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Capturing system complexity in maritime decarbonization: a multilayer modeling perspective

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1. Intricate challenges of maritime decarbonization

The maritime sector plays a key role in facilitating the international movement of goods and people, supporting over 80% of all international cargo movements by weight (UNCTAD 2023). It is also considered a hard-to-abate sector (IRENA 2024), responsible for around 3% of global CO_2 emissions (IMO 2021), due to limited electrification potential and substantial energy storage requirements for long-distance shipping, long vessel lifetimes, and the resulting slow turnover of the global fleet, which together lock in fossil-fuel use. This has triggered the approval of several regulatory measures by the International Maritime Organization (IMO) in recent years, including ship energy efficiency management plan, energy efficiency existing ship index, energy efficiency design index, and carbon intensity indicator. Together with regional initiatives such as the EU's FuelEU Maritime and the inclusion of shipping into the emissions trading system[12] (European Commission 2023), these regulations aim at fostering the maritime sector's transition to a clean energy future.

Nevertheless, maritime decarbonization faces a rising tide of geopolitical, economic, technological, and environmental challenges. While the adoption of longer-term regulatory measures such as IMO's Net-zero framework is still under discussion, geopolitical uncertainties and climate change impacts continue to cast a long shadow over global trade, supply chains, and maritime operations. Maritime shipping is not an isolated sector, but a core infrastructure that enables global trade and links production, consumption, and energy systems across regions. As a result, shipping demand, costs,

[12] It should be noted that while both initiatives are aimed at facilitating the decarbonization process, the mechanisms behind them are rather different. In particular, while the EU-ETS targets absolute emissions in each sector regardless of their origin, FuelEU Maritime (similarly to the pending IMO Net zero framework) sets a pathway to reduce the emission content of marine fuels, with the aim of facilitating a transition to non-fossil fuels.

and fuel choices are shaped by developments outside the sector, including shifts in trade patterns, energy markets, and climate policy. This interdependence makes maritime decarbonization a system-level challenge, necessitating a more comprehensive analytical framework for maritime decarbonization to address the interplay of factors, ranging from technological innovation and infrastructure development to economic considerations, regulatory enforcement, and global trade dynamics (Bouman *et al* 2017). For example, while the development and adoption of cleaner fuels like green ammonia, e-methanol, and green hydrogen require large-scale production infrastructure (Smith *et al* 2015, Stargardt *et al* 2024), advances in ship propulsion systems, vessel design, and alternative fuel bunkering are essential to enabling the transition (Lee 2024). Both operational and technical energy efficiency measures enforced by IMO and EU may support the transition by lowering the total cost of operation. In addition, ports must upgrade their infrastructure to support new fuel supply chains and ensure interoperability across international routes (Gilbert *et al* 2018). Such a transformation requires not only substantial investments that pose economic and equity challenges (Zanobetti *et al* 2023), but also a well developed and stable regulatory landscape for the mitigation of financial risks and supporting the demand uptake of net-zero fuels (Baresic *et al* 2025).

Furthermore, while many environmental policies and regulations aim at the global or multi-regional levels, a local (e.g. port- or city-level) action and community engagement is often required to address them, with the impacts of this action having, in turn, implications for the global supply chains, thus feeding back to the global scale of processes. This represents a complex global-to-local-to-global (GLG) type of processes, which are particularly challenging to analyze using the conventional modeling tools (Baldos *et al* 2023). Previous studies indicate that the environmental impacts of maritime activities extend well beyond climate change, affecting the nitrogen cycle, aerosol loading, biodiversity, and ocean acidification, among other dimensions (Jägerbrand *et al* 2019, Moldanová *et al* 2022, Ankhi and Rahman 2026). In this paper, we argue that the unique characteristics of the maritime sector, coupled with the challenging and rapidly evolving policy landscape, require a new multi-layer modeling approach for a comprehensive analysis of maritime decarbonization pathways. The rest of the perspective is organized as follows. In the next section, we provide a stocktaking of selected modeling frameworks that have been used for the assessment of maritime decarbonization, highlighting key strengths and weaknesses of each approach. We then proceed with the proposed conceptual assessment framework that combines multiple approaches, providing a nuanced and realistic representation of the maritime industry. Finally, we close with a discussion of the key data and methodological advancements that are needed to enable the development of the proposed multi-layer assessment framework, providing directions for future research in this area.

2. Typology of the existing models

Considering the complexity and GLG nature of the maritime sector, a wide range of modeling frameworks have been developed and applied in an attempt to explore various aspects of maritime sector operations and future decarbonization pathways. Table 1 provides an overview of the selected models that have been (e.g. Naghash *et al* 2024) or could be used for the assessment of various aspects of the maritime sector decarbonization, highlighting their key features, strengths and weaknesses. A more detailed description of each type of model, examples of selected applications of the corresponding modeling frameworks, and a discussion of the key challenges and potential improvements needed to advance the corresponding quantitative tools are provided in the supplementary information.

Recent methodological advances in socio-economic model coupling for climate policy integrate decisions across spatial, temporal, and institutional scales to offer a promising yet untapped avenue for maritime GLG assessments (Filatova *et al* 2025). Our proposed model selection builds on this notion and covers a broad set of assessment tools, ranging from economy-wide models, such as computable general equilibrium (CGE) and integrated assessment models (IAMs), to more specialized sector- or process-specific tools, such as technoeconomic models (TEMs), ship weather routing models (WRMs) and international freight models (IFMs), as well as behavioral agent-based models (ABMs). As shown in table 1, outputs from some types of models (e.g. macroeconomic indicators from CGE and IAMs) can serve as inputs for more technologically detailed, partial-equilibrium models such as weather routing or freight models, while insights from these sector-specific models can in turn feed back into economy-wide frameworks through costs, performance, and behavioral responses.

Although some recent studies have recognized these important complementarities by proposing multi-model assessment frameworks featuring selected model interactions, almost all such applications feature one-way linkages between two models of different types, substantially simplifying the complexity of the GLG dynamics of the maritime sector (Halim *et al* 2018, UNCTAD, 2025, Sang *et al* 2026), here we

Table 1. Overview of the modeling frameworks for the assessment of maritime decarbonization.

Dimension\ model	Computable general equilib-rium (CGE)	Integrated assessment mod-els (IAM)	International freight models (IFM)	Technoeconomic models (TEM)	Weather routing models (WRM)	Agent-based models (ABM)
Key features	Economy-wide, multi-sector representation (production, consumption, trade)	Global energy–economy–climate models integrating emissions, energy systems, and climate impacts	Model transport flows from international trade, modal choice and routing on the global or regional levels	Evaluate alternative maritime technologies (e.g. fuels, engines) by coupling engineering models with cost assumptions	Identify an optimal ship route by leveraging marine weather data and balancing competing objectives under operational constraints	Simulate decision-making of heterogeneous actors (shipowners, ports, regulators, fuel suppliers) interacting over time
Typical applications	Quantify the economy-wide implications of maritime decarbonization policies (carbon prices, fuel taxes)	Explore the role of the maritime sector in global net-zero pathways; assess how carbon budgets and carbon prices affect marine fuel use and emissions	Impact of trade patterns and decarbonization efforts on modal choices, maritime transport demand, route selections, infrastructure capacity, fuel use, and emissions.	Compare alternative fuel pathways (LNG, ammonia, methanol); estimate abatement cost curves; fleet renewal pathways; fuel production and bunkering site optimization	Quantify emission savings from operational measures; evaluate weather-dependent voyage topology and energy efficiency indicators	Study adoption dynamics of new fuels/technolo-gies, policy acceptance, and investment coordination across the maritime sector agents
Scale	Global and economy-wide	Global and economy-wide	Global or regional, sector-specific	Vessel, fleet, and/or fuel production and distribution	Single voyage or vessel	System-wide (interacting agents)
Typical time horizon	Medium to long-term (2030–2050)	Long-term (2050–2100)	Medium- to long-term	Short- to medium-term	Short-term (hours or days)	From short- to long-term
Technical detail	Low	Low to medium	Medium (route level)	Medium (distribution level) to high (vessel level)	Very high (operation)	Medium to high
Representation of uncertainty and the type of dynamics	Mostly deterministic (sensitivity analysis over selected parameters, policy variables or scenarios); recursive dynamic	Mostly deterministic (sensitivity analysis over selected parameters, policy variables or scenarios); forward-looking options	Often deterministic; scenario-based sensitivity analysis; discrete dynamics	Discrete exogenous dynamics; stochastic versions available	Deterministic dependence on meteo-marine fields from dynamical models; extensions to model outputs ensemble possible	Explicit behavioral uncertainty

(Continued.)

Table 1. (Continued.)

Dimension\ model	Computable general equilibrium (CGE)	Integrated assessment models (IAM)	International freight models (IFM)	Technoeconomic models (TEM)	Weather routing models (WRM)	Agent-based models (ABM)
Strengths	Capture economy-wide linkages; comprehensive macroeconomic analysis; useful for cross-sectoral policy evaluation	Global perspective; climate impact feedbacks; integrates maritime activity with energy system details	Links global trade and spatial details of shipping demand between countries; realistic transport activity and costs baseline; able to assess the impact of policy measures on transport costs and demand, useful input to fleet/energy models	High technological realism; quantify costs, emissions, payback; can evaluate vessel-level or fleet-level pathways.	High operational fidelity; highly relevant for real-time decision-making	Captures heterogeneity, bounded rationality, and non-linear adoption patterns; useful for exploring policy design and uncertainty.
Limitations	Rather coarse level of technological details (maritime activity often represented as a single sector)	Coarse resolution for shipping; simplified treatment of fuels, vessels, and infrastructure; rarely capture operational dynamics	Typically exclude technical or fuel-switch detail; exogenous representation of energy system, economic drivers and feedbacks	Narrow scope; lacks macroeconomic context and trade feedbacks	Not suited for long-term transition analysis; single-vessel focus; exogenous representation of market/economic drivers	High data demand; computationally complex; often lack empirical calibration; require uncertainty handling
Additional details and sample applications	See SI sections 1.1 and 1.7	See SI sections 1.2 and 1.7	See SI sections 1.3 and 1.7	See SI sections 1.4 and 1.7	See SI sections 1.5 and 1.7	See SI sections 1.6 and 1.7

aim to detail a blueprint for a more comprehensive model coupling. The proposed set of models could be further complemented or explicitly embed other modeling tools. Bottom-up energy models could be either embedded within the IAM and/or TEM frameworks or used to complement CGE runs in the part of the energy system parametrization (e.g. Böhringer 1998, Krook-Riekkola *et al* 2017) if neither IAM nor TEM include the desired level technological details. Life cycle analysis (LCA) tools could be directly incorporated into the TEM by linking the emission factors to fuel-technological choices supplied by the TEM. For selected downstream emission flows LCA could further rely on the CGE/IAM outputs, allowing for a more comprehensive representation of the entire supply chain (e.g. emission embedded in capital goods). Other approaches such as evolutionary game theory (Liang *et al* 2025) and system dynamics (Gao *et al* 2023) have been used for studying different maritime decarbonization aspects but not considered in our framework as they overlap with one or some of the models listed in table 1.

3. Toward a new multilayer modeling framework

To tackle the complex interdependencies discussed above, this paper proposes a novel multilayer modeling framework that combines in a comprehensive manner key maritime decarbonization assessment tools, used for the assessment of specific aspects of the maritime decarbonization sector in previous studies, utilizing their strengths and addressing weaknesses through bidirectional model interactions (figure 1).

Macroeconomic models, such as the CGE and IAM, provide quantification of the global trade scenarios under alternative futures. These models offer critical insights into how bilateral trade flows and energy trajectories evolve under varying climate policy targets, trade restrictions, technological developments, and external shocks, including those related to climate impacts. CGEs are particularly well-suited for capturing global trade patterns and economy-wide feedbacks, while IAMs specialize in representing

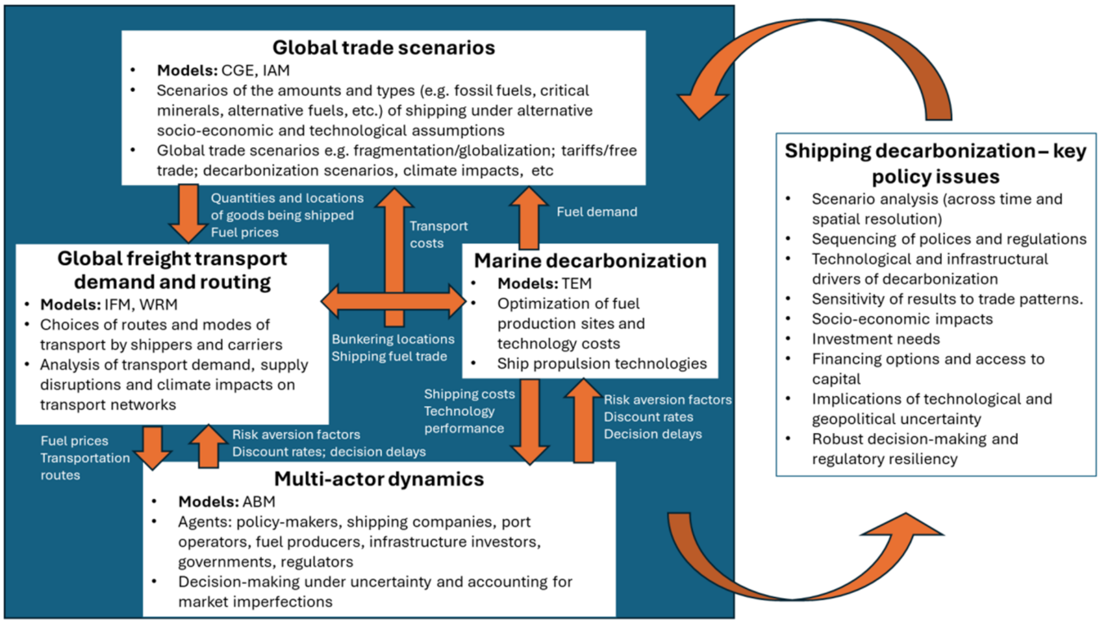

Figure 1. Schematic representation of the multilayer modeling framework for the maritime decarbonization analysis. *Notes:* CGE stands for Computable General Equilibrium, IAM (integrated assessment model), IFM (international freight model, TEM (technoeconomic model), WRM (weather routing model), ABM (Agent-based model).

technology spillovers, endogenous cost reductions, energy system transitions, and climate-related constraints. Together, they provide a comprehensive perspective on the broader economic and policy landscape, addressing cross-sectoral dynamics that sector-specific models cannot independently capture.

While CGEs and IAMs provide a comprehensive multi-sectoral view of the evolution of global economy and trade patterns, they usually lack more refined details about the maritime routes, fuel use and cost, and shipping technologies. Therefore, the main goal of CGE and IAM is to provide boundary conditions to the more specialized modeling tools that are in a better position to address these aspects. Quantities and geographical distribution of shipped goods, estimated by the CGE and IAM, as well as changes in fuel costs (e.g. changing energy prices due to changes in demand following a specific policy implementation) will be transferred to sector-specific models such as IFM and WRM.

The IFM is designed to estimate international freight transport activities for a range of commodities, across major transport modes and routes, taking into account different policy measures (e.g. the development of new infrastructure networks, emission reduction measures such as carbon taxation, etc.). To analyze transport costs, modal share, and spatial patterns of maritime transport, the IFM makes use of a network model of the multimodal transport routes. While providing a higher level of spatial details than the CGE and IAM, the IFM does not comprehensively consider dynamic characteristics faced by carriers/shipowners in determining their route choices, such as the weather conditions. To account for these factors, our proposed framework utilizes a WRM which provides optimal maritime routes between designated ports, taking into account actual meteo-marine conditions at the time of the voyage and the specific vessel performance data. Ideally, models in this category can process wave, current, and wind data, in either forecast or hindcast mode. They should also consider vessel-specific seakeeping and performance characteristics (see, e.g. Mannarini *et al* 2024). When combined, the IFM and WRM will provide a comprehensive estimate of the shipping routes, fuel use and port utilization. However, other aspects related to fuel supply, including their techno-economic constraints and available fuel supply networks are beyond the scope of both models.

These aspects are instead evaluated by the TEM which determines the capacities and optimal locations of potential sustainable fuel supply for international shipping, with fuel demand driven by the estimates from both the IFM and WRM. The top-level optimization in a TEM solves a network for fuel delivery across thousands of ports and possible supply locations. The key strength of the TEM includes the coupling of detailed plant-level optimization with global network optimization, resulting in a high spatial resolution. The TEM's output can be fed back into both the IFM and WRM, providing refined estimates of the optimal bunkering locations and shipping fuel trade.

Combining the IFM, WRM, and TEM will result in refined estimates of maritime fuel demand and transportation costs, which can be further fed to the CGE and IAM and used for a more comprehensive assessment of future trade patterns. Linking variables include adjustments in bilateral transportation costs (e.g. implemented via iceberg trade costs), as well as adjustments in the fuel demand by type (could be implemented using preference shifters). Iterative exchange of inputs and outputs between the models in this framework will facilitate the convergence of optimal solutions for key decision variables. Such solutions would be obtained under a general assumption of rational behavior of actors and perfect market conditions. In real-world decision making, this is often not the case. Therefore, we propose the inclusion of the ABM in this framework which will support a more comprehensive representation of behavioral choices of key stakeholders, evaluating decision-making under uncertainty and explicitly embodying observed market imperfections. The ABM receives inputs from the CGE and IAM (fuel and carbon prices), the IFM and WRM (freight capacity and energy demand by route), and the TEM (shipping costs and technology performance). In turn, ABM provides insights on adjustments to the agents' behavior, such as potential delays in investment decisions due to uncertainty in regulatory environment (decision delays), non-market consideration for the choice of specific transportation routes (risk aversion factors), additional investment risk consideration due to non-market factors (alternative discount rates), etc. (figure 1). These inputs are used for re-parametrizing other models (e.g. to better account for market imperfections) via additional factors in the optimization functions (e.g. penalty functions, risk aversion factors, alternative discount rates, etc.).

Additional details on the proposed model-coupling workflow, including a step-by-step operationalization of model interactions for the hypothetical case of carbon pricing policy implementation, are provided in supplementary information (section 3). At the same time, it is important to note that the discussed workflow is not aimed at providing a prescriptive approach to the multi-model analysis of the maritime decarbonization but is primarily aimed at inspiring further research in this area, in particular, case studies with actual model implementations, which should further refine and extend the ideas discussed here.

The proposed modeling framework is therefore expected to generate more realistic and robust decarbonization pathways for maritime transport, addressing a wider range of policy questions and reducing exogenous variables in the systems as they are included as part of the framework (figure 1). In addition to the comprehensive coverage of various spatial and temporal aspects of the maritime sector, one of the key strengths of the proposed framework is the possibility of exploring uncertainties arising from the heterogeneity of actors and decision-making processes, spatial structures (global, regional, and local), and technology options (e.g. alternative fuels).

While enhancing the existing analytical tools and supporting future research on maritime decarbonization, better informing the international climate community (organizations and panels), as well international maritime regulators, the proposed framework will be of even more relevance to the private agents and institutions. By explicitly combining global (national) and local (e.g. port-level) representations, the proposed framework could support the decision-making process at the level of ship companies, port authorities, fuel supply companies, private investors, as well as non-governmental organizations, among other stakeholders.

4. Research agenda for the future

To implement the proposed multilayer modeling framework, key data and methodological gaps must first be addressed. In this section, we highlight some areas of future research that have a high potential to advance the existing analytical capacity.

First, many of the existing CGEs and IAMs do not have a detailed quantification of the fuel use across bilateral ship routes, nor do these models have a detailed representation of the bilateral trade and transportation costs. Commonly used databases for CGE models such as GTAP, also suffer from an oversimplification of transport costs or known as 'transport margins' calculation. In particular, the standard GTAP database uses extrapolated modal share data based on US export data to calculate transport margins for all bilateral trade of the countries included in the model (Nuno-Ledesma and Villoria 2019).

One particular development includes incorporation of bilateral energy use, emission data, and transportation costs (by commodity types and specific routes) sourced from the IFM and WRM databases to the CGEs and IAMs. This step may require formulating an optimization problem in which inputs from CGE and IAM frameworks act as boundary conditions (i.e. high-level targets), while detailed route-specific information from the IFM and WRM—together with available cargo fleet movement data—inform the parameterization of route-level weights and constraints. Another essential development within the economy-wide analysis regards enhancing the models' database with additional energy carriers such as hydrogen, ammonia and other clean energy sources which would enable reproducing more accurately the decarbonization of the shipping sector and other economic activities. Advancing data availability and model developments in this area will allow for a more refined representation of the maritime activities in the economy-wide models and facilitate linkages with the sectoral spatially-detailed models.

Second, empirical operational behavior of maritime vessels is not well-represented in most sectoral models, including the WRM, TEM and IFM, as the latter largely rely on generic performance curves without utilizing high-resolution vessel data. Developing validated performance curves for major vessel types including alternative-fuel propulsion is an important development. Ideally, the performance should account for dynamic ambient conditions (e.g. meteo-oceanographic fields) as well as for the vessel's servicing status (e.g. time since last hull cleaning). The parametrization of these curves could refine transport model's estimation of travel time and time costs for bilateral trade for commodities and routes that are sensitive to weather conditions or specific fuel types. This, in turn, will increase the robustness of the economic analysis both on detailed route level and on global level. In addition, the availability of detailed vessel movement data taken from automated identification system (AIS) has also opened opportunities for validating the estimated trade volume across global shipping routes and to refine the calculation of fuel or energy use which is central to TEM.

Third, the representation of technological uncertainty and endogenous learning-by-doing remains limited in many CGE, IAM and TEM frameworks, as cost trajectories are often imposed exogenously rather than derived from deployment dynamics. Incorporating empirically grounded learning curves—for instance, for electrolyzers, alternative fuel production pathways, selected renewable technologies, and marine engine retrofits—would better capture path-dependency and infrastructure lock-in. Likewise, multi-fuel optimization in TEMs could be strengthened by integrating high-resolution techno-economic and operational data on fuel switching across vessel classes (e.g. ammonia vs methanol vs LNG vs electrification for short-sea shipping) and port-level infrastructure constraints, allowing for a better parametrization of substitution elasticities, retrofit costs, and operational constraints.

Fourth, port-level data on fleet ages, investments, risk preferences and financial constraints, as well as agent-specific policy behavior to properly constrain the ABM is scarce and, in many cases, not publicly available. More efforts toward constructing such datasets would be essential to facilitate representation of key maritime stakeholders within the proposed modeling framework. Increasing availability of vessel tracking data from AIS, combined with advances in computational capabilities, provides new opportunities for empirically grounded ABM applications in this domain.

Finally, not all proposed data and model enhancements are of equal significance. In some instances, reduced-form (aggregate-level) representations may adequately capture the underlying processes; in others, such simplifications risk materially biasing results, distorting decision-relevant insights. Systematically identifying these trade-offs is therefore essential, yet, in many cases, it is only feasible once the full modeling framework is operational and key assumptions and impact channels can be selectively activated or deactivated. In this context, a promising area for future research lies in quantifying the marginal contribution of specific data improvements and model couplings to overall model outcomes, thereby informing the research community on priority areas of data and model developments.

While data and methodological developments are essential enablers of the implementation of the proposed multilayer analytical framework, the design of the framework and its technical implementation, including bidirectional interactions and linkages between models, constitutes a major challenge by itself. To facilitate model-linking, additional model intercomparisons, data harmonizations, and computational experiments are essential. The latter includes harmonization of the emissions and fuels consumption data across models and designing tractable computational procedures which allow effective comparisons of model outputs which typically have large file sizes. Benchmark intercomparison would be helpful to establish the validity and usefulness of the utilized models. In addition, development of robust model-linking protocols and data exchange routines is an essential step towards the implementation of the proposed framework. Leveraging the existing body of knowledge within the research community—particularly advances emerging from model intercomparison projects and prior model-coupling implementations (e.g. Krook-Riekkola *et al* 2017, Durack *et al* 2025)—could help address some of these challenges by providing tested methodological frameworks, harmonized assumptions, and validated pathways for cross-model integration. While increasing modeling framework sophistication could imply potential computational challenges, recent developments in computational algorithms and AI, as well as rapid upscaling of the computing capacities available to researchers, provide ample opportunities for implementing complex analytical frameworks, like the one proposed here.

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During the preparation of this manuscript, the authors used ChatGPT (GPT-5.2, OpenAI) to

improve the readability and language of the text. The authors reviewed and edited the content after using the tool and take full responsibility for the final version of the manuscript.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Supplementary data 1 available at https://doi.org/10.1088/1748-9326/ae61ce/data1.

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