EU Green Deal, in compliance with the EU claim to responsible research.
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1. Introduction

The global energy and climate agenda has been progressing fast, going through different stages and co-evolved with scientific

* Corresponding author.
E-mail address: h_doukas@epu.ntua.gr (H. Doukas).

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advancements [1], as stocktaken in the assessments of the Intergovernmental Panel on Climate Change (IPCC). It has also been through significant challenges, including among others the recent rise to power of narratives that have been hostile towards energy transitions and climate action [2] and to some extent impeding international efforts; or the COVID-19 global health emergency [3] and associated recovery efforts looming large over policy prioritisation [4].

Nonetheless, the European Union (EU) has consistently taken a leading role in international climate policy [5] throughout, adopting relevant strategies in as early as 1992, and currently pushing forward an ambitious Green Deal to achieve climate neutrality by 2050 [6]. But, despite its ambition and current success in achieving most 2020 goals, the EU is not on easy track to meet its 2030 climate and energy targets [7]. This diverging trajectory is frequently attributed to governance issues [8] and challenges of monitoring nature [9]: the submission of a collective, supranational set of Nationally Determined Contributions (NDC) at the EU level requires that collective targets be appropriately disaggregated at the national level, as well as that Member States live up to their national commitments and that the Community successfully monitor progress made at both scales. So far, strong discrepancies have been observed among Member States [10]. These inter alia include renewable support schemes, bottlenecks in transmission lines, societal resistance levels, fossil fuel lock-ins, progress in energy efficiency, and prioritisation of the climate agenda, as well as misalignment of National Energy and Climate Plans (NECPs) with collective targets, as reflected in the EU action pledges to the UNFCCC. European capacity to explore the envisaged pathways to achieve its near- and long-term climate and energy objectives, therefore, needs to be significantly enhanced.

In this perspective, we briefly discuss how this capacity is supported by models, and how international modelling teams are organised within dedicated consortia and coordinate multi-model analyses to provide robust scientific evidence. We note the lack of such a structured communication channel for the diverse and highly active, yet currently fragmented, European modelling landscape and review the necessary steps to delivering comprehensive and comprehensible modelling exercises. We highlight the importance of transparency of modelling capabilities and processes, harmonisation of modelling (socioeconomic, technoeconomic, emission, and policy) parameters, full disclosure of input and output datasets, interlinkages among models of different geographic granularity, as well as employment of models that transcend the highly harmonised group of IAMs, in model inter-comparison exercises. Finally, drawing from the COVID-19 pandemic, we discuss the need to expand the modelling comfort zone, by exploring extreme scenarios, disruptive innovations, and questions across the sustainability spectrum. Progress on all these fronts will ensure that modelling is established as a critically useful tool to support the complexities of policy and decisions around rapid decarbonisation of Europe in the coming years.

2. Simulating the future: models, international consortia, and inter-comparisons

The design of a multi-dimensional set of policy instruments and measures of technological, economic, and legislative nature that altogether comprise the European energy and climate policy agenda is supported by an equally diverse set of energy system, sectoral and climate-economy modelling activities [11]. Integrated assessment modelling (IAM) exercises constitute the backbone of numerous research and innovation projects [12], aimed at assessing how specific actions can steer the world, including Europe, towards climate neutrality goals, by embracing the complex interplay between energy, economy, and environment [13].

These modelling frameworks have undoubtedly contributed to both knowledge and policy, but the extent to which they have decisively helped policymakers and supported effective governance of climate policy has long been debated (e.g. Ref. [14]). Models have been criticised over being detached from policymakers [15], featuring inflexibility to represent the diversity of policy instruments and the national focus [16], displaying limited interconnectivity among the represented subsystems [17], having little capacity to assess different types of uncertainty [18], or being opaque about modelling mechanisms and assumptions. Furthermore, emerging criticisms focus on technological representation: for example, despite the significant role of renewable energy and negative emissions technologies in a low-carbon future [19,20], many studies have questioned the realism of modelled scenarios [21,22], or highlighted current modelling limitations in adequately representing demand-flexibility, energy storage, interconnection or other flexibility required to promote penetration of renewables [23], leading to compromising modelling assumptions [24] or calling for higher resolution capacity [25,26] that incurs impractical computational costs [27], respectively. And, although the knowledge produced is contingent on the modelling perspective and carries meaning in the scientific discourse, it is nonetheless used in policy, business, and other processes outside the boundaries of the modelling world [28].

In addressing these challenges, voices within the scientific community have been calling for transformations towards a new generation of advanced modelling frameworks [23] and complementarities with other analytical approaches [29]. These voices have been heard, as reflected in a series of new, ongoing research initiatives funded by the European Commission (EC), like LOCOMOTION[1] or NAVIGATE[2] and PARIS REINFORCE[3] or ENGAGE,[4] respectively. But, as the envisaged energy transitions in Europe and worldwide require radical socioeconomic, technological, institutional, and structural changes [30] in energy supply and demand [31], there is an ever-pressing need for a diversified set of strongly coordinated modelling approaches, with collectively improved capacity and detail, to support the development and use of plural knowledge in this field. Following climate modellers' example, IAM researchers have been trying to enhance robustness and consistency of resulting policy prescriptions by instigating model inter-comparison projects [32]. These constitute exercises aimed at addressing specific research questions based on numerous models of different theory, structure, approach, and coverage [33].

Major model inter-comparison studies have been organised and successfully carried out in the context of recent EC-funded projects, like ADVANCE [34] or CD-LINKS [35], essentially forming the bedrock of the recent IPCC 1.5 °C Special Report [36]. In coordinating such efforts, energy system and climate-economy modelling teams have been organised in international, multilateral communication initiatives and consortia. Among these initiatives, Stanford's Energy Modeling Forum (EMF)[5] has the longest history and reputation of conducting multi-model exercises with a thematic (e.g. Refs. [37]) or regional focus (e.g. Ref. [38]), and bridging the policy-science gap [39]. The Integrated Assessment Modeling Consortium (IAMC)[6] was later developed to coordinate research activities within the IAM community and convene the process of

[1] https://www.locomotion-h2020.eu/.
[2] https://navigate-h2020.eu/.
[3] https://www.paris-reinforce.eu/.
[4] http://www.engage-climate.org/.
[5] https://emf.stanford.edu/.
[6] https://www.iamconsortium.org/.

producing the current generation of reference modelling scenarios [40], including the Shared Socioeconomic Pathways (SSPs) [41] and Representative Concentration Pathways (RCPs) [42]. Motivated by EMF and IAMC, regional efforts have been mobilised, like the China Energy Modeling Forum (CEMF), which recently published its first inter-comparison results [43].

But, while numerous EU research projects have also oriented on or eventually produced model inter-comparison exercises, inter alia contributing to major assessments like ADAM [44], AMPERE [24] and LIMITS [45] in IPCC AR5, there currently is no structured, multilateral communication among European integrated assessment modellers, and between them and other stakeholders, as is the case for the global scene and other regions. Even the Energy Modelling Platform for Europe (EMP-E)[7] [46] is supported by some EC-funded projects and orients only on energy system modelling.

Hundreds of climate-economy energy, electricity, and sectoral models have been established in the literature [47–49] and used across research and innovation projects, for the purposes of underpinning climate and energy policy. This is also evident in the number of literature reviews on modelling frameworks (e.g. Ref. [50]) as well as the different scope and focus of each of these reviews (e.g. Refs. [51,52]). This diversity is embedded in the range of scientific disciplines and methodologies involved in their development and use. It reflects that no single model can cover the broad spectrum of issues relevant to policymaking, like effort sharing under the Paris Agreement principles [53,54], synergistic effects across policies corresponding to different sustainability dimensions [55], quantification of costs associated with realistically covering the gaps between cumulative NDC contributions and 1.5 °C trajectories [9], realistic interpretation of the potential of negative emissions technologies [56], and so on. But, despite the high proliferation of modelling tools designed to cover vastly different or similar aspects in varying levels of detail, it is a consistent core of highly harmonised global models that have dominated the literature [57]. Model inter-comparison projects based on these models have long been used as justification of exploring a broad part of the future possibility space, but may end up hampering policy action [1], showing huge ranges of outcomes without elaborating in detail the origins of these ranges.

To help policymakers act in the face of such huge possibility sets, the modelling world should start investigating whether a more diversified portfolio of modelling tools can answer specific questions through targeted sensitivity or stochastic parameter perturbations, to identify genuinely robust patterns of mitigation, whilst exploring a genuinely large possibility space [58]. As different types of modelling structure focus on specific sectors/aspects thereby offering different types of insights, establishing connections between models that deploy different methodologies and structures in multi-model analyses can produce better, more robust policy prescriptions [59], in contrast to individual modelling exercises [60]. This is why effective climate policy must be underpinned by modelling ensembles that altogether draw from different structures and methodologies, provide insights for different geographic scales, as well as cover in detail all economic sectors, represent different types of policies, and provide insights for the broad range of greenhouse gases and aerosols, thereby capturing the multiplicity of aspects of climate-economy interactions and enlightening the origin of uncertainties and ranges by means of inter-comparison projects.

[7] http://www.energymodellingplatform.eu/.

3. Comprehensiveness and comprehensibility

The motivation driving international consortia can be summarised in four principles. These begin from the fundamental basis that decision support is effective when (a) addressing targeted policy and research questions, and (b) when no single perspective is favoured over others. More importantly, they extend to the need of data being (c) open and comprehensive, requiring assumptions, parameters, data sources, and uncertainty sensitivities be fully disclosed; and produced knowledge being (d) comprehensible, with downloadable datasets, customisable visualisations, and detailed and focused policy prescriptions. This is contrary to the norm of crisp data decoupled from the assumptions driving modelling runs and detached from the policy context and understanding, as well as of graphs labelled with naming conventions that probably mean nothing outside a core group of modelling experts.

These principles mean more than facilitating knowledge exchange among modellers and extend to involving non-experts into the scientific processes, since complex societal challenges imply multidimensional trade-offs and require science diplomacy, i.e. coordinated action of vastly different stakeholders and, across nations, scales and discourses [61]. Corresponding political choices must be based on thorough analyses of the complex interactions; and stakeholders need to trust said analyses. Otherwise, policy and other decision makers will adopt inefficiently low levels of trust in the modelling results and associated policy/decisions. Successful decarbonisation dictates that the modelling community interact with science's end-users in industry, government, and civil society, and develop strategies that transcend their traditional disciplinary boundaries [62], thereby incorporating political and societal realities [63] spanning all sectors of industry, government, and society, and producing recommendations to be trusted by a majority of stakeholders within the climate science-policy interface [64]. Involving all relevant stakeholders is aligned with the concept of responsible science [65], promoting socially acceptable, robust, and sustainable transitions, and is proven to increase the level of trust on both ends [66], while helping make modelling findings both intelligible in terms of real-world implications and actionable in terms of concrete recommendations.

Dating back decades [14], however, a growing concern associated with climate- and energy-economy modelling tools orbits on their legitimacy: why should scenario users, i.e. policymakers and other decision makers using modelling insights in decision processes [67], have confidence in modelling outputs, and in what levels [68]? As also reflected in one of the four scientific working groups of the IAMC, the modelling community has lately attempted to respond to such concerns: diagnostic indicators [69] and evaluation methods [70] have been defined for IAMs, efforts have been made to document models in less technical language (e.g. the ADVANCE/IAMC[8] and the openmod initiative[9] wiki pages), and research initiatives have been carried out to improve model development, evaluation and inter-comparisons (e.g. Ref. [71]). And yet little progress can be claimed [72] in opening the black box [73] to the extent of non-experts' acknowledging inputs and showing trust in outputs of modelling processes [9].

Among relevant efforts, the I^{2}AM PARIS platform[10] includes concise, dynamic summaries of this documentation by mapping these capabilities in interactive infographics, towards boosting understanding and ownership among non-expert audiences. These

[8] https://www.iamcdocumentation.eu/index.php/IAMC_wiki.
[9] https://wiki.openmod-initiative.org/wiki/Main_Page.
[10] http://paris-reinforce.epu.ntua.gr/main.

efforts, however, must be extended to represent and compare the multiplicity and diversity of models with one another, for all audiences to appreciate why each model can be used to address specific policy questions. Documentation of model characteristics and capabilities will also enable scientists from different disciplines and viewpoints to share a common language. Before stakeholders own why modelling tools can be trusted to address each question, any attempt to promote legitimacy must also entail transparency of the knowledge production process. This goes beyond using open source tools and implies that scientists develop and implement open protocols for interpreting scenarios and parameters, harmonising datasets of input sources across models in multi-model analyses, defining diagnostics indicators, and designing shared formats for documenting outputs.

Technical improvement of technoeconomic and socioeconomic representation in models is a good starting point, yet insufficient in ensuring robustness of resulting trajectories, if the datasets driving the simulations that lead to specific policy recommendations are not fully disclosed. Simply looking under the hood of modelling tools and exercises [74] says little if these datasets are not authoritative and shared within the modelling community, as is the case of a few major socioeconomic parameters [75]. Efforts must be put into defining each socioeconomic, technoeconomic and historical emissions parameter (glossary, units, definition) and their data sources (organisation, time span, database), towards harmonising inputs across models, for given questions, so that outcomes can be tied to modelling assumptions, and the broad spectrum of cross-scale insights across boundaries and disciplines can be effectively communicated [76].

Furthermore, not much progress has hitherto been done to ensure that those involved in scenario design are fully aware of whether their motivation and intentions are reflected in the produced knowledge, upon communication to policy and society, or whether their scenarios are indeed linked to the research and societal needs [54,77]. Except for high media coverage cases [78], lack of guidance from modellers renders scenarios prone to misconceptions and distortions in their interpretation by external users [79]. During the last decade, literature, as reflected in major scientific assessments and consortia, has been swarmed by thousands of scenarios, many of which may have been developed and modelled on the basis of scientists' interpretations of scenarios that they themselves perceive as useful [80]. There appears to be misinterpretation of scenarios, not only in policy but also among scientists and experienced users of these scenarios [81]. This interpretation-driven production of knowledge partly explains why for example SSP2 [82], narrating an extrapolation of historical trends in the future, has been applied significantly more than other socioeconomic scenarios, with hundreds of studies featuring its combination with selected RCPs. It also means that no scenario or modelling exercise is necessarily meaningful. For example, specific SSP-RCP combinations are presumed implausible and yet count hundreds of recent studies, with RCP8.5 being in principle inconsistent with most SSPs [83,84]. Despite the clock ticking the window of opportunity for climate action away, it could take years of modelling work to validate or invalidate these scenarios along the way [85], unless a more pragmatic evaluation of scenarios, or outputs [86,87], is carried out. Recent qualitative efforts, for example, include applying a risk lens coupled with different methodologies (e.g. Ref. [88]) or enabling expert elicitation that reflects policy perspectives of what can go right or wrong in the future [89].

Acknowledging these challenges, the European and international modelling community must put significant effort into ensuring that their scenario frameworks match the policy needs at all levels and address the actual research capacity needed. For Europe, in particular, employing and coupling integrated assessment models with EU-wide representation and models with more detailed granularity, at the Member State or sub-national (e.g. NUTS-3 and NUTS-2) level [90,91], should be a core aim. Upon streamlining research at different scales, which is critical to bridging EU-wide and national-level modelling analyses and policymaking, coordination among different research projects must be enhanced, providing improved scientific basis for multi-model and/or inter-comparison exercises. Among others, this first requires harmonisation of data inputs across models regardless of theory, including socioeconomic and technoeconomic parameters, fossil fuel prices, and historical emissions, with data source selection driven by reliability and consistency of the assumptions at all scales. Assumptions shared across policy pledges must be considered, making use of the best available science, including matching global datasets [92,93] and their national-level disaggregation, e.g. on the human [94], urbanisation [95] and economic dimensions [96], without overlooking the associated localisation and downscaling challenges potentially leading to several-fold increases of plausible futures [97].

Fostering inter-comparison projects that are globally and regionally meaningful finally requires a harmonised interpretation of actual climate policies for the EU and other countries (NDC level) and for national action pledges within the EU (NECP level), despite potential differences across pledges in terms of target type, base year, and horizon. Significant progress was made in the CD-LINKS project [98], contributing to capacity building for national modelling teams; as the climate agenda progresses fast, modellers must ramp up efforts to ensure up-to-date representation of both current policies and future action pledges worldwide. This will allow for model inter-comparison exercises, where models provide a more robust response to research needs and where differences among trajectories resulting from different models can be attributed to their specificities alone [99]. Efforts must also be put into clearly exploring the scope of modelling interlinkages, by defining capacity for data exchange, and enabling integration of models; by combining, for example, long-range IAMs with short-term models of the macro-economy, useful insights can be gleaned on the full range of potential impacts of shocks, such as COVID-19 and associated policy and societal responses [100].

4. Expanding the modelling comfort zone: disruptions, extremes, and sustainability

The policy and market responses to the coronavirus pandemic led to temporary reductions of emissions, which have been comparable to the annual decrease rates that are in turn compliant with the Paris Agreement [101]. Discussions have focused on governments' efforts to recover, make up for lost economic ground and even push towards rebounds with even higher emission pathways compared to pre-pandemic trajectories, with implications for progress in climate action. This pandemic reminds us of the need to actively engage with extreme events [102], which may not be part of typical scenarios underpinning mitigation strategies. Game-changing disruptions may be positive or negative but, regardless of the direction of their impact, it is critical that energy and integrated assessment modelling encompass considerations of a large range of possible events in the coming years and decades [103]. Failure to do so risks developing mitigation or adaptation plans that do not pass the resilience test.

Example issues that modellers must seek to explore through the deployment of a combination of appropriate modelling tools across fit-for-purpose scenarios include the implications of services digitalisation on energy demand and supply, through considering shifting consumer demand patterns [104], as well as electricity and other energy vector supply changes resulting from increasingly smart and interconnected energy networks. But they should also include energy citizenship and sustainable lifestyles as well as economic shocks resulting, for example, from changing trade relations, oil and other commodity price changes, or penetration of artificial intelligence and robotics into manufacturing; and implications of rapid political and societal changes in sentiment towards urgency of tackling the climate crisis, for example in response to climate shocks, which raise the issue to the top of society's agenda. Moreover, there is a critical need to reflect on the technological progress that confounded all expectations over the last decade, particularly concerning the cost reductions and market penetration of solar PV, wind, and electric vehicles, as well as battery electric storage. Other such technological innovation "miracles" (be they in ultra-cheap and scalable amines for CO_2 capture and atmospheric removal, or electrolysers for hydrogen production) are almost inevitable in the coming years. Modelling activities, which fail to explore the plausible extremes of cost reductions in such technologies, will be redundant or misleading in the face of these inevitable breakthroughs.

Finally, although mostly remembered for the Paris Agreement, the year 2015 also featured the UN-wide adoption of the 2030 Agenda for Sustainable Development, embodied in 17 distinct yet highly intertwined Sustainable Development Goals (SDGs). These inter alia include poverty and hunger elimination, social and gender equalities, quality education and decent work, strong institutions and responsible production, environmental and biodiversity protection, good health, and climate action. Seemingly two separate agendas, sustainable development and climate action are highly intertwined [55]: the former is an explicit part of the Paris Agreement, while the latter constitutes one of the seventeen goals. The need to assess climate action in conjunction with the other SDGs has in the literature been addressed mostly by means of treating SDGs as trade-offs of low-carbon mitigation pathways [105], either explicitly (e.g. Ref. [106,107]) or implicitly (e.g. Ref. [108]). But, despite having been designed and/or adapted to support climate policy, integrated assessment modelling frameworks have been found well-equipped to deal with most other goals of sustainable development [109]. As such, the modelling community must instead place climate action in the entire framework of sustainable development, by exploring co-benefits of working across the broad sustainability spectrum. Dealing with sustainable development questions that transcend the boundaries of global, EU, or national climate action can contribute to exploring decarbonisation pathways that are beneficial from multiple perspectives [110] and more robust against different plausible futures [111].

5. Conclusions

In this perspective, we argue that the European modelling community must start delivering information that is not only open and comprehensive but also comprehensible and attached to specific questions, modelling assumptions, and multi-faceted uncertainties, so as to restore stakeholders' faith in modelling tools [112]. This is especially true now, considering how science has in the past failed to drive policy [113] or incidentally become adjunct to political causes, as the COVID-19 policy response highlighted [114]. Enhancing the science-policy interface should therefore be underpinned within a structured and transparent communication channel that designs and maintains protocols shared across the scientific community as well as to tools, datasets, results, and analyses that are open, clear, and useful for all stakeholders. This goes well beyond opening data and software [115], developing detailed interfaces between modelling tools [116], or providing policymakers with technical information [99]. It rather implies that knowledge be effectively transformed, tailored, and disseminated in customised visualisations and convincing policy recommendations. It also goes beyond carrying inter-comparisons that treat models as having attributes separate from the inputs and assumptions on structure (e.g. Ref. [117]), or anchoring to the comfort zone of exploring the well-established space of 'unknowns' [118].

It is about time the currently fragmented European modelling landscape be brought together and coordinate its efforts in a Europe-wide platform for energy- and climate-economy modelling. This should undoubtedly build on the knowledge produced by the highly harmonised global IAMs dominating model inter-comparisons for decades [57]; assessing EU policy in a global context and in consideration of international cooperation is not only key to resolving the global threat of climate change, but also critical to understanding the contribution of other major emitters to the international climate agenda [119] and to implementing the European Green Deal [120]. But it should allow adding further insights and layers of detail and granularity [121], reinforcing technical feasibility, viability, effectiveness, and robustness of transition pathways at the European and national level, co-created with stakeholders, thereby promoting responsible science and enhancing science diplomacy, which constitute top priorities of the EU research agenda. Only by doing so in a structured, transparent and legitimate manner, will the European climate and energy modelling landscape be able to host multi-model analyses with appropriate geographic detail and sectoral diversity, and with the capacity to highlight costs, benefits, impacts, and trade-offs at different levels, as reflected in the policy discrepancies across EU nations and the gaps between the sum of national strategies and collective action [122]. And only then will it avoid being detached from real-world policy needs [9] or featuring bias that can render it lagging policy advancements [123].

Credit author statement

Alexandros Nikas: Conceptualization, Investigation, Writing - original draft, Writing - review & editing, Project administration. Ajay Gambhir: Conceptualization, Investigation, Writing - original draft. Evelina Trutnevyte: Conceptualization, Writing - original draft, Writing - review & editing. Konstantinos Koasidis: Investigation, Writing - review & editing. Henrik Lund: Conceptualization, Writing - original draft. Jakob Z. Thellufsen: Investigation, Writing - original draft. Daniel Mayer: Conceptualization, Writing - original draft. Georg Zachmann: Writing - original draft. Luis Javier Miguel: Conceptualization, Writing - original draft. Noelia Ferreras-Alonso: Conceptualization, Writing - original draft, Writing - review & editing. Ida Sognnaes: Investigation, Writing - original draft. Glen Peters: Conceptualization, Writing - original draft. Emanuela Colombo: Conceptualization, Writing - original draft. Mark Howells: Conceptualization, Writing - original draft. Adam Hawkes: Conceptualization, Writing - original draft. Machteld van den Broek: Conceptualization, Writing - review & editing. Dirk-Jan Van de Ven: Conceptualization, Writing - original draft. Mikel Gonzalez-Eguino: Conceptualization, Writing - original draft. Alexandros Flamos: Conceptualization, Writing - original draft, Supervision. Haris Doukas: Conceptualization, Writing - original draft, Writing - review & editing, Supervision, Funding acquisition.

Declaration of competing interest

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

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