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Designing for Impact: Engaging Stakeholders With System Dynamics Models

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ABSTRACT

System dynamics models offer powerful tools for understanding complex systems and informing policy. Yet, their impact often falls short due to limited stakeholder engagement and poor implementation. Here, we explore how system dynamics models can be designed for real-world impact by integrating analytical rigor, transparent modeling, and interactive stakeholder engagement. We build on the literature on engaging stakeholders through management flight simulators, gamification and storytelling, and utilize the C-ROADS and En-ROADS climate simulators and insights from the MIT Climate Pathways Project. To date, more than 492,000 people in 185 countries, including more than 23,000 leaders in government, business, investing, and civil society, have participated in interactive sessions with these simulators. We present three key design principles: (1) rigorous modeling and model transparency, (2) intuitive model interfaces, and (3) facilitated, interactive simulation-based experiences. These principles enable users—from students to senior policymakers—to challenge mental models, explore trade-offs in a safe, engaging environment, and learn for themselves. We discuss limitations and directions for refinement of these principles. The paper contributes to the system dynamics and broader practice literature by offering actionable insights for designing models and protocols for their use that catalyze learning and informed decision-making in complex policy environments.

1 | Introduction: Engaging Users With System Dynamics Models for Impact

Policymakers must often make decisions under time pressure, yet the complex systems they manage are characterized by long time delays, non-linearities, and multiple intertwined feedback loops. These complexities overwhelm our ability to understand the underlying structure of problems, leading to failed interventions, policy resistance, and harm. System dynamics (SD) practitioners and others working in the domain of complex dynamic systems have long developed models and simulations intended to help policymakers make better decisions. However, many such studies, across diverse disciplines, not only SD, do not lead to sustained or, in many cases, even initial implementation (e.g., Alley et al. 2023; Churchman 1964; Größler 2007; Homer et al. 2020; Little 1970; Meadows and Robinson 1985; Milstein et al. 2011; Randers 2019; Roberts 1977; Smith et al. 2020; Sterman 2018a). Such implementation gaps are well documented including (i) in public health, where short time horizons and reluctance to invest in preventive measures reduce the adoption and impact of well-supported strategies (Milstein et al. 2011); (ii) in business, where consultants and academics frequently produce recommendations that managers do not implement (Oliva and Sterman 2001; Repenning and Sterman 2002); and (iii) in environmental policy, where costly models and analyses often

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have limited impact due to unrealistic assumptions, inadequate documentation, poor relationships with key stakeholders, and failure to consider organizational politics (Meadows and Robinson 1985; Sterman 2018a).

A common cause of poor implementation is analysts' failure to engage the decision-makers and stakeholders needed for implementation in the learning process so that they can learn for themselves. Exposing decision makers to the best evidence and science generally does not change mental models or behavior (Sterman 2011)—"research shows that showing people research doesn't work" (Sterman 2018b). People generally learn about problems through feedback from the environment, whether by experience or experimentation (Sterman 2000). However, for many problems, experiments are impossible or unethical, and feedback from experience comes too late to be useful. To overcome this, simulators enable users to experiment, gain experience, and learn in a safe space without endangering people or nature (Sterman 2000). System dynamicists have developed simulators for policymakers across various disciplines (e.g., health (Rahmandad et al. 2021; Thompson and Tebbens 2007), organizational strategy (Repenning and Sterman 2002), environmental sustainability (Sterman et al. 2013), and many more) to improve understanding and give decision-makers the confidence to take action.

Here we argue that facilitated interactive simulations that actively engage people in learning for themselves help them better understand the underlying structures of wicked problems, leading to better decision-making and informed action. Specifically, we utilize the SD-based C-ROADS and En-ROADS simulators and insights from the MIT Climate Pathways Project (CPP) to explore how SD models can be designed, developed, and evaluated for analytical rigor, stakeholder engagement, and impact. We describe how these simulators are used and the evaluative research we and others have carried out to assess their impact. We introduce SD approaches to engaging stakeholders, and describe the design principles critical for the development of C-ROADS and En-ROADS. We then introduce a conceptual model that may help guide future research and close with a discussion of lessons learned, limitations, and directions for further improvement.

2 | Engaging Stakeholders With C-ROADS and En-ROADS in the MIT Climate Pathways Project

The CPP was established in 2019 as a joint project by the MIT Sloan Sustainability Initiative, the MIT Climate Policy Center, and the non-profit think tank, Climate Interactive. The CPP aims to leverage interactive climate simulators, such as C-ROADS (Sterman et al. 2013) and En-ROADS (Kapmeier et al. 2026; Siegel et al. 2024), and research insights (e.g., Sterman et al. 2022, 2018) to advance the adoption of evidence-based climate policy through leaders in the public and private sectors (MIT Climate Pathways Project 2026). Both C-ROADS and En-ROADS (co-developed by Climate Interactive and the MIT Sloan School of Management) are freely available, accessible in multiple languages, grounded in the best-available science, fully documented, and transparent.

Assessment studies show that facilitated interactive engagements with the simulators, like the World Climate Simulation (with C-ROADS), the Climate Action Simulation (with En-ROADS), or the En-ROADS Climate Workshop lead to improved understanding of climate dynamics, increased affective engagement, and greater commitment to action (Rooney-Varga, Cheney, et al. 2026; Rooney-Varga et al. 2025; Rooney-Varga, Hensel, et al. 2021; Rooney-Varga et al. 2020, 2018). Participants in interactive C-ROADS or En-ROADS engagements learn more about the climate challenge and discover which actions and policies have low or high potential to reduce future warming. Beyond such cognitive learning, participants' affective engagement and commitment to action improve, as engaging with the simulators increases their sense of urgency and belief that what they do matters (Rooney-Varga, Cheney, et al. 2026; Rooney-Varga et al. 2025; Rooney-Varga, Hensel, et al. 2021; Rooney-Varga et al. 2020, 2018). Furthermore, engagement with En-ROADS increases participants' awareness of how to address climate change and understanding which climate policies and actions can be more effective (Rooney-Varga, Cheney, et al. 2026; Rooney-Varga et al. 2025)—such as pricing carbon emissions (Stechemesser et al. 2024) and increasing energy efficiency (Daioglou et al. 2022)—and which actions, while popular, have limited impact, such as afforestation, which does little to sequester carbon in the critical next decades because it takes time to acquire land and for the trees to grow, or actually make climate change worse, such as wood bioenergy (Sterman et al. 2022; Sterman 2018a, 2018b). Almost half of participants in Rooney-Varga et al. (2025) study said that engaging with En-ROADS convinced them to take actions they were not otherwise planning; when asked 6 months later, almost 30% of a smaller follow-up group said they had taken actions they attributed to their En-ROADS experience.

Because the simulators and multiple training and engagement materials are freely available, many people have volunteered to undertake a free four-week "Mastering En-ROADS" training program (see https://learn.climateinteractive.org/) to become certified as "En-ROADS Climate Ambassadors." Participants learn about the basics of climate science; En-ROADS, its core structures, and how these drive the dynamics of the climate-energy system, highlighting the systems thinking perspective; different climate solutions; climate equity; and how to facilitate simulation events such as workshops and roleplaying games. As of March 2026, there are more than 951 En-ROADS Climate Ambassadors in 91 countries who have engaged over 372,000 people, making En-ROADS the most-widely used SD model. En-ROADS Climate Ambassadors are vital for advancing the adoption of science-based climate action beyond teams at Climate Interactive and the CPP. Nearly 500,000 people in 185 nations have participated in interactive sessions with both simulators (Climate Interactive 2026), including more than 23,000 leaders in government, business, and civil society (MIT Climate Pathways Project 2026).

3 | Design Principles

To foster stakeholder engagement with SD models, a range of approaches emerged to involve users actively in the

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learning and decision-making processes with simulation models. These approaches vary in depth and complexity to meet the needs and experience of different participants (Morecroft and Sterman 1994). Group model building (GMB) is a participatory process in which stakeholders are actively engaged in the development of feedback diagrams, fostering shared understanding and ownership. While GMB is particularly effective for problem structuring and consensus-building (Andersen et al. 2007; Vennix 1996), it is time-intensive, requires skilled facilitation to navigate group dynamics, and mostly focuses on qualitative modeling. Management flight simulators (MFS) allow stakeholders to interact with pre-built quantitative simulators in controlled, exploratory environments. MFS help users test policies and observe long-term consequences, enhancing strategic thinking and systems literacy (Sterman 2014a, 2014b). However, MFS require substantial development and testing for rigorousness, but risk disengagement if users find the interface or model assumptions opaque or overly complex. To enhance user engagement with pre-built models, "serious games" embed simulators in interactive learning experiences (Hämäläinen et al. 2022). Gamification increases engagement and learning (Creutzig and Kapmeier 2020; Cunico et al. 2022; Looyestyn et al. 2017; Robson et al. 2016); yet, games must be carefully designed to avoid trivializing or oversimplifying serious issues. Finally, in storytelling, existing qualitative and quantitative SD models are embedded within narratives and connected to real-world experiences. Storytelling increases the models' relatability and emotional resonance (Booth Sweeney and Meadows 1995; Gordon et al. 2024; Oliver 2023), but risks introducing bias through the developers' narratives.

SD modelers can use these approaches to engage stakeholders with simulation models. However, models designed to inform real-world policy must meet two fundamental criteria: First, they must be rigorously grounded in the best available science and evidence, fully documented, and replicable so that anyone can assess and critique them. Second, they must be embedded in interfaces and engagements that enable policymakers, other leaders, and the public—not only experts—to learn for themselves. Both are essential: "The most insightful model accomplishes nothing if the interface is obscure and the protocol for its use ineffective. The converse is worse: a poor model embedded in a potent interface may teach harmful lessons more effectively than ever before. Effective virtual worlds require both substantive fidelity and a productive learning process that enables people to challenge and improve their mental models" (Sterman 2006, 512).

Building on these criteria, we articulate and integrate three interrelated design principles highlighted in prior work: Rigorous, empirically grounded modeling and transparency, intuitive and effective interfaces, and facilitated, interactive simulation-based experiences. The En-ROADS modeling team explicitly designed the simulator with these criteria in mind. Figure 1 depicts how these principles operate jointly to affect users' learning and climate-action outcomes. Interface usability together with model rigor and transparency affects learning and action

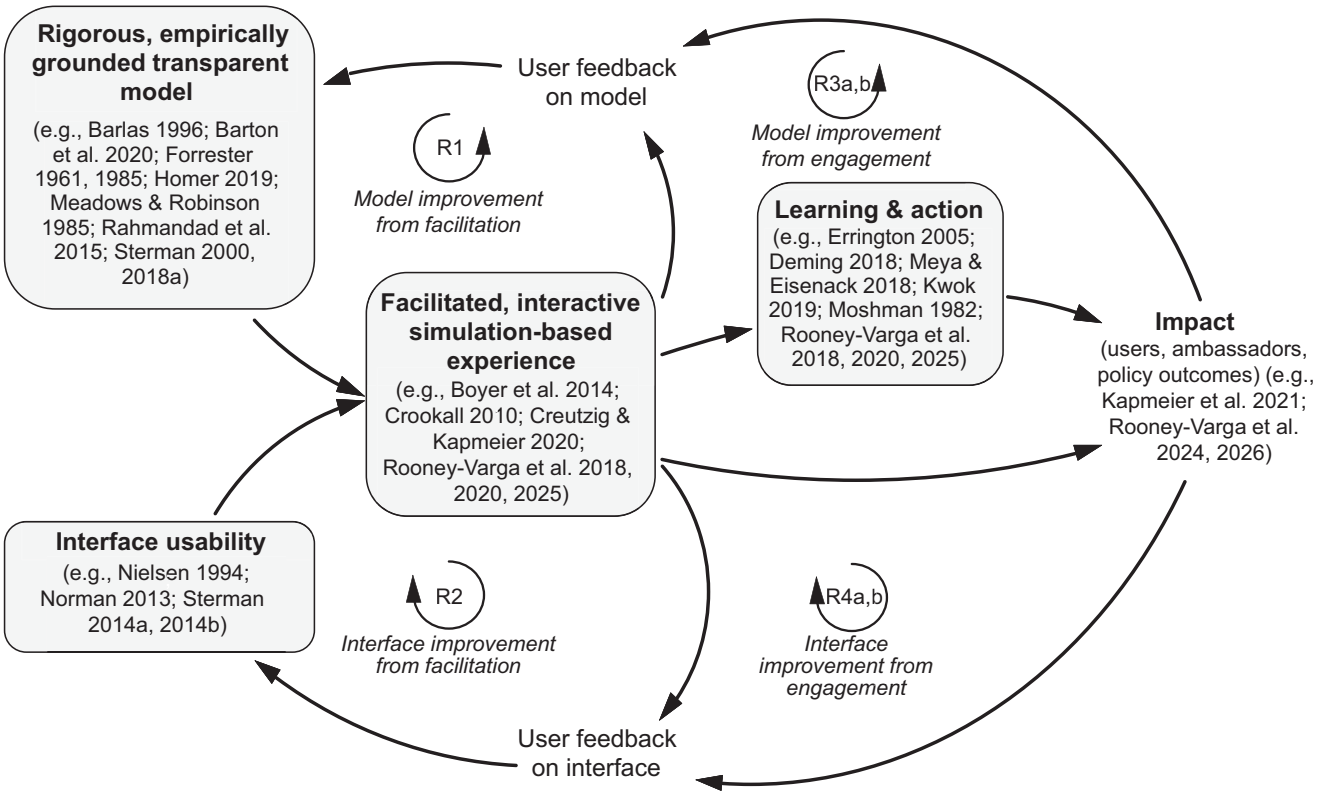

FIGURE 1 | Relationships and their interrelated feedback loops between the design principles. Rigorous, empirically grounded transparent models, together with highly usable interfaces drive engaging facilitated, interactive simulation-based experiences, which foster learning and stimulate action opportunities. Simulation experiences and learning and action increase impact, captured by users, facilitators, and policy outcomes. Reinforcing feedback loops from simulation experiences and from impact provide opportunities for continuously improving interfaces and models.

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outcomes indirectly via facilitated, interactive simulation-based engagement.

Rigorous, empirically grounded modeling and simulator transparency require adherence to established standards for structure and behavior testing and open documentation to support credibility and critique (e.g., Barlas 1996; Barton et al. 2020; Forrester 1961, 1985; J. Homer 2019; Meadows and Robinson 1985; Rahmandad et al. 2015; Sterman 2000, 2018a). Interface usability captures whether the simulator enables intuitive navigation and clear perception of information (e.g., Sterman 2014a, 2014b). Consistent with research on human–computer interaction, interfaces enable efficient exploration and support learning during interaction if they (i) make actions and options visible rather than requiring users to recall them, (ii) employ minimalist design to reduce cognitive load, (iii) enable users to discover insights for themselves, and (iv) provide clear feedback on the results of user actions (e.g., Nielsen 1994; Norman 2013).

Facilitated, interactive simulation-based experience refers to the structured, social, and reflective work, including debriefing, through which participants articulate expectations, discuss surprising results, and make sense of model behavior (e.g., Creutzig and Kapmeier 2020; Crookall 2010). Finally, learning and action outcomes encompass gains in topic knowledge, affective engagement, and action intention or reported behavior following C-ROADS/En-ROADS engagements (e.g., Errington 2005; Rooney-Varga et al. 2025; Rooney-Varga et al. 2020, 2018). Simulation experience and participant learning and action contribute to simulator impact, captured by e.g., the number of simulator users and ambassadors, critical for simulator diffusing (e.g., Rooney-Varga et al. 2024), and policy outcomes (Kapmeier et al. 2021; Noiseux 2022, 2024, 2025; Rooney-Varga, Cheney, et al. 2026).

Both, simulation-based experience and the resulting impact provide opportunities for continuous learning to improve the model and the interface, thereby enabling even greater impact, which in turn provides opportunities for further improvement (e.g., Keating et al. 1999; Sterman 2000, 2015). These dynamics are captured with the reinforcing feedback loops in Figure 1. Participant feedback from facilitated, interactive simulation experiences (R1; R2) can inform refinements of both the model and the interface, enhancing the simulator's rigor, transparency, and useability. Likewise, feedback from users and policymakers (R3a, b; R4a, b) guides further improvements. Growth in the number of participants yields more, and more diverse, feedback, strengthening the reinforcing learning feedbacks and leading to greater growth in model users, skilled facilitators, and other forms of impact. These feedbacks thus link learning and improvement to the growth, scaling, and real-world impact of the simulator.

3.1 | Ensuring Rigorous, Empirically-Grounded Modeling and Model Transparency

System dynamics scholars and practitioners have, from the beginning of the field, argued that modelers should rigorously test model behavior to build confidence (Barlas 1996; Forrester 1961, 1985; J. Homer 2019; Meadows and Robinson 1985; Rahmandad et al. 2015; Sterman 2000, 2018a). To do so, Climate Interactive uses an iterative approach comprising development and testing of both the model and interface, internally and with external experts (Figure 2). New model structures are added based on the scientific literature and new data on the climate, energy system, and economy. Model testing includes partial and full model testing, ensuring new structures are robust under a wide range of conditions (Homer 2012; Morecroft 1985; Oliva and Sterman 2001). Calibration endogenously replicates both historical data and projections from major integrated assessment models (IAMs) across multiple scenarios, such as the scenarios from the

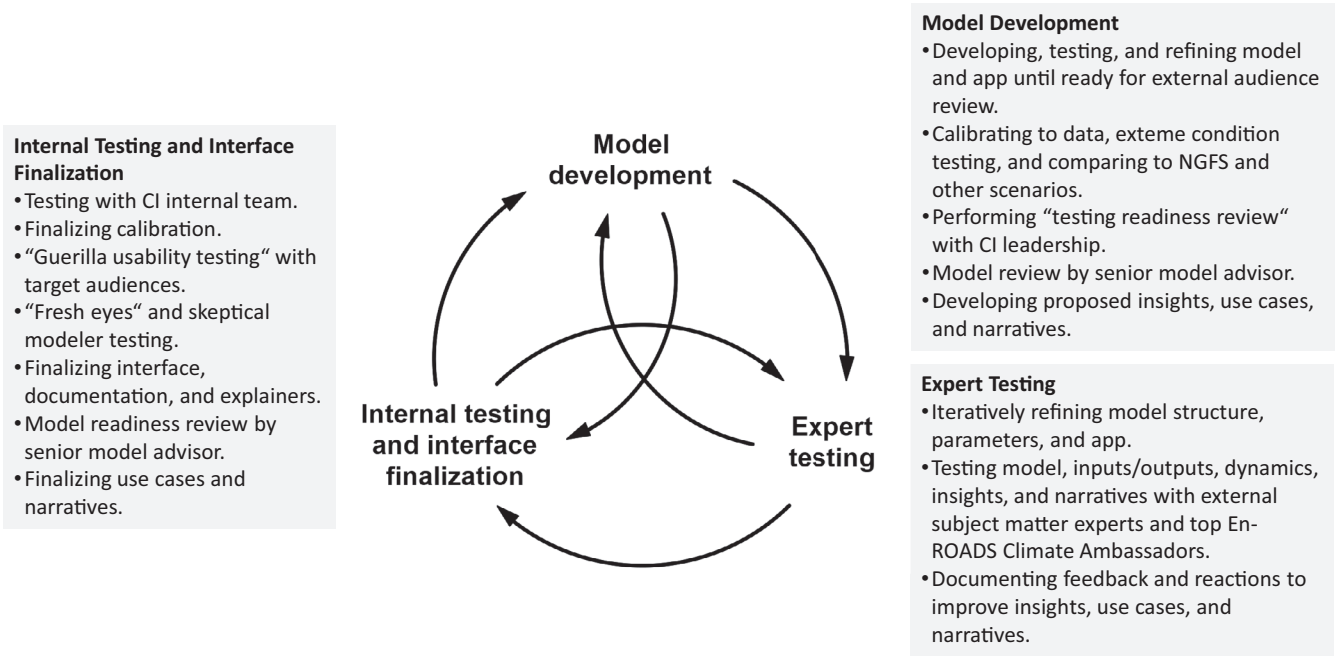

FIGURE 2 | Climate Interactive's model development and testing process comprises three phases.

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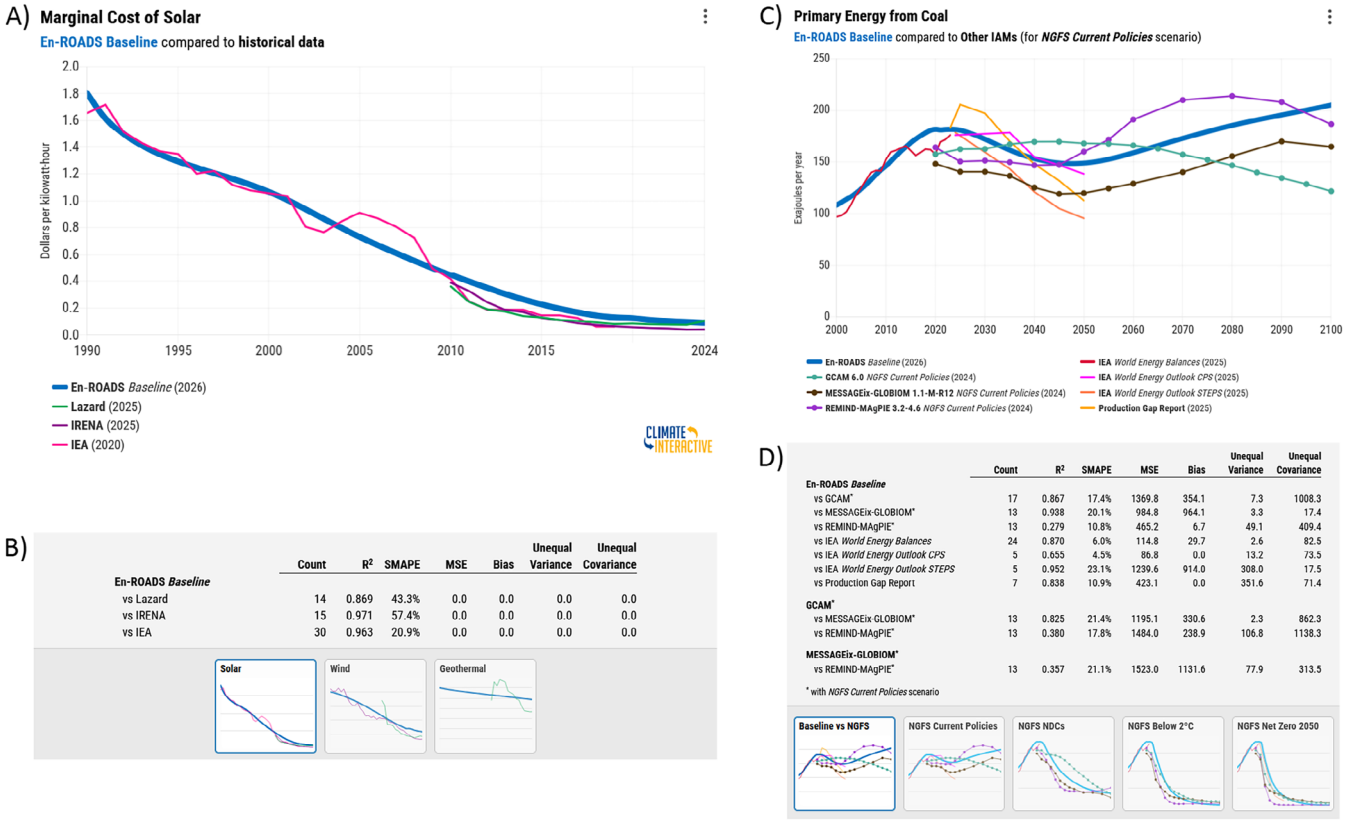

	Count	R^2	SMAPE	MSE	Bias	Unequal Variance	Unequal Covariance
En-ROADS *Baseline*							
vs Lazard	14	0.869	43.3%	0.0	0.0	0.0	0.0
vs IRENA	15	0.971	57.4%	0.0	0.0	0.0	0.0
vs IEA	30	0.963	20.9%	0.0	0.0	0.0	0.0

	Count	R^2	SMAPE	MSE	Bias	Unequal Variance	Unequal Covariance
En-ROADS *Baseline*							
vs GCAM*	17	0.867	17.4%	1369.8	354.1	7.3	1008.3
vs MESSAGEix-GLOBIOM*	13	0.938	20.1%	984.8	964.1	3.3	17.4
vs REMIND-MAgPIE*	13	0.279	10.8%	465.2	6.7	49.1	409.4
vs IEA *World Energy Balances*	24	0.870	6.0%	114.8	29.7	2.6	82.5
vs IEA *World Energy Outlook CPS*	5	0.655	4.5%	86.8	0.0	13.2	73.5
vs IEA *World Energy Outlook STEPS*	5	0.952	23.1%	1239.6	914.0	308.0	17.5
vs Production Gap Report	7	0.838	10.9%	423.1	0.0	351.6	71.4
GCAM*							
vs MESSAGEix-GLOBIOM*	13	0.825	21.4%	1195.1	330.6	2.3	862.3
vs REMIND-MAgPIE*	13	0.380	17.8%	1484.0	238.9	106.8	1138.3
MESSAGEix-GLOBIOM*							
vs REMIND-MAgPIE*	13	0.357	21.1%	1523.0	1131.6	77.9	313.5

* with *NGFS Current Policies* scenario

FIGURE 3 | Comparison of En-ROADS to historical data (A, B) and future scenarios (C, D). (A) Over-time graph in En-ROADS compared to historical data from IEA (2020, pink), IRENA (2023, purple), and Lazard (2023, green). (B) Statistical analysis of model comparison of En-ROADS to historical data with R^2, SMAPE, RMSE, bias, unequal variance, unequal covariance; other marginal cost comparisons are shown in small graphs below. (C) Online documentation of future behavior of primary energy from coal in the En-ROADS baseline scenario compared to NGFS scenarios of IAMs (green: GCAM; brown: Message-Globiom: Pink: REMIND-MAgPIE; red: IEA: Light pink: IEA; orange: Production gap report); (D) Goodness-of-fit metrics for the En-ROADS baseline scenario for primary energy from coal between En-ROADS and other sources, with R^2, SMAPE, RMSE, Bias, unequal variance, and unequal covariance. Screenshots from En-ROADS version 2026.3.0, accessed Mach 15, 2026, https://en-roads.climateinteractive.org.

Network for Greening the Financial System (NGFS 2022), GCAM (Calvin et al. 2017), MESSAGE-GLOBIOM (Riahi et al. 2017), and REMIND-MAgPIE (Kriegler et al. 2017). The simulators undergo expert reviews by external domain specialists, users, and the CI team. In internal testing, the team finalizes calibration, use cases, interface features, and narratives based on potential insights for user to ensure the simulators are accessible, fully documented, and effective in stakeholder engagement. Insights from each phase feed back to the others, creating a cycle of continuous improvement in both the model and the interface.

Model transparency is equally critical as modeling rigor. When models are used to guide policy and corporate decision-making, the stakes are high and lives can be at risk. Transparency is essential so that model results can be evaluated and replicated (Barton et al. 2020), and build credibility with users.

To do so, En-ROADS provides multiple levels of documentation for model structure, tests, and assumptions. The action sliders, output graphs, and user-configurable assumptions in En-ROADS include a short explanation with citations to the underlying literature including links to those sources. Every action slider includes text describing the action in detail, with examples, sources, potential co-benefits, risks, and impacts on equity. Many include links to explanatory videos. For those seeking deeper understanding, En-ROADS offers extensive interactive online documentation, including a user guide, technical reference, and comparison of model behavior against historical data (Figure 3A,B; comparisons against historical data are available at https://docs.climateinteractive.org/projects/en-roads/en/latest/guide/historical_graphs.html) and the projections of major IAMs (see comparison online at https://docs.climateinteractive.org/projects/en-roads-reference-guide/en/latest/pages/comparison_future.html; Figure 3C,D), allowing users at all levels to understand and assess model behavior. Full technical model documentation—including visual representation of the model structure in Vensim, model equations, data sources, and so forth—is available online (https://docs.climateinteractive.org/projects/en-roads-reference-guide/en/latest/index.html), alongside training materials and events including live webinars, videos, blog posts, papers, and an online user guide. During interactive engagements, facilitators are encouraged to share insights into these tests and comparisons with historical data and other models and their scenarios. When time permits, facilitators show participants graphs illustrating how En-ROADS compares to historical data and further online documentation including statistical analyses.

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The multiple modalities and levels of documentation allow users with different backgrounds and levels of expertise to look "under the hood" of the model, addressing a limitation of many MFS—opaqueness and overwhelming complexity—and highlight the value of storytelling approaches designed so complex models become relatable and emotionally resonant.

To ensure participants understand the reference case, facilitators can show how the En-ROADS baseline scenario compares to IAM scenarios, highlighting similarities and differences, and discussing underlying assumptions and outcomes. Helping users understand the reference case surfaces assumptions about population and economic growth, technological progress affecting each energy source, and others, and shows the likely impacts of the resulting energy use, GHG emissions, global warming, and multiple harms arising from it. This framing helps participants understand critical climate dynamics and the need to consider a wide range of impacts to assess the policy actions they choose when designing their own scenarios.

Finally, to address parametric uncertainty and differences of opinion, users can interactively vary key assumptions and parameters to explore the robustness of results to uncertainty and test their own beliefs about the Earth system, economy, energy, and technology, and the interaction therein. In interactive simulation experiences with En-ROADS, facilitators show how participants can access and change these assumptions, encouraging them to explore the range of scientific uncertainty for themselves based on their own beliefs and mental models. Bob Inglis, a former member of the U.S. House of Representatives from South Carolina, emphasizes the importance of model transparency and credibility:

> En-ROADS is a tremendously valuable tool for testing the connection between policy and emissions. It's great to have such a transparent and credible source.

3.2 | Designing Interactive and Effective Model Interfaces for Use Cases

Successfully enabling decision-makers to learn from and take effective action based on insights from a simulation model requires that the model be rigorously grounded in evidence, carefully tested, and be embedded in a user interface and protocol for use that invites and enables users to explore the model for themselves. Advances in computer power and the development of web design applications (e.g., Forio, STELLA Architect by isee systems, Venapp by Ventana Systems) provide new possibilities for effective SD model interface design (Sterman 2014a, 2014b). However, providing access to all variables, relationships, assumptions, and model output risks cognitive overload that can overwhelm users and cause disengagement.

Rather than simply presenting the model structure, effective interfaces guide users to discover critical insights for themselves, even without facilitation. To develop the En-ROADS interface, the Climate Interactive team followed an iterative rigorous formal and a "designed discovery" approach through guerilla usability testing (e.g., Davis and Song 2020), an efficient technique to refine user experience. The team iteratively presented target users, from pre-college students to adult climate professionals, with different interface designs. They were asked "Please do something," without any further guidance. The Climate Interactive team then evaluated outcomes such as whether they could create a scenario that limited global warming below 2°C within 5 min and articulate the primary insights regarding high- versus low-leverage (or "too little, too late") insights. After exploring the simulator, they had to be able to articulate that (i) climate action is still possible, (ii) no single climate solution is sufficient, and (iii) multiple coordinated actions are needed to meet the Paris Agreement goals.

The En-ROADS interface aims to work for both individual exploration and facilitated group interventions. This is accomplished through a layered design, focusing on simplicity and displaying information in an intuitive manner, building on interface innovations from MFS. To enhance user engagement, the interface allows for exploration of the simulator dynamics in real-time, fostering user curiosity and experimentation. The interface also supports storytelling by allowing facilitators to follow their storylines when developing an En-ROADS scenario with participants, potentially mirroring discussions and policy actions in the real world.

The interface's top layer (Figure 4A,B) depicts the most relevant graphs, climate action parameters, and the main outcome: global average surface temperature in 2100 versus preindustrial levels. The top-layer policy levers use linguistic rather than numerical values to show the strength of each action. The top layer thus invites users to explore the simulator, without requiring deep knowledge of climate science, energy production and use, or the economy. Simultaneously, the interface provides expanded and more quantitative options (Figure 5), enabling users to examine model details, change about 250 parameters and assumptions and explore over 180 graphs of model output. Among the latter, the impact graphs and maps play a critical role as they help users translate abstract climate impacts such as atmospheric GHG concentrations or mean global temperature change into more concrete and locally relevant impacts. Outcome maps—such as projected sea-level rise (Figure 4F), days of exposure to extreme heat (Figure 4C), wildfire risk (Figure 4E), drought likelihood, and local temperature change (Figure 4D)—make abstract impacts more salient and emotionally resonant. Such visual representations help users grasp the real-world implications of policy choices, enhance affective engagement, and strengthen users' sense of urgency (Rooney-Varga et al. 2025; Rooney-Varga, Fracassi, et al. 2021). Visualizations of climate change often make a stronger impression than numerical indicators (Rooney-Varga, Cheney, et al. 2026).

Interfaces should enable users to interact in real-time, and adapt to different devices and screen sizes while maintaining usability. Thus, in En-ROADS, browser-based operation means the simulator works on any laptop, desktop, or tablet, and any screen size. While the core model is developed in Vensim, the interface is designed with SDEverywhere (https://sdeverywhere.org/), which includes tools to transform an SD model into C, JavaScript, and WebAssembly code. Hence, when En-ROADS is opened the compiled model code is downloaded to the user's browser and then runs locally without requiring internet

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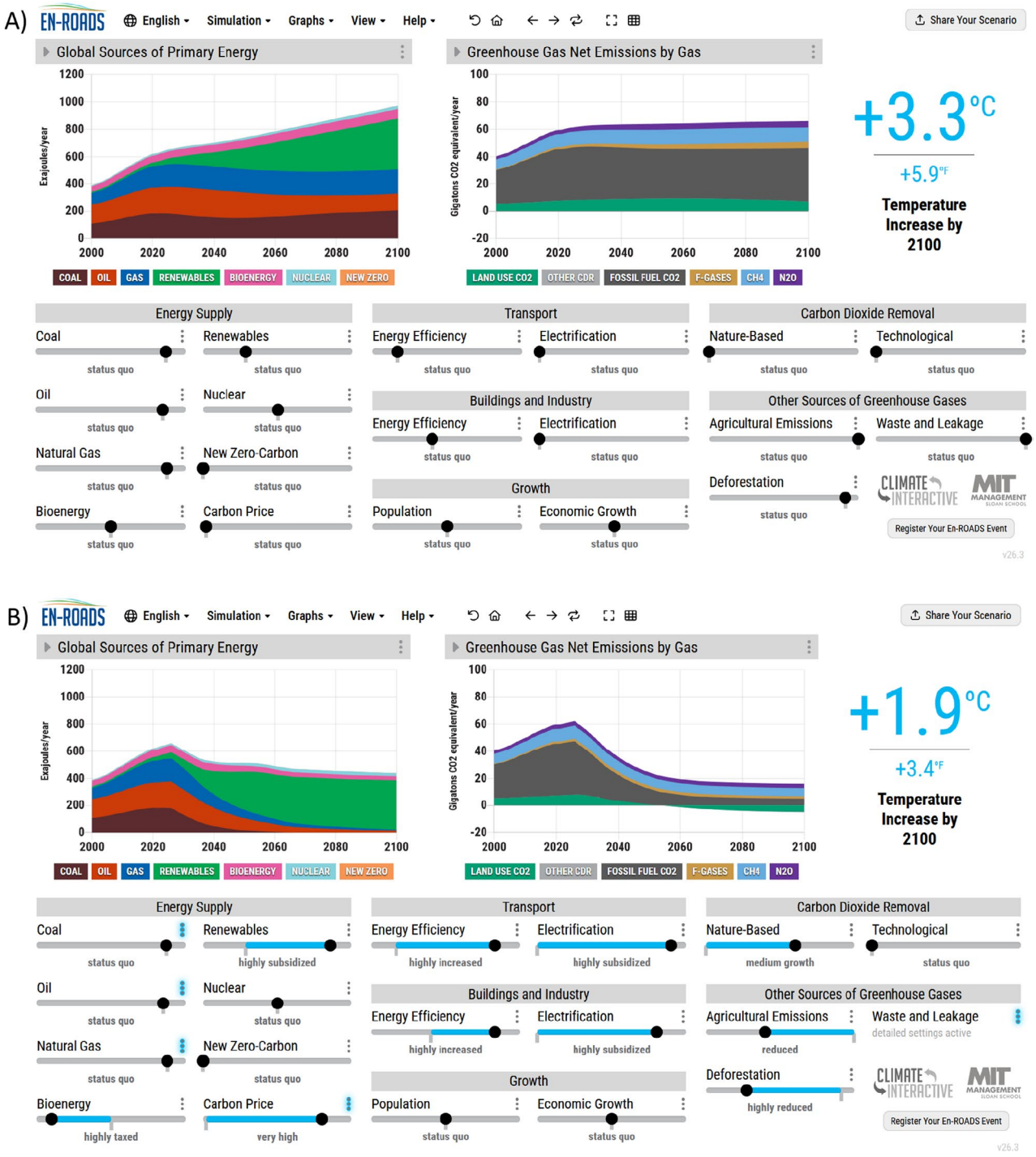

FIGURE 4 | Top layer of the En-ROADS interface. (A) Top layer showing global sources of primary energy (upper left) and greenhouse gas emissions (top center) as over-time behavior with main outcome, the temperature increase in 2100 versus preindustrial times (upper right). Below are sliders that allow users to try 19 policy actions affecting "energy supply" (left), energy end uses in transportation and buildings and industry (center), assumptions about population and economic growth (center), various carbon dioxide removal options (top right) and greenhouse gas emissions from sources other than fossil fuels (bottom right). Menus at the top allow users to select the language, access and alter key assumptions, choose from dozens of graphs, choose metric or English units for, for example warming and sea-level rise, and access help including the online users' guide and model documentation. (B) Top-layer interface showing a "silver buckshot" scenario that reduces expected warming from 3.3°C above preindustrial levels to 1.9°C. Clicking on the three dots to the right of each policy slider opens advanced policies, enabling users to access more, and more detailed, policies and actions. Policy actions at the advanced layer are shown by the blue highlighting on the three dots. Link to the scenario: https://en-roads.climateinteractive.org/scenario.html?v=26.3.0&p196=100&p198=50&p200=50&p16=-0.04&p23=20&p39=200&p42=500&p43=2070&p44=25&p47=2.5&p50=2.5&p373=45&p375=40&p60=60&p417=60&p209=1&p405=30&p404=30&p441=30&p406=30&p415=30&p57=-7&g0=2&g1=63. (C–F) Maps showing local impacts in the reference case (baseline) in the year 2100 for: (C) Extreme heat days in Asia (from India to China); (D) Local temperature change, indicating temperature change in Greenland; (E) Wildfire risk in North America; (F) Sea level rise with storm surge in Shanghai. Screenshots from En-ROADS version 2026.3.0, accessed March 15, 2026, https://en-roads.climateinteractive.org.

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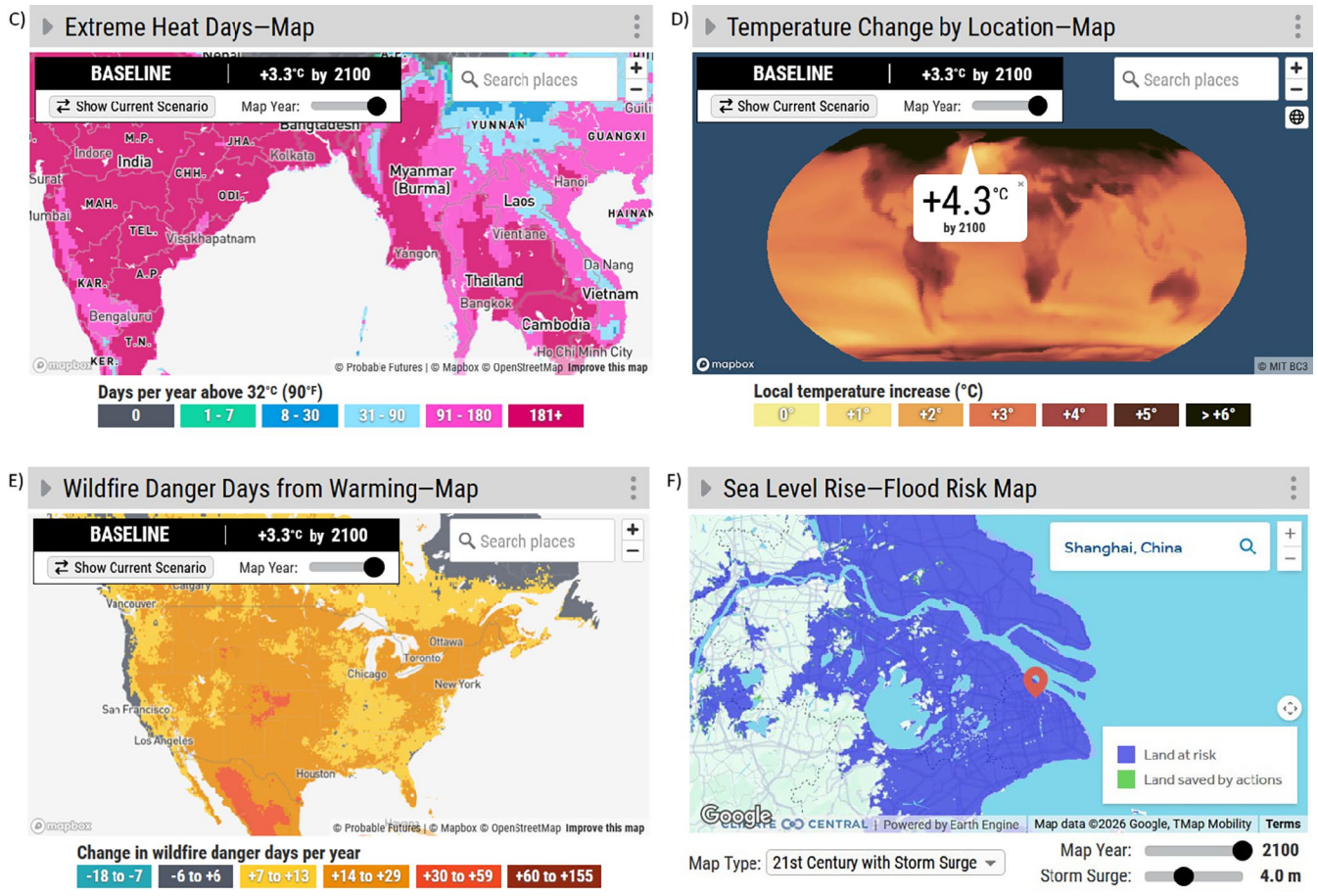

FIGURE 4 | (Continued)

access.[1] This enables En-ROADS to be used in low-connectivity environments and ensures rapid simulation speed. The results of user actions are computed and displayed in approximately 60 milliseconds so that the response of the model seems nearly instantaneous. To further expand its reach, En-ROADS is available in 22 languages, and users can instantly switch among them.

Rooney-Varga et al. (2026) found that the interactive design of the En-ROADS interface is engaging, enhances learning, and makes the underlying complex concepts accessible. For example:

> If you get more interaction, you can keep and take more away...Doing something and really playing with the levers it's much more effective than only reading a text, listening to a podcast, or watching a video.
>
> (Vice president of communication for an energy utility company)

The interactive nature of En-ROADS enhances stakeholders' engagement, learning experience, and recall ability. For example:

> The actual visual impact was probably the thing that made me feel the most sense of urgency as opposed to, like, the temperature number.
>
> (Policy fellow of an NGO)

Likewise:

> I think actually being able to play with those dials ... really etched in my mind—[it] was really easy to understand in a way that having read a lot and heard a lot, wasn't as clear as it was with the tool.
>
> (U.S. Government foreign service officer)

Many users understand that the interactivity and ease of use, together with the multiple levels of documentation, make En-ROADS a serious tool, not a video game (Sterman 2008, 2011; Sterman and Sweeney 2007), as Dr. Georg Stamatelopoulos, CEO of the German energy utility EnBW AG, explained:

> Don't be fooled by the fast, fun interface. En-ROADS is a serious, science-based tool for climate decision-making. The model is fully documented, right down to its key assumptions, which you, as the user, can change. En-ROADS enables you to test, in mere seconds, your own hypotheses on how we can combat climate change. It helped me visualize why it's so critical to prioritize policies that help us move away from fossil fuels and drive the energy transition.

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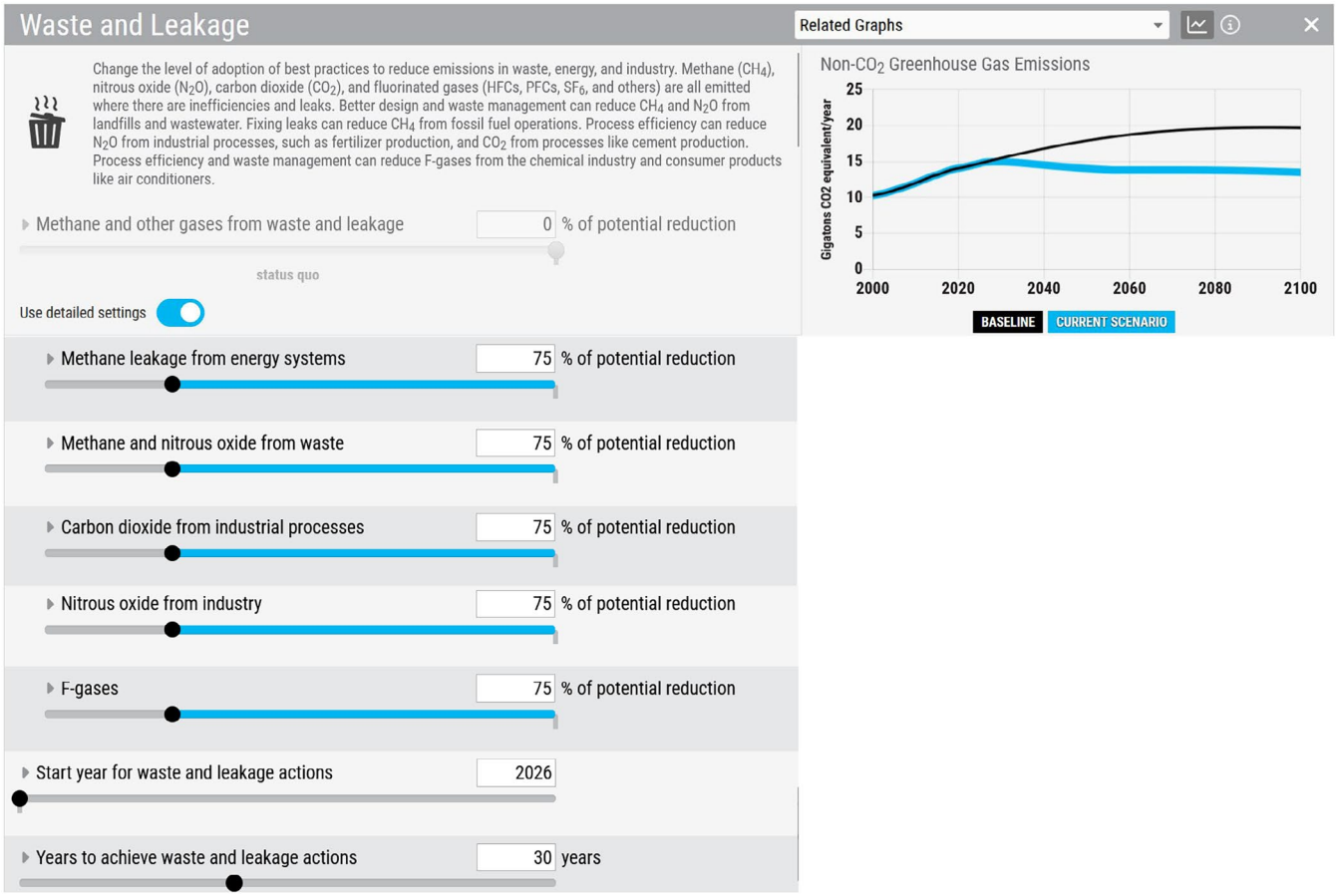

FIGURE 5 | Advanced settings in En-ROADS. Many advanced policy actions are available through dropdown menus, shown here using the example of greenhouse gas emissions from waste and leakage. Screenshot from En-ROADS version 2026.1.0, accessed January 24, 2026, https://en-roads.climateinteractive.org.

3.3 | Creating Facilitated, Interactive Experiences With Mental Simulation

Most people rely on intuitive mental models of cause–effect relationships, intuitions that are powerful but frequently incorrect and misleading in complex dynamic systems. These misconceptions cannot be overcome by presenting the results of model analyses. Interactive simulations, in contrast, can surface and challenge these misconceptions, helping people develop more accurate mental models. Facilitators should enable self-directed learning (Boyer et al. 2014; Knowles 1975) by framing model engagement as exploratory exercises in which participants discover insights for themselves through experimentation and discussion: When participants themselves can change parameter settings or assumptions, test strategies, and observe consequences, they become active participants in the learning process.

A third design principle is incorporating analytic and affective cognition by integrating En-ROADS into social and emotionally engaging experiences. The team developed three facilitated interactive modes of engagement around the C-ROADS and En-ROADS simulators, of which the first two are "serious games" (Creutzig and Kapmeier 2020). All three utilize the participatory nature of GMB to foster shared learning, not in the actual modeling but through joint scenario development, and integrate ideas of storytelling, as facilitators frame scenarios within real-world contexts, making abstract insights from simulation models more tangible and personally relevant. The engagement protocols are: (1) the World Climate Simulation (Rooney-Varga et al. 2018), a role-playing game around the UN climate change negotiations with C-ROADS, for up to 80 participants; (2) the Climate Action Simulation (CAS; Rooney-Varga et al. 2020), a role-playing game with En-ROADS for a similar group size in which participants represent global stakeholders including nations, the fossil fuel industry, industry and commerce, clean tech, land and agriculture, climate activists, and others, charged with negotiating actions and policies to meet the goals of the Paris Agreement and limit global warming to well below 2°C (UNFCCC 2015) at a fictitious UN climate summit; and (3) the En-ROADS Climate Workshop, a facilitated interactive experience to test climate strategies used in high-level briefings of senior leaders in government, business, and civil society, as well as students from middle school through executive education. It is effective with individuals, but more engaging in groups with up to a several hundred participants. Participants are encouraged to work in teams of 2–3 as doing so encourages them to articulate their ideas and build mutual understanding as they suggest policies and explain the results to one another. In all these protocols C-ROADS and En-ROADS provide immediate feedback on the expected outcomes of proposed solutions and encourage participants to explore the models to understand the reasons for the results. The process is iterative, with the goal of creating outcomes limiting global warming to less than 2°C above preindustrial

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levels. Debriefing is an essential component in all three protocols. Participants are encouraged to share what they learned, including which policies and actions were more effective than others, why, and which outcomes were surprising to them; how they feel about their experience, and what they will do next to take action in the real world, personally, professionally, and politically (i.e., as citizens). Reflective discussion is a critical learning moment and often the most important part of the experience because it enables participants to interpret their experiences, draw meaning from them, and begin to integrate the model results into their own thinking (Crookall 2023). That is the moment when the simulation experience is transformed into learning (Crookall 2010).

Three characteristics enhance the effectiveness of interactive simulations in these engagement protocols. First, framing them as challenges or game-based experiences (Creutzig and Kapmeier 2020) encourages participants to experiment actively, deepening their understanding of the underlying complexity and dynamics of the climate-energy-economic system. Active experimentation fosters critical thinking about trade-offs and unintended consequences. For instance, instead of simply showing the impacts of changing assumptions, participants are invited to work together toward a goal—such as reducing emissions to meet the Paris Agreement goals—by changing policy levers in the simulator. Facilitators invite the audience to suggest which parameters to change, hence making participants owners of the scenario they create. If the audience is small, this can happen through direct verbal interaction (Figure 6B); if larger, polling software is recommended (Figure 6A). Having participants, rather than facilitators or experts, choose the policies and

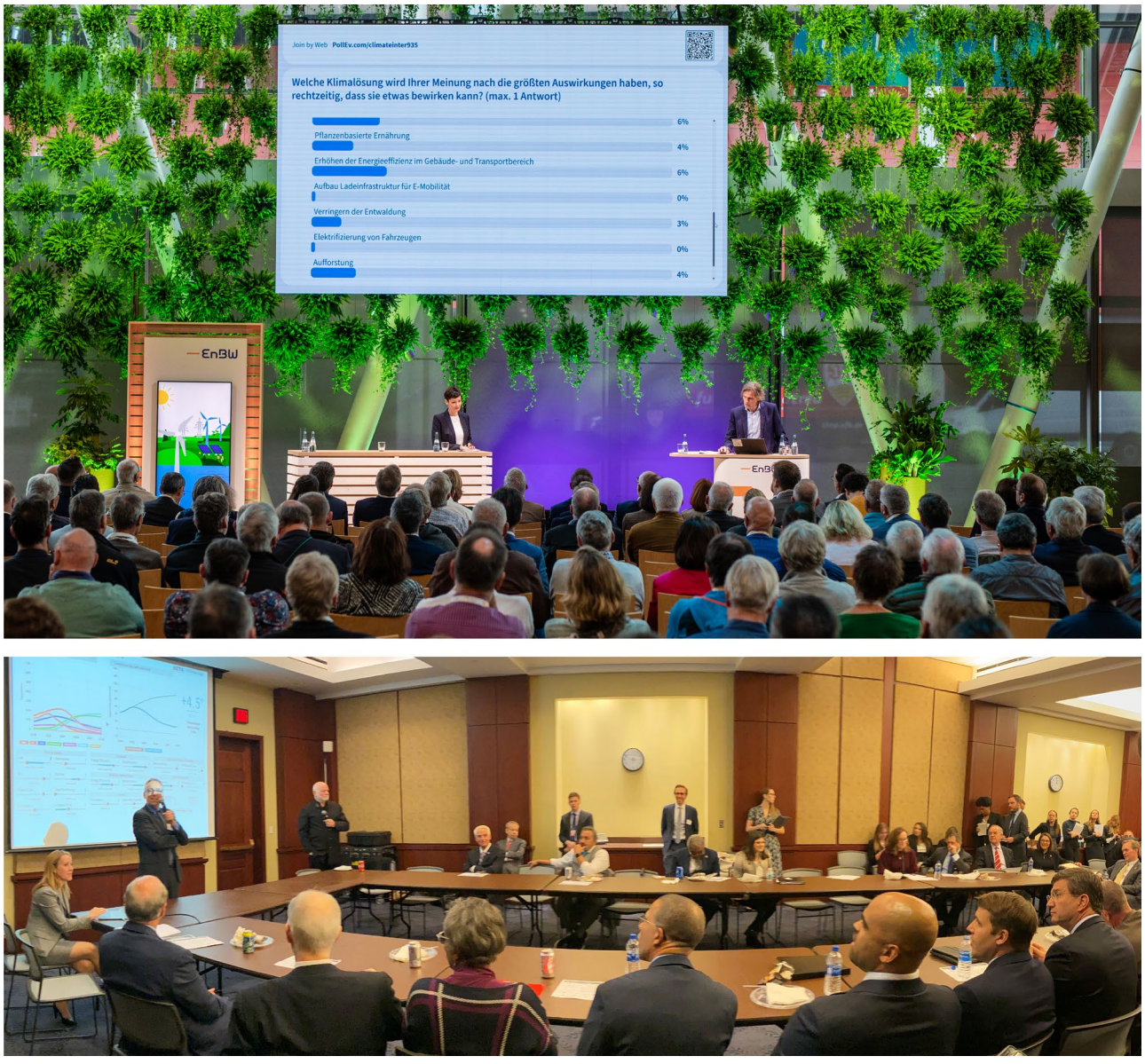

FIGURE 6 | Making the audience part of the scenario development. (A) In large groups (here, 850 local leaders at the Energy Municipal Day in October 2023 in Stuttgart, Germany), participants actively participate in scenario development using online polling software; photo: ARTIS-Ulli Deck. (B) A facilitated conversation with a relatively small group (here, 20 members of the US Congress and staffers); photo: Climate Interactive.

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actions to explore, and seeing the resulting impacts, can generate feelings of urgency (Rooney-Varga et al. 2018).

Second, through scenario-based learning (Errington 2005), inspired by Deming's (2018) principle of "no theory, no learning," participants are encouraged to reflect critically and articulate their expectations about anticipated simulation results based on their own mental models *before* changing levers and running scenarios (see Figure 7). Doing so reveals discrepancies between their own mental models and system behavior, creating cognitive disequilibrium—a critical step in constructivist learning (Moshman 1982). Active experimentation also engages participants more deeply in the exercise and makes them more curious about the underlying reasons for the outcomes, prompting further discussion and exploration of the model. For example, in En-ROADS simulation experiences, facilitators ask participants to state how much their suggested climate policies will reduce expected warming by 2100. Results are immediately displayed as the policy slider is moved, allowing participants to compare their estimates to the model outcome. Facilitators highlight discrepancies and use En-ROADS to show, rather than tell, what happened and why.

Third, when engaging multiple participants, social learning can be fostered through discussions and collaborative activities (Kwok 2019; Meya and Eisenack 2018). When engaged in conversations about model behavior, participants both clarify their own understanding and influence and learn from peers. To support these interactions, facilitators should encourage structured dialogue by pausing frequently during engagements to allow participants to reflect and discuss insights with one another. This is especially important in complex policy environments with multiple interests and perspectives. In

FIGURE 7 | Encouraging participants to reflect critically and articulate their expectations about the anticipated simulation results. The coauthors with (A) John Kerry, former U.S. special presidential envoy for climate, Boston, February 2020; photo: Bethany Patten. (B) John Curtis, US Senate, Republican, Utah; photo: Climate Interactive. (C) Member of the European Parliament Raphaël Glucksmann, Paris, May 2025; photo: Chloé Berthon.

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FIGURE 8 | Fostering social learning through discussions and exercises in CAS and an En-ROADS Climate Workshop. (A) Government, business, and civil society leaders from Southeast Asia, MIT Sloan School of Management, June 2024; photo: Otto Scharmer. (B) Executive MBA students, MIT Sloan School of Management, 2019; photo: Marty Nee. (C) About 100 local leaders present their En-ROADS scenarios after having worked together in groups of two or three to develop climate scenarios with En-ROADS in the Enz District in Germany; photo: Florian Kapmeier.

En-ROADS Workshops, for example, facilitators often encourage participants to "turn to your neighbor and discuss," which increases engagement and peer-to-peer learning (Rooney-Varga et al. 2020, 2018). Alternatively, facilitators may invite the audience to work on the climate scenario in small groups with En-ROADS on tablets. After testing two or three climate actions together with the audience, the facilitator shares the scenario with the audience via a QR code. Participants then open the scenario with tablets and work together in small groups to achieve the goal (Figure 8C). After some time, the facilitator reconvenes the plenary session, asking the audience which climate actions they would like to test next until the climate goals are met. The results can be shared via online tools such as Google slides, so that participants see their own scenarios and those of others instead of one the facilitator creates.

To highlight this, Landmann et al. (2024) analyzed learning outcomes from En-ROADS when university students interacted with the simulator individually. They found that while knowledge about specific climate solutions increased, it did not significantly affect participants' sense of urgency. In contrast, the participatory nature of the Climate Action Simulation, where En-ROADS is embedded in a simulation of social dynamics, participants' sense of urgency, agency, and their desire to learn more and take action increased (Rooney-Varga, Cheney, et al. 2026; Rooney-Varga, Coleman, et al. 2025; Rooney-Varga et al. 2020) (Figure 8A,B). Such social interactions in En-ROADS engagements is key to learning and action, underlining that interactions with others during engagements plays a key role:

> [Social interaction]'s a very important factor, to give a thought of group feeling [...] and to, to push us to work together and to be creative
>
> (Regional Group Spokesperson of an NGO).

Taken together, these three design principles highlight how rigorous, empirically grounded models with transparent, fully documented, intuitive interfaces, used in facilitated, interactive experiences jointly support learning and engagement. In the next section, we introduce a conceptual model intended to guide future empirical research to further improve the design and use of interactive simulations to foster learning and action.

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4 | Discussion and Future Research Directions

How can models be designed for real-world impact? With the example of En-ROADS and our experience bringing these tools to diverse audiences around the world, we highlight three model design principles: rigorous modeling and simulator transparency, interactive and effective model interface, and facilitated, interactive simulation-based experience. These enable En-ROADS users to learn about climate change, the energy system, and the economy—and what can be done to mitigate the climate crisis. Rigorous modeling and transparent documentation build confidence in the simulator. Interface usability increases interest in exploring the simulator dynamics and the underlying structure. Mental simulation in facilitated, interactive simulation-based experiences, including interactive workshops and role-playing games, encourages participants to actively test assumptions, learn for themselves, and engage socially with others, motivating the desire to learn more and take action.

Even though climate change is an archetypal wicked problem (Grundmann 2016), the mechanisms through which simulation-based engagement supports learning are broadly relevant to many other domains. Similar characteristics of complex dynamic systems—delays, nonlinearities, and intertwined feedback loops—challenge decision-makers in public health, supply chains, and organizational strategy just as they do in climate. Therefore, while our focus is climate change, the design principles we outline apply to all settings in which policymakers must make decisions in complex dynamic systems under time pressure. That said, the design principles must be adopted to the problem under study. Data availability may vary between domains, which might require participatory approaches for validation (Vennix 1996). Interface design will differ: the designers of a successful interactive simulation to improve operations and safety in the chemical industry chose a physical board game instead of a computer model to ensure transparency and enhance interactivity for their primary audience, front-line mechanics and operators (Repenning and Sterman 2001). Situations with high uncertainty, such as the COVID pandemic, increase the risk that compelling interfaces may inadvertently communicate false precision (Barton et al. 2020). Facilitation protocols may differ depending on social dynamics including organizational culture and conflicts and heterogeneity in stakeholder background, goals, and power (e.g., Andersen et al. 2007; Hovmand 2014; Vennix 1996).

To enhance model implementation and real-world impact, future research should explore a wide range of models and protocols for their use. Figure 9 shows a conceptual model with four latent constructs, enhancing Figure 1. It hypothesizes that facilitated, interactive simulation-based experiences mediate the effects of rigorous, empirically grounded, transparent models and interface usability on learning and action. Each construct is linked to observable outcomes such as potential survey items or behavioral indicators. Measures of rigorous modeling and transparency could include a range of model tests and assessments of documentation quality and clarity; for interface usability these could include ease of user navigation and visual clarity; and for facilitated, interactive simulation-based experience they could be affective engagement and cognitive insight. Outcomes could be captured through knowledge gained, participants' intent to take action, actions taken, reported behavior change, and system outcomes. The model provides a foundation for additional empirical validation using, for example factor analysis or structural equation modeling. Collecting data from En-ROADS engagements would allow modelers and other researchers to improve the design of future simulators and engagements, enabling practitioners to tailor interventions to meet the needs of their audiences.

The underlying design principles are not independent from each other. The development of En-ROADS relies on an iterative process (Figures 1 and 2): Insight from facilitation informs interface refinements, usability testing highlights where design

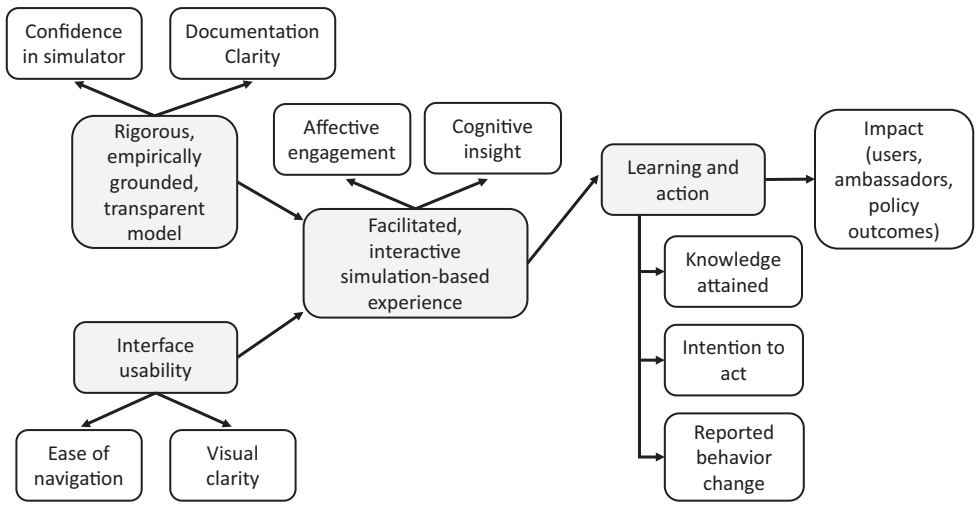

FIGURE 9 | Conceptual model for future empirical research on simulation-based engagement, illustrating hypothesized relationships among four latent constructs, rigorous, empirically grounded modeling, & simulator transparency, interface usability, facilitated, interactive simulation-based experience (mediator), and learning and action (outcome). Each construct is linked to observable outcomes from, for example surveys or actions. Latent constructs are in grey boxes, observed variables in white boxes, and directional relationships are shown with black arrows. The model provides a foundation for empirical testing using factor analysis or structural equation modeling. The feedbacks driving continuous improvement and scaling shown in Figure 1 are omitted.

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must better support exploration and storytelling, and modeling updates expand the learning experiences facilitators can create. This interdependency ensures alignment between model design and engagement practice, enabling the three principles to support each other.

As shown in Figure 1, the En-ROADS Climate Ambassador program plays a critical role in scaling its impact. Building a community of trained facilitators is essential to foster adoption of educational innovations in sustainability (Rooney-Varga et al. 2024). As an example, the EU Pact Ambassadors (Tosun et al. 2023) "inform, inspire, and support climate policy and action in their communities and networks" (European Commission 2025) to increase citizen involvement in politics. Likewise, Climate Interactive trains facilitators through a structured curriculum and certifies them to lead En-ROADS events to enhance reach, consistency, and quality. We view this scaling as a broader diffusion process that complements the learning processes represented in Figure 9.

Researchers could also examine how facilitator expertise and training affect outcomes. Group model building research (e.g., Andersen et al. 2007; Hovmand 2014; Vennix 1996) demonstrates that facilitation quality strongly affects the learning experience. Facilitators shape the learning experience by framing discussions, encouraging reflection, and inviting participants to engage in social interaction. Their ability to adapt to diverse audiences—ranging from students to senior policymakers—can influence the success of any simulation. Understanding how the simulator experience affects the recruitment, development, and impact of skilled facilitators can enhance the effectiveness of system dynamics-based interventions.

Facilitator development and quality strongly affect the ability to scale the use of interactive simulations. Facilitators devote their time voluntarily and must balance the time commitment with other professional and personal commitments. Understanding what motivates people to join such communities, remain active, and attract more members (Rooney-Varga et al. 2024), can help expand simulation use and real-world impact.

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Ethics Statement

The authors have nothing to report.

Data Availability Statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

Endnotes

[1] A small number of model outcomes require data exchange with remote servers, including maps showing sea-level rise, extreme heat days, and wildfire risk.

References

Alley, Z. M., J. E. Chapman, H. Schaper, and L. Saldana. 2023. "The Relative Value of Pre-Implementation Stages for Successful Implementation of Evidence-Informed Programs." *Implementation Science* 18, no. 1: 30. https://doi.org/10.1186/s13012-023-01285-0.

Andersen, D. F., J. A. M. Vennix, G. P. Richardson, and E. A. J. A. Rouwette. 2007. "Group Model Building: Problem Structuring, Policy Simulation and Decision Support." *Journal of the Operational Research Society* 58, no. 5: 691–694. https://doi.org/10.1057/palgrave.jors.2602339.

Barlas, Y. 1996. "Formal Aspects of Model Calidity and Calidation in System Dynamics." *System Dynamics Review* 12, no. 3: 183–210.

Barton, C. M., M. Alberti, D. Ames, et al. 2020. "Call for Transparency of COVID-19 Models." *Science* 368, no. 6490: 482–483. https://doi.org/10.1126/science.abb8637.

Booth Sweeney, L., and D. Meadows. 1995. *The Systems Thinking Playbook. Exercises Sto Stretch and Build Learning and Systems Thinking Capabilities*. Chelsea Green.

Boyer, S. L., D. R. Edmondson, A. B. Artis, and D. Fleming. 2014. "Self-Directed Learning:A Tool for Lifelong Learning." *Journal of Marketing Education* 36, no. 1: 20–32. https://doi.org/10.1177/0273475313494010.

Calvin, K., B. Bond-Lamberty, L. Clarke, et al. 2017. "The SSP4: A World of Deepening Inequality." *Global Environmental Change* 42: 284–296. https://doi.org/10.1016/j.gloenvcha.2016.06.010.

Churchman, C. W. 1964. "Managerial Acceptance of Scientific Recommendations." *California Management Review* 7, no. 1: 31–38. https://doi.org/10.2307/41165618.

Climate Interactive. 2026. "Our Impact. Climate Interactive." https://www.climateinteractive.org/strategy-and-impact/.

Creutzig, F., and F. Kapmeier. 2020. "Engage, Don't Preach: Active Learning Triggers Climate Action." *Energy Research & Social Science* 70: 101779. https://doi.org/10.1016/j.erss.2020.101779.

Crookall, D. 2010. "Serious Games, Debriefing, and Simulation/Gaming as a Discipline." *Simulation & Gaming* 41, no. 6: 898–920. https://doi.org/10.1177/1046878110390784.

Crookall, D. 2023. "Debriefing: A Practical Guide." In *Simulation for Participatory Education: Virtual Exchange and Worldwide Collaboration*, edited by M. L. Angelini and R. Muñiz, 115–214. Springer International Publishing. https://doi.org/10.1007/978-3-031-21011-2_6.

Cunico, G., E. Aivazidou, and E. Mollona. 2022. "System Dynamics Gamification: A Proposal for Shared Principles." *Systems Research and Behavioral Science* 39, no. 4: 723–733. https://doi.org/10.1002/sres.2805.

Daioglou, V., E. Mikropoulos, D. Gernaat, and D. P. van Vuuren. 2022. "Efficiency Improvement and Technology Choice for Energy and Emission Reductions of the Residential Sector." *Energy* 243: 122994. https://doi.org/10.1016/j.energy.2021.122994.

Davis, R. C., and X. Song. 2020. "Uncovering the Mystery of How Users Find and Use eBooks Through Guerilla Usability Testing." *Serials Review* 46, no. 3: 193–200. https://doi.org/10.1080/00987913.2020.1806648.

10991727, 2026, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/sdr.70024 by Hochschulbibliothek Reutlingen, Wiley Online Library on [30/06/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Deming, W. E. 2018. *The New Economics for Industry, Government, Education*. MIT Press.

Errington, E. 2005. *Creating Learning Scenarios: A Planning Guide for Adult Educators*. CoolBooks.

European Commission. 2025. "Become an Ambassador or a 'Friend of the Pact'. European Commission." https://climate-pact.europa.eu/get-involved/become-pact-ambassador_en.

Forrester, J. W. 1961. *Industrial Dynamics*. Productivity Press.

Forrester, J. W. 1985. "The "Model Versus a Modeling" Process." *System Dynamics Review* 1, no. 1: 133–134. https://doi.org/10.1002/sdr.4260010112.

Gordon, D., A. N. Mashayekhi, A. Tomoaia-Cotisel, et al. 2024. "Developing Model-Based Storytelling to Share Systemic Insights to the Public During the COVID-19 Pandemic." *System Dynamics Review* 40, no. 3: e1771. https://doi.org/10.1002/sdr.1771.

Größler, A. 2007. "System Dynamics Projects That Failed to Make an Impact." *System Dynamics Review* 23, no. 4: 437–452. https://doi.org/10.1002/sdr.365.

Grundmann, R. 2016. "Climate Change as a Wicked Social Problem." *Nature Geoscience* 9, no. 8: 562–563. https://doi.org/10.1038/ngeo2780.

Hämäläinen, R. P., K.-R. Kumpulainen, J. T. Harviainen, and E. Saarinen. 2022. "Design Gaming for Learning Systems Intelligence in Socio-Emotional Systems." *Systems Research and Behavioral Science* 39, no. 1: 163–167. https://doi.org/10.1002/sres.2750.

Homer, J. 2019. "A Comment on John Sterman's "System Dynamics at Sixty: The Path Forward"." *System Dynamics Review* 35, no. 1: 5–7. https://doi.org/10.1002/sdr.1615.

Homer, J. B. 2012. "Partial-Model Testing as a Validation Tool for System Dynamics (1983)." *System Dynamics Review* 28, no. 3: 281–294. https://doi.org/10.1002/sdr.1478.

Homer, J., B. Milstein, and G. B. Hirsch. 2020. "System Dynamics Modeling to Rethink Health System Reform." In *Complex Systems and Population Health*, edited by Y. Apostolopoulos, M. K. Lemke, and K. Hassmiller Lich, 185–200. Oxford University Press. https://doi.org/10.1093/oso/9780190880743.003.0013.

Hovmand, P. S. 2014. "Group Model Building and Community-Based System Dynamics Process." In *Community Based System Dynamics*, edited by P. S. Hovmand, 17–30. Springer New York. https://doi.org/10.1007/978-1-4614-8763-0_2.

Kapmeier, F., A. S. Greenspan, A. P. Jones, and J. D. Sterman. 2021. "Science-Based Analysis for Climate Action: How HSBC Bank Uses the En-ROADS Climate Policy Simulation." *System Dynamics Review* 37, no. 4: 333–352. https://doi.org/10.1002/sdr.1697.

Kapmeier, F., J. N. Rooney Varga, A. P. Jones, and J. D. Sterman. 2026. "The Interactive En-ROADS Climate Policy Simulator: Leveraging Systems Thinking for Climate Action and Sustainability." In *Mastering Complexity, Achieving Sustainability*, edited by M. Schwaninger and A. Espinosa. Edward Elgar Publishing Ltd. In Press.

Keating, E., R. Oliva, N. Repenning, S. Rockart, and J. Sterman. 1999. "Overcoming the Improvement Paradox." *European Management Journal* 17, no. 2: 120–134. https://doi.org/10.1016/S0263-2373(98)00072-3.

Knowles, M. S. 1975. *Self-Directed Learning: A Guide for Learners and Teachers*. Prentice Hall.

Kriegler, E., N. Bauer, A. Popp, et al. 2017. "Fossil-Fueled Development (SSP5): An Energy and Resource Intensive Scenario for the 21st Century." *Global Environmental Change* 42: 297–315. https://doi.org/10.1016/j.gloenvcha.2016.05.015.

Kwok, R. 2019. "Can Climate Change Games Boost Public Understanding?" *Proceedings of the National Academy of Sciences* 116, no. 16: 7602–7604. https://doi.org/10.1073/pnas.1903508116.

Landmann, H., W. Ziegler, and R. Gaschler. 2024. "Simulating Climate Policies Influences How Laypersons Evaluate the Effectiveness of Climate Protection Measures." *Environment, Development and Sustainability* 28: 05028. https://doi.org/10.1007/s10668-024-05028-z.

Little, J. D. C. 1970. "Models and Managers: The Concept of a Decision Calculus." *Management Science* 16, no. 8: B-466–B-485. https://doi.org/10.1287/mnsc.16.8.B466.

Looyestyn, J., J. Kernot, K. Boshoff, J. Ryan, S. Edney, and C. Maher. 2017. "Does Gamification Increase Engagement With Online Programs? A Systematic Review." *PLoS One* 12, no. 3: e0173403. https://doi.org/10.1371/journal.pone.0173403.

Meadows, D. H., and J. M. Robinson. 1985. *The Electronic Oracle*. Wiley.

Meya, J. N., and K. Eisenack. 2018. "Effectiveness of Gaming for Communicating and Teaching Climate Change." *Climatic Change* 149, no. 3: 319–333. https://doi.org/10.1007/s10584-018-2254-7.

Milstein, B., J. Homer, P. Briss, D. Burton, and T. Pechacek. 2011. "Why Behavioral and Environmental Interventions Are Needed to Improve Health at Lower Cost." *Health Affairs* 30, no. 5: 823–832. https://doi.org/10.1377/hlthaff.2010.1116.

MIT Climate Pathways Project. 2026. "MIT Climate Pathways Project. MIT Sloan School of Management." https://mitsloan.mit.edu/centers-initiatives/climate-policy-center/mit-climate-pathways-project/welcome.

Morecroft, J. D. W. 1985. "Rationality in the Analysis of Behavioral Simulation Models." *Management Science* 31, no. 7: 900–916.

Morecroft, J. D. W., and J. D. Sterman. 1994. *Modeling for Learning Organizations*. Productivity Press.

Moshman, D. 1982. "Exogenous, Endogenous, and Dialectical Constructivism." *Developmental Review* 2, no. 4: 371–384. https://doi.org/10.1016/0273-2297(82)90019-3.

NGFS. 2022. "Seven Different Scenarios to Assess Transition and Physical Risks. Network for Greening the Financial System." https://www.ngfs.net/ngfs-scenarios-portal/explore/.

Nielsen, J. 1994. "Heuristic Evaluation." In *Usability Inspection Methods*, edited by J. Nielsen and R. L. Mack, 25–62. John Wiley & Sons, Inc.

Noiseux, K. 2022. "Hitting Home: The Mayor Who Thinks Globally and Acts Locally Using En-ROADS. MIT Climate Policy Center." https://mitsloan.mit.edu/centers-initiatives/sustainability-initiative/hitting-home-mayor-who-thinks-globally-and-acts-locally-using-en-roads.

Noiseux, K. 2024. "Possible Futures: How En-ROADS Can Help Investors Quantify Climate Risks and Opportunities. MIT Climate Policy Center." https://mitsloan.mit.edu/centers-initiatives/sustainability-initiative/possible-futures-how-en-roads-can-help-investors-quantify-climate-risks-and-opportunities.

Noiseux, K. 2025. "Five Insights From the C-Suite: How En-ROADS Changed the Way One Business Leader Thinks. MIT Climate Policy Center." https://mitsloan.mit.edu/centers-initiatives/climate-policy-center/mit-climate-pathways-project/five-insights-c-suite-how-en-roads-changed-way-one-business-leader-thinks.

Norman, D. 2013. *The Design of Everyday Things: Revised and Expanded Edition*. Basic Books.

Oliva, R., and J. D. Sterman. 2001. "Cutting Corners and Working Overtime: Quality Erosion in the Service Industry." *Management Science* 47, no. 7: 894–914.

Oliver, C. A. 2023. "The Social Brain and the Neuroscience of Storytelling." In *Teaching Science Students to Communicate: A Practical Guide*, edited by S. Rowland and L. Kuchel, 31–38. Springer International Publishing. https://doi.org/10.1007/978-3-030-91628-2_4.

Rahmandad, H., T. Y. Lim, and J. Sterman. 2021. "Behavioral Dynamics of COVID-19: Estimating Underreporting, Multiple Waves, and Adherence Fatigue Across 92 Nations." *System Dynamics Review* 37, no. 1: 5–31. https://doi.org/10.1002/sdr.1673.

10991727, 2026, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/sdr.70024 by Hochschulbibliothek Reutlingen, Wiley Online Library on [30/06/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Rahmandad, H., R. Oliva, and N. D. Osgood. 2015. "Introduction." In *Analytical Methods for Dynamic Modelers*, edited by H. Rahmandad, R. Oliva, and N. D. Osgood, pp. XV-XXVI. MIT Press.

Randers, J. 2019. "The Great Challenge for System Dynamics on the Path Forward: Implementation and Real Impact." *System Dynamics Review* 35, no. 1: 19–24. https://doi.org/10.1002/sdr.1623.

Repenning, N. P., and J. D. Sterman. 2001. "Nobody Ever Gets Credit for Fixing Problems That Never Happened: Creating and Sustainaining Process Improvement." *California Management Review* 43, no. 4: 64–88.

Repenning, N. P., and J. D. Sterman. 2002. "Capability Traps and Self-Confirming Attribution Errors in the Dynamics of Process Improvement." *Administrative Science Quarterly* 47, no. 2: 265–295.

Riahi, K., D. P. van Vuuren, E. Kriegler, et al. 2017. "The Shared Socioeconomic Pathways and Their Energy, Land Use, and Greenhouse Gas Emissions Implications: An Overview." *Global Environmental Change* 42: 153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009.

Roberts, E. B. 1977. "Strategies for Effective Implementation of Complex Corporate Models." *Interfaces* 8, no. 1: 26–33. https://doi.org/10.1287/inte.8.1.26.

Robson, K., K. Plangger, J. H. Kietzmann, I. McCarthy, and L. Pitt. 2016. "Game on: Engaging Customers and Employees Through Gamification." *Business Horizons* 59, no. 1: 29–36. https://doi.org/10.1016/j.bushor.2015.08.002.

Rooney-Varga, J. N., L. Cheney, R. L. Coleman, et al. 2026. "Interactive Simulation With En-ROADS Spurs Climate Action Among Decision-Makers." *npj Climate Action*. https://doi.org/10.1038/s44168-026-00348-4.

Rooney-Varga, J. N., R. L. Coleman, A. P. Jones, et al. 2025. "Interactive Role-Play With Climate Policy Simulation Can Motivate Evidence-Based Climate Action." *Communications Earth & Environment* 6, no. 1: 769. https://doi.org/10.1038/s43247-025-02744-w.

Rooney-Varga, J. N., E. Fracassi, T. Franck, et al. 2021. "A Simulation Game That Motivates People to Act on Climate." In *World Scientific Encyclopedia of Climate Change*, edited by J. W. Dash, vol. 3, 231–243. World Scientific Publishing Co. Pte. Ltd. https://doi.org/10.1142/9789811213960_0029.

Rooney-Varga, J. N., M. Hensel, C. McCarthy, et al. 2021. "Building Consensus for Ambitious Climate Action Through the World Climate Simulation." *Earth's Future* 9, no. 12: e2021EF002283. https://doi.org/10.1029/2021EF002283.

Rooney-Varga, J. N., F. Kapmeier, C. Henderson, and D. N. Ford. 2024. "Community-Based Propagation to Scale Up Educational Innovations in Sustainability." *Nature Sustainability* 7: 1740–1750. https://doi.org/10.1038/s41893-024-01446-z.

Rooney-Varga, J. N., F. Kapmeier, J. D. Sterman, A. P. Jones, M. Putko, and K. Rath. 2020. "The Climate Action Simulation." *Simulation & Gaming* 51, no. 2: 114–140. https://doi.org/10.1177/1046878119890643.

Rooney-Varga, J. N., J. D. Sterman, E. Fracassi, et al. 2018. "Combining Role-Play With Interactive Simulation to Motivate Informed Climate Action: Evidence From the World Climate Simulation." *PLoS One* 13, no. 8: e0202877. https://doi.org/10.1371/journal.pone.0202877.

Siegel, L. S., C. Campbell, A. Delibas, et al. 2024. "En-ROADS Technical Reference. Climate Interactive." https://docs.climateinteractive.org/projects/en-roads-reference-guide/en/latest/index.html#index.

Smith, J. D., D. H. Li, and M. R. Rafferty. 2020. "The Implementation Research Logic Model: A Method for Planning, Executing, Reporting, and Synthesizing Implementation Projects." *Implementation Science* 15, no. 84. https://doi.org/10.1186/s13012-020-01041-8.

Stechemesser, A., N. Koch, E. Mark, et al. 2024. "Climate Policies That Achieved Major Emission Reductions: Global Evidence From Two Decades." *Science* 385, no. 6711: 884–892. https://doi.org/10.1126/science.adl6547.

Sterman, J. D. 2000. *Business Dynamics: Systems Thinking and Modeling for a Complex World*. Irwin McGraw-Hill.

Sterman, J. D. 2006. "Learning From Evidence in a Complex World." *American Journal of Public Health* 96, no. 3: 505–514. https://doi.org/10.2105/ajph.2005.066043.

Sterman, J. D. 2008. "Risk Communication on Climate: Mental Models and Mass Balance." *Science* 322: 532–533.

Sterman, J. D. 2011. "Communicating Climate Change Risks in a Skeptical World." *Climatic Change* 108, no. 4: 811–826. https://doi.org/10.1007/s10584-011-0189-3.

Sterman, J. D. 2014a. "Interactive Web-Based Simulations for Strategy and Sustainability: The MIT Sloan LearningEdge Management Flight Simulators, Part I." *System Dynamics Review* 30, no. 1–2: 89–121. https://doi.org/10.1002/sdr.1513.

Sterman, J. D. 2014b. "Interactive Web-Based Simulations for Strategy and Sustainability: The MIT Sloan LearningEdge Management Flight Simulators, Part II." *System Dynamics Review* 30, no. 3: 206–231. https://doi.org/10.1002/sdr.1519.

Sterman, J. D. 2015. "Stumbling Towards Sustainability: Why Organizational Learning and Radical Innovation Are Necessary to Build a More Sustainable World—But Not Sufficient." In *Leading Sustainable Change*, edited by R. Henderson, M. Tushman, and R. Gulati, 51–80. Oxford University Press.

Sterman, J. D. 2018a. "System Dynamics at Sixty: The Path Forward." *System Dynamics Review* 34, no. 1–2: 5–47. https://doi.org/10.1002/sdr.1601.

Sterman, J. D. 2018b. "This Tool Is Pushing People to Take Action on Climate Change [Interview]. MIT Sloan School of Management." https://mitsloan.mit.edu/ideas-made-to-matter/tool-pushing-people-to-take-action-climate-change.

Sterman, J. D., T. Fiddaman, T. Franck, et al. 2013. "Management Flight Simulators to Support Climate Negotiations." *Environmental Modelling & Software* 44: 122–135. https://doi.org/10.1016/j.envsoft.2012.06.004.

Sterman, J. D., W. Moomaw, J. N. Rooney-Varga, and L. Siegel. 2022. "Does Wood Bioenergy Help or Harm the Climate?" *Bulletin of the Atomic Scientists* 78, no. 3: 128–138. https://doi.org/10.1080/00963402.2022.2062933.

Sterman, J. D., L. Siegel, and J. N. Rooney-Varga. 2018. "Does Replacing Coal With Wood Lower CO2 Emissions? Dynamic Lifecycle Analysis of Wood Bioenergy." *Environmental Research Letters* 13, no. 1: 015007. https://doi.org/10.1088/1748-9326/aaa512.

Sterman, J. D., and L. B. Sweeney. 2007. "Understanding Public Complacency About Climate Change: Adults' Mental Models of Climate Change Violate Conservation of Matter [Journal Article]." *Climatic Change* 80, no. 3: 213–238. https://doi.org/10.1007/s10584-006-9107-5.

Thompson, K. M., and R. J. D. Tebbens. 2007. "Eradication Versus Control for Poliomyelitis: An Economic Analysis." *Lancet* 369, no. 9570: 1363–1371. https://doi.org/10.1016/S0140-6736(07)60532-7.

Tosun, J., J. Pollex, and L. Crumbie. 2023. "European Climate Pact Citizen Volunteers: Strategies for Deepening Engagement and Impact." *Policy Design and Practice* 6, no. 3: 344–356. https://doi.org/10.1080/25741292.2023.2199961.

UNFCCC. 2015. "Decision 1/CP.21-Adoption of the Paris Agreement Report of the Conference of the Parties on Its Twenty-First Session, Held in Paris From 30 November to 13 December 2015. Addendum. Part Two: Action Taken by the Conference of the Parties at Its Twenty-First Session, Issue." https://unfccc.int/sites/default/files/resource/docs/2015/cop21/eng/10a01.pdf.

Vennix, J. A. M. 1996. *Group Model Building: Facilitating Team Learning Using System Dynamics*. Wiley.

10991727, 2026, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/sdr.70024 by Hochschulbibliothek Reutlingen, Wiley Online Library on [30/06/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License