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Building the Bridge: How System Dynamics Models Operationalise Energy Transitions and Contribute towards Creating an Energy Policy Toolbox

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Abstract: The complexity and multi-dimensionality of energy transitions are broadly recognised, and insights from transition research increasingly support policy decision making. Sustainability transition scholars have been developing mostly qualitative socio-technical transition (STT) frameworks, and modelling has been argued to be complementary to these frameworks, for example for policy testing. We systematically evaluate five system dynamics (SD) energy models on their representation of key STT characteristics. Our results demonstrate that (i) the evaluated models incorporate most of the core characteristics of STT, and (ii) the policies tested in the models address different levels and aspects of the multi-level perspective (MLP) framework. In light of the increasing emergence of energy (transition) models, we recommend to systematically map models and their tested policy interventions into the MLP framework or other sustainability transition frameworks, creating an overview of tested policies (a "policy navigator"). This navigator supports policy makers and modellers alike, facilitating them to find previously tested policy options and related models for particular policy objectives.

Keywords: system dynamics; socio-technical transitions; sustainability transitions; public policy; energy transition; governance

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1. Introduction

Transforming the energy sector to emit net zero greenhouse gas emissions is a critical component to fight climate change [1], and so the subject of energy transition has become increasingly important to policy makers and academics alike. However, designing and implementing science-based policies to promote energy transition is proving to be a complex, multi-dimensional and highly demanding task, implying the need for models that are able to capture this complexity. Since current policy decision making is largely informed by more linear quantitative decision tools, with limited representation of the real-world complexities and feedback involved [2,3], the potential value for policy making of quantitative models able to capture real-world transition aspects is evident.

At the same time, socio-technical transition (STT) scholars focus on the question of how to govern system-wide, structural change in socio-technical systems, such as energy systems. In this field, energy transitions are considered to be a long-term, system-wide and multi-dimensional STT [4,5] (and characterised by complexity, path dependency, non-linearity and interdependencies between multiple heterogeneous agents, including institutions, organisations and individuals. Studying energy transition thus requires a "wider system" perspective that considers techno-economic energy system components as well as societal, economic, political and governance elements [6–8]). Transition scholars often apply qualitative analytical frameworks of STT (e.g., the multi-level perspective (MLP) framework) that have been derived from historical, large-scale system transition case studies [5,8]. Transition researchers indicate the potential for quantitative (transition) modelling to complement qualitative frameworks [9–11]. Several scholars have already suggested system dynamics (SD) modelling as a promising avenue to close the gap between the qualitative socio-technical transition research and the potential for quantitative transition decision support tools [12–15]. Finally, in the context of the emergence of a growing number of energy (SD) models, the policy landscape has become significantly more diverse, and policy makers face the challenging task of finding the "right" model for their particular policy challenge.

Given the above, this study investigates the following research questions:

1. Which typical transition characteristics (e.g., path dependency) are captured by the five evaluated SD energy transition models? Which characteristics are excluded?
2. Can theoretical frameworks from the sustainability transition research strand serve as an overarching framework to organise and position existing SD models with their gained policy insights to support modellers and non-modellers (e.g., policy makers) in navigating to the "right" model for a specific purposes?

Our main focus lies on the second research question. (In this study, "policy" is interpreted in a similar way to "governance measures". That is, policies include all types of measures aimed at facilitating and accelerating sustainability transitions, and relatedly, policy makers can include different types of actors that undertake governance measures, such as regulators, civil society organisations or networks (e.g., climate change movements), industrial companies or individuals (e.g., consumers)).

To investigate the first research question, we undertake an in-depth review of the following five recently developed SD models (as examples): (i) the Economic Risk, Resources and Environment (ERRE) model, (ii) the Green Investment Barrier Model (GIBM), (iii) the Advocacy Coalition Framework Model (ACFM), (iv) TEMPEST (Technological Economic Political Energy Systems Transition) model and (v) the TREES model. These models were selected for their focus on different energy transition aspects and policy questions. Subsequently, to explore the second research question, we relate these models and their tested policy interventions to two different theoretical sustainability transition research frameworks (the MLP framework [16] and the policy intervention points framework [17]).

The main motivations for conducting this study are the increasing demand for models that capture relevant features of the energy transitions (e.g., complexity) as well as the increasing diversity of the energy modelling landscape, leading to difficulties in finding the "right" model for a particular policy challenge. Indeed, in the field of system dynamics, it is widely recognised that there is no one "right" model, but that selecting the "right" model for a particular task is a challenging task [18,19]. Especially, by exploring the second research question, we hope to help modellers and policy makers alike to find the "right" model for their particular policy challenge.

There are a number of already existing studies demonstrating that SD models are suitable to simulating complex energy transitions [14–20]. Moreover, [15,21,22] focused on investigating the suitability of system dynamics modelling for the operationalisation of sustainability transition theories. Further, some SD models have explicitly been defined as transition models, including the BLUE model [23]; the SD models presented in [24,25], the model presented in [12,26]. Finally, reviews of existing sustainability transition models can be found in [3,27,28]. However, the novelty of our paper lies in the integration of (reviewed SD) models and their policy recommendations into coherent sustainability transition frameworks, namely the MLP framework [6,16] (and the policy intervention framework [17]). We are not aware of any other study that explored this endeavour.

The paper is organised as follows. Section 2 introduces the relevant background on socio-technical transition concepts and system dynamics modelling, Section 3 describes our methodology, Section 4 describes and discusses the results and Section 5 concludes.

2. Background

This section provides an overview of sustainability transition concepts relevant for this study, namely the multi-level perspective (MLP) framework, the policy intervention framework developed by [17] and the desired features of STT energy transition models [3].

2.1. The Multi-Level Perspective

Sustainability transition scholars have developed several conceptual frameworks to study STT, including the multi-level perspective (MLP) [6], the technological innovation system approach (TIS) [29], strategic niche management (SNM) [30] and transition management) [31]. The MLP framework is the most widely used and among the best known [8,27]. It is also the most suitable for our purpose, which is the use of a cohesive framework to relate to both the structure as well as the tested policy interventions of the evaluated SD models.

The MLP framework offers a sophisticated conceptual framework for theorising STT, in which STTs occur through the interactions between three levels: the level of niche innovation, the socio-technical regime and the level of the landscape [6,7,32]. Niches can be described as protected spaces (e.g., specific application domains or markets) in which radical innovation, including technological, business or system innovations, can develop without selection pressure from the regime level. The socio-technical regime is the established system of technology production and use, governed by actor networks and institutions. The regime is the result of the co-evolution of technologies, industry practices, political actors and institutions, culture, societal behaviours and perceptions, and production and consumption patterns. Socio-technical regimes include dimensions of science and engineering, economy, policy, energy practices, consumer behaviours and culture. For example, the energy system includes the mutual alignment of energy firms, grid infrastructure, flexibility technologies, energy regulations, energy tariffs, business models and consumer practices. The landscape is the environment in which the regime operates. It contains various pressures that act upon regimes and niche innovations. Examples include climate change impacts, changes in the international policy framework for energy and emissions or changes in economic growth. Landscape factors can contribute to fundamental changes or shifts in regimes and support the development of niche innovations, and the combination of these two can lead to STT. To conclude, the MLP is a suitable framework for the discussion and structuring of energy transition policy interventions, which we describe in the following section. It is portrayed in Figure 1.

The scale of STT for energy transition can be bounded in several ways. For example, around a type of mass consumer technology, a type of energy supply technology, a particular industry, or encompassing the interdependencies between regimes in energy supply and energy demand. We can view energy transition at the national scale as several STTs occurring simultaneously, or in series, often with dependencies between different STTs.

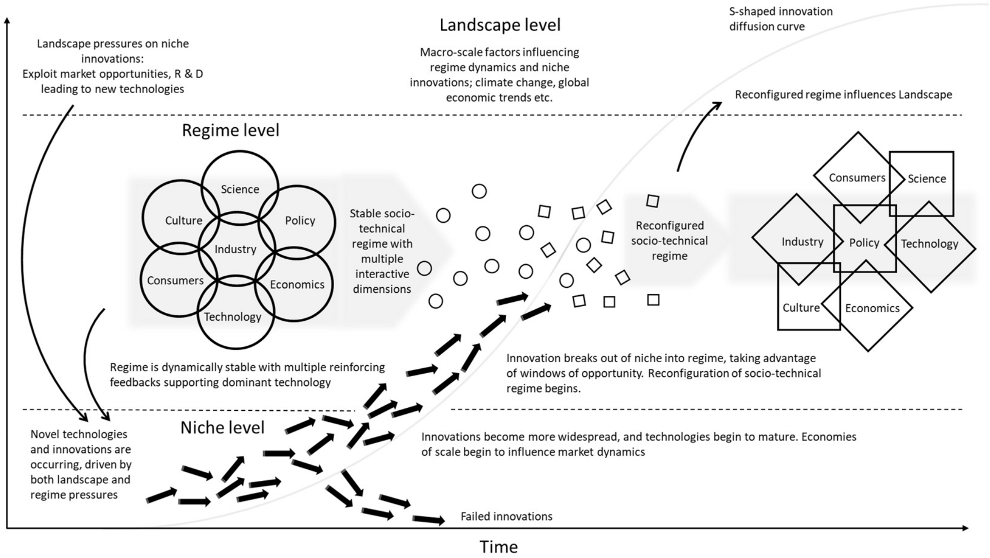

Figure 1. Multi-level perspective (MLP) framework. Source: author elaboration, derived from [33].

2.2. Features of Socio-Technical Sustainability Transition Models

STTs towards sustainability share common features, and models should be able to represent such features. This section describes the main transition features with regard to energy transition models in particular. These features are foremost taken from studies of [30,34], and an additional feature, uncertainty, from [8]. A socio-technical energy model with all the outlined key features can be described as a type of (optimal) blueprint model, which captures all the relevant characteristics of energy transitions. Models are by definition abstractions from reality, however, and therefore most energy transition models will not represent all features to the same level of detail. The suggested STT model features are the following [8,30,34]:

1. Techno-economic details: The techno-economic structure of energy systems is critical for models to include. Models should include a disaggregated set of technologies. They should be capable of simulating technological changes, including (i) the emergence of niche energy technologies; (ii) the diffusion of new low-carbon technologies and/or the decline of incumbent technologies; (iii) system constraints, including resource constraints and technical potential constraints; (iv) the need for network flexibility technologies to deal with intermittency issues. On the economic side, models should include the direct financial costs of new energy technologies and the macroeconomics of different energy transition pathways [30].

2. Multi-dimensionality, systems perspective and interdisciplinary: STTs entail system-wide, structural changes along different interconnected dimensions, including technological, industrial, material, organisational, institutional, political, economic, consumption and socio-cultural domains [5,8], Models should represent those domains and mechanisms that are relevant to the model subject, as well as the mechanisms and dynamics that arise from interrelations between regimes. For example, energy transition affects not only the energy sector but also the structure of related sectors such as housing, the labour market, manufacturing, supply chains, planning and policy making [5].

3. Path dependency, lock-in, inertia and self-reinforcement of change: STTs are complex processes characterised by multiple and interlinked feedback loops that can give rise to lock-in and path dependency or rapid change. Transition models should be able to identify relevant feedback loops and leverage points that weaken or strengthen them. While lock-in and path dependency can be difficult to overcome, the existence of reinforcing feedback loops within the system also creates opportunities for small changes in the system to be amplified in the desired direction through targeted policies at leverage points [8].

4. Multiple actors and heterogeneous behaviours: STTs are driven and shaped by a range of actors, often with heterogeneous roles in and responses to transitions. Actors include individuals (e.g., consumers, policy makers or regulators), civil society organisations or networks (e.g., climate change movements), industrial firms (e.g., from the incumbent regime) or policy-making bodies. Energy transition models should include the influential role of actors of various types in the process of transition. For example, the influence of actors on policy making that varies with access to those in power, or alliances that either drive or challenge transitions [8].

5. Sustainability transition pathway dynamics: STTs can be evaluated by the triple bottom line of sustainable development, which requires the balancing of economic, social and ecological goals. Transition models should capture key sustainability indicators, and be capable of not only evaluating whether normative goals are attainable but describe different goal-reaching transition pathways. Since energy transition unfolds over several decades, transition models should represent long-term dynamics, and where possible, include pre-commercialised technologies that are expected to become available [30]. Transition models should also be able to explain the dynamics of particular analytical transition frameworks such as the MLP, thus contributing to theory building.

6. Open-endedness and uncertainty: Deep uncertainty implies that there are known and unknown future possibilities. It is not possible to rank or order the known outcomes in terms of likelihood or importance [30]. Sustainability transition models should be able to address the uncertainty and open-endedness of sustainability transitions. In all domains, there are multiple promising innovations and initiatives, leading to multiple possible transition pathways [33,35]. It is impossible to predict with any certainty which of these will eventually succeed. Uncertainty arises from the non-linearity of innovation processes, which may experience failures or rapid success, hype–disappointment cycles or accelerated performance changes. There may also be unexpected political and socio-cultural processes and new knowledge breakthroughs. Uncertainty also arises from the novelty of the energy transition process, since never before has such a large, complex and critical system ever been deeply transformed while still providing services [8].

2.3. A Policy Intervention Framework for Transformative Change

Sustainability transition research has focused on the description of preconditions, key mechanisms, patterns and opportunities for accelerating and upscaling sustainability transitions [5,8]. Such objectives are usually accomplished through applying "policy mixes"—a set of policy goals, strategies, instruments and policy processes that influence a given sector or system. Policy mixes have been researched in the fields of environmental economics, innovation studies and policy sciences [17]. The policy intervention framework introduced by [17] bridges the level of policy instruments (means) and desired changes in the directionality of socio-technical transitions (objective), identifying six policy intervention points. There are six specific areas in the MLP—policy intervention points—where the introduction of policy instruments is likely to trigger the required transformative change (drawing on [17]). Policy strategies would include measurable targets, concrete plans as well as roadmaps, guidelines or conventions. In contrast, policy interventions would clearly emphasise ". . . what to target and why targeting it would be a good idea" [17] (underlying aim). Here, it is important to remember that this study interprets "policy" in a broader sense and similar to "governance measures". That is, policies include all types of measures that aim to facilitate and accelerate sustainability transitions, and relatedly, policy makers can include various type of actors that undertake governance measures, such as regulators, civil society organisations or networks (e.g., climate change movements), industrial firms or individuals (e.g., consumers). The six policy interventions with their underlying aims are summarised as follows [17]:

1. Stimulate the different niches: Interventions support different emerging niches to become mature and enter the market. Examples of this type of measure include R&D funding schemes, public procurement, foresight exercises to create intersubjective visions, and relaxing certain regulatory conditions [36]. This intervention point aims to support a variety of niche innovations being available to be used in the energy transition [17]. *Underlying aim: to guarantee the presence of various alternatives for systems change*.

2. Accelerate the niches: Interventions support technology niches to cross the "valley of death" between R&D activities and commercialisation [37]. Upscaling niches also includes systemic changes, such as the combination of technological, organisational and institutional innovations, including new business models and user practices. Such systemic interventions can also support broader system building by the alignment of developments in distinct niches that complement or reinforce each other. *Underlying aim: to scale up single niches and to align different niches with each other*.

3. Destabilise the regimes: Interventions target the destabilisation of the current dominating socio-technical regime to allow niches to become mainstream. Such measures include the removal of unsustainable subsidies, the introduction of taxes for unsustainable practices, banning specific technologies or practices as well as balancing the involvement of incumbents and niche actors in policy advisory [36]. *Underlying aim: to weaken the position of incumbent regime actors hindering the transition*.

4. Address the broader repercussions of destabilisation: Interventions respond to any unintended consequences of socio-technical regime changes in the regime's environment, reducing negative impacts and assisting the transition in connected regimes. For example, compensating industry for the closure of fossil-based plants, and the provision of educational support for managing structural unemployment and skill mismatches [38]. *Underlying aim: to anticipate and manage the broader societal impacts resulting from systems change*.

5. Provide coordination to multi-regime interaction: Interventions ensure that interactions between regimes during socio-technical changes remain functional. The trajectories of socio-technical regimes are influenced by mutually reinforcing developments between multiple systems [16,39]. For example, developments in energy supply systems are tightly interlinked with the transition of the mobility, industry and housing sectors to facilitate fuel switching from high- to low-carbon fuels. *Underlying aim: to ensure that the input-output relations between the regimes would be complementary*.

6. Tilt the landscape: Interventions deal with broad framework conditions that exist in the landscape. The recent sustainability transition literature investigates the impacts of changes on landscape pressures, such as international climate change agreements [39,40]. Examples of measures to tilt the landscape include the banning of chlorofluorocarbons (CFCs) via regulations created by the international community, and the Paris Agreement. *Underlying aim: to alter the broader framework conditions enabling change in the directionality of locally bounded socio-technical systems*.

Figure 2 illustrates the framework from [17] combined with the MLP.

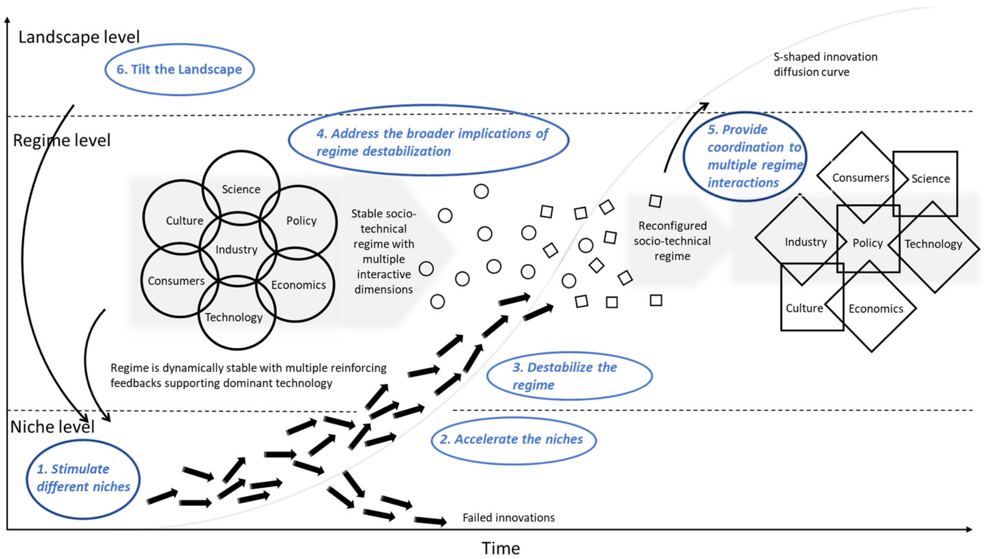

Figure 2. Six intervention points for transformative system change. Source: own elaboration, based on [17,33].

2.4. System Dynamics Modelling

System dynamics (SD) was created during the mid-1950s by Professor Jay Forrester of the Massachusetts Institute of Technology. SD is a theoretical perspective, a set of conceptual tools and a modelling method used to investigate the underlying structure of dynamic, complex problems involving multiple interacting dynamic system components, non-linearity, feedback loops, lock-in and path dependency [34,41,42]. Based on this knowledge, leverage points are identified, and policy interventions are suggested that will move the system to a more desirable state or behaviour pattern. Policy interventions at leverage points can amplify small changes through reinforcing feedback loops or eliminate undesirable dynamics through triggering balancing feedback loops [41].

Mathematically, an SD model is a set of non-linear differential equations solved in continuous time. A software tool (Vensim 10.2.1) is used to solve the equations and perform the model simulations. An SD model links differential equations with infographic type modelling, resulting in stock and flow diagrams (SFD). Further, causal loop diagrams (CLDs), visually representing the causal links between key model variables, are often developed during the model conceptualisation phase or for communication purposes [41]. CLD diagrams allow for the systematic visualisation of main (circular) causal model linkages that explain the behaviour patterns of simulation results.

SD can be used for participatory modelling workshops [43] to explore or validate the model structure via the inclusion of the workshop participants (e.g., mapping exercise). Participatory SDM involves stakeholders, experts or clients in various phases of the modelling process and allows for the elicitation of model variables, causal relationships, parameter values and non-linearities from stakeholders with diverse backgrounds [44]. In addition, the model-building process enables the development of the model and supports model validation as well as shared learning. The suitability of SD for participatory modelling workshops is due in particular to (i) the possibility of using CLDs (that are easily created or understood by stakeholders) as a means of model structure presentation and (ii) its flexibility, allowing for the inclusion of new model structures and knowledge from different disciplines.

The decisive properties of the SD methodology are summarised as follows [34,41,42]:

1. Complexity: SD is typically applied to address complex, dynamic problems that are characterised by accumulation processes, multiple interrelated feedback loops, non-linearities and often organised into sub-systems and components.

2. Endogenous perspective: SD takes an "endogenous" or "systemic" perspective. It aims to explain a policy problem, or problem space, by modelling its underlying causal system structure and how this structure contributes to system behaviours. This approach allows for the understanding of the key mechanisms involved, and the identification of key leverage points for policy intervention. Feedback loops (these are a causal chain of elements where a change in one element is amplified (reinforcing loop) or reduced (balancing loop) as it moves along the chain) are key elements of SD.

3. (Deep) uncertainty: SDM acknowledges uncertainty at the level of model construction; system complexity means that future system behaviours are not predictable based on past behaviours. Further, SD model agents do not possess perfect information on the future. "Deep uncertainty" includes the "unknown unknowns", which by definition cannot be fully represented in any model. However, there are approaches to estimating the size of uncertainty. For example, Kwakkel and Pruyt's [45] Exploratory Model Analysis (EMA) uses wide-range parameter and structure testing of SD models to explore fundamental uncertainty in exogenous conditions and system structure.

4. Non-linearity: SD considers non-linearities in two ways: (1) those that are used to define structural relationships between two variables, and (2) those that emerge due to the interacting feedback loops.

5. Feedback loops, path dependency and lock-in: The interplay of non-linearities, delays and feedback loops can lead to path dependency and lock-in effects, where initial model conditions determine the final equilibrium state of the simulation model. In complex systems, when small parameter changes become amplified by reinforcing feedback loops, model behaviour can display lock-in and path dependency. Path dependency and lock-in explain, for example, how economies of scale favour established technologies over innovations; as more capacity of a technology is installed, the cheaper it becomes, creating economic barriers to higher priced innovations.

6. Multiple equilibria/disequilibrium: The existence of non-linearity and feedback loops can lead to multiple equilibria, a system behaviour with more than one equilibrium state, or disequilibrium dynamics. Thereby, the relative strength of reinforcing and balancing feedback loops and their interplay with system delays can cause the system to oscillate, become stable, or unstable.

7. Agents' heterogeneity and decision making: SD aims to represent how model agents make decisions, considering both relevant economic as well as socio-psychological factors (e.g., agents' values or preferences). SD typically represents agents in an aggregated way, from a top-down perspective, and drawing on a relatively fixed system structure (although that may change over time to some extent). Some SD software packages offer arrays that can model segments of actors as distinct agents (e.g., low-income vs. high-income consumers). In contrast, a strength of agent-based models lies in the representation of the dynamic interactions among multiple (e.g., 1000) heterogeneous agents (e.g., firms) from a bottom-up perspective, leading to a flexible model structure by the emergence of the macro-behaviour of a specific agent (e.g., firms). There are ways to combine SD with agent-based modelling (e.g., by the software package "AnyLogics").

8. Interdisciplinary: SD can be used in an interdisciplinary way, facilitating the integration of knowledge and concepts from different perspectives and disciplines. SD model equations can be informed by various research disciplines and data sources, including, for example, quantitative parameter values from controlled experiments or econometric studies, social science studies, and data that are informed by judgement—for example, from case studies, expert interviews or multi-stakeholder workshops.

9. Long-term simulation tool: SD is often applied to long-term simulation periods, from months to decades, rather than minutes or hours. Given the large uncertainty of the outcomes of long-term modelling, identifying the key feedback loops and distinct system behaviour patterns, rather than estimating specific parameter values, provides the most value to decision makers (we note that some SD models produce specific values to inform policy making. They may also be short-term models, but these are not the models that describe socio-technical transitions).

The features of SD modelling can nicely be compared with energy STT features as shown in Table 1.

The overlap between the key features shows that SDM is a suitable tool to represent and analyse the decisive processes of energy transition [13–15,20,21].

Table 1. Overview of sustainability transition features vs. system dynamics features.

Socio-Technical Transitions (STT) Features	System Dynamic Modelling (SDM) Features
(1) Techno-economic details	SDM is suitable for including all of the techno-economic details relevant for modelling energy transition, such as marginal abatement costs of mitigation measures, energy consumption, emissions and energy demand. This is conducted through stocks, flows, variables, constants, equations and data inputs and outputs.
(2) Multi-dimensionality, systems perspective and interdisciplinarity	SDM is based on systems thinking and can address problems from a long-term, holistic systems perspective (SD characteristics 2, 6 and 7).
(3) Multiple actors and heterogeneous behaviours	SDM can represent actor behaviours and decision making (e.g., personal preferences or values, or perceptions of risks) and heterogeneity in agent populations (e.g., low vs. high-income earners) (SD characteristic 5).
(4) Path dependency, lock-in, inertia and self-reinforcement of change	SD models can represent the dynamics of path dependency and self-reinforcement of changes, through combinations of balancing and reinforcing loops, combined with stocks and flows. (SD characteristics 1, 3 and 4).

Table 1. *Cont.*

Socio-Technical Transitions (STT) Features	System Dynamic Modelling (SDM) Features
(5) Sustainability transition pathway dynamics	SD models can capture dynamics such as multiple equilibria and disequilibrium and can model system changes over long time periods. (SD characteristics 2, 3, and 7).
(6) Open-endedness and uncertainty	Uncertainty testing through Monte Carlo Analysis and other analytical tools can reveal the range and causes of uncertainty in model outputs. (SD characteristic 2).

3. Methods

3.1. Research Approach

This section introduces our research approach and Figure 3 gives an overview thereof.

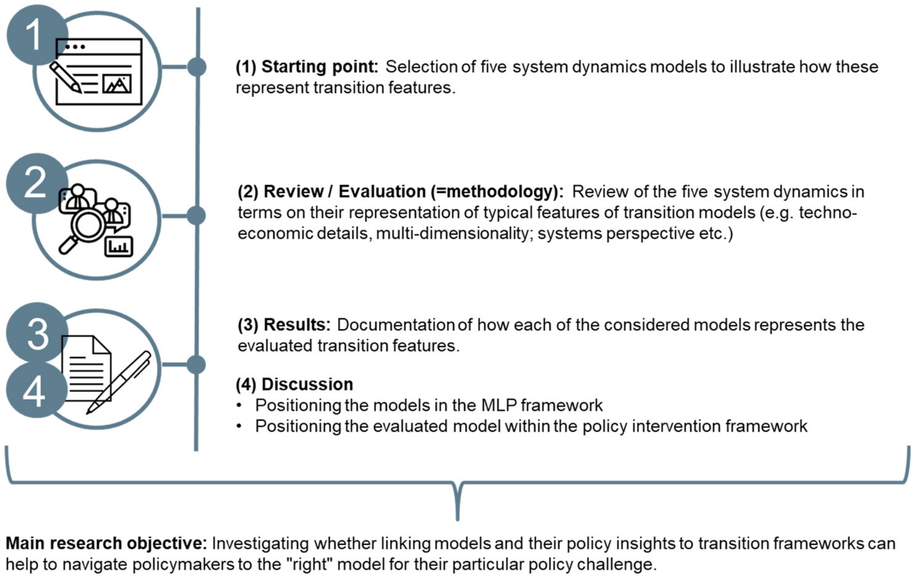

Figure 3. Overview of our research approach.

(1) The starting point of our research is the sample of five recently developed SD models, on which we subsequently focus our in-depth review. These models are the following (for more information see Section 3.2):

i. the Economic Risk, Resources and Environment (ERRE) model [46];
ii. the Green Investment Barrier Model (GIBM) [47,48]
iii. the Advocacy Coalition Framework Model (ACFM) presented in [49]
iv. the TEMPEST (Technological EconoMic Political Energy Systems Transition) model [50]
v. the TREES model [51–55].

These models were selected for their focus on different energy transition aspects and policy questions. Thereby, we underline that our objective is not a systematic review of all existing system SD models. Instead, we selected a sample of relevant model in order to investigate whether linking SD models with theoretical transition frameworks can be useful to help find policy makers the right models for their purpose.

(2) The second step of our research is the review of the five SD models. This review is based on model documentation and specific inputs by the modellers.

(3) The results describe how the five reviewed models account for the evaluated transition features (e.g., uncertainty, techno-economic details, systems perspective, etc.)

(4) Discussion: In the discussion, we relate the reviewed model to the MLP framework. Moreover, tested policy interventions of the reviewed models are discussed using a policy intervention framework developed by [17].

3.2. Model Sample

This section describes the five SD energy transition models, which were selected based on their focus on distinct energy transitions aspects and policy questions. They differ with respect to aggregation level, regional scope, disciplinary perspective, audience and model purpose. The models have all been applied for the investigation of recent policy challenges within the energy transitions towards a fossil-free energy future and have all been published in peer-reviewed journals. While the results of the models were used to inform policy makers (e.g., via reports or white papers), it is unclear how much policy makers have relied on these particular results of the considered models. The models are introduced below in descending regional scope, and Appendix A presents an extended summary, including a detailed description of the key feedback loops included in the models. The employed software for the models is Vensim and the time step 0.25 years.

1. The Economic Risk, Resources and Environment (ERRE) model

Model purpose and policy insights: The Economic Risk, Resources and Environment model is a globally aggregated stock and flow consistent (stock-flow-consistent (SFC) models provide an integrated framework for the analysis of both the real and the financial side as well as their connections in one framework [56] (SD model whose purpose is to analyse the financial risks emerging from economic growth while coping with natural limits in energy, agricultural and climate systems. It also assesses the impact of energy transitions on food security. ERRE adopts a global perspective and shows the implications of climate change damage on both the real economy and the financial system, taking into account the feedback dynamics between the two. It demonstrates the urgency of policy action and the danger of the lack of more stringent policy implementation.

Regional scope: global

Simulation horizon: short-term: 2000–2030; long-term: 2000–2100

Sources: [46].

2. The Green Investment Barrier Model (GIBM)

Model purpose and policy insights: The GIBM is a national model calibrated to the UK. It includes key macroeconomic sectors (e.g., production, consumption, and labour market), a public sector and a power supply sector. The GIBM informs the national policy makers on the macroeconomics of (i) various centralised low-carbon power transitions [49] and (ii) a policy scenario closing the green finance gap in the context of an energy transition [49]. It highlights potential co-benefits (e.g., GDP, employment) of jointly applying a scenario that upscales green finance with one that accelerates the uptake of renewables.

Regional scope: national, UK

Simulation horizon: 2020–2050

Sources: [47,48].

3. The Advocacy Coalition Framework Model (ACFM)

Model purpose and policy insights: The ACFM adopts a regional perspective, which is relevant for the understanding of the political dynamics for climate policy introduction in the case of the US. It builds on new electricity capacity expansion SD models by incorporating political competition for policy enactment. Renewables still depend on supportive policies; however, energy policy tends to be highly politicized, subject to manipulation by vested interest groups. The ACFM specifically addresses the political lobbying process and policy manipulation by vested corporate interests, which influences the diffusion of low-carbon energy technologies. It demonstrates that these “soft factors” have to be considered alongside other financial incentives (e.g., carbon price or feed in tariffs). It evaluates the impact of political competition for energy policy on transition rates.

Regional scope: Regional, California, US

Simulation horizon: 2018 to 2050

Sources: [49].

4. The Technological EconoMic Political Energy Systems Transition (TEMPEST) model

Model purpose and policy insights: TEMPEST is a SD simulation model of the UK's socio-politically driven energy transition. In TEMPEST, mitigation measures that reduce $MtCO_2$ emissions (i.e., million tonnes of greenhouse gas emissions) from energy are modelled along with political and social factors in energy transitions. That is, it estimates the importance of social and political factors in the diffusion of mitigation measures and makes recommendations for reducing the uncertainty in achieving the UK's net zero target. It thus informs policy makers about issues important to the achievement of an energy transition that are not usually included in energy planning models—societal and political factors. TEMPEST models feedback between government, policy makers and the actors who carry out energy transition actions—the energy sector and the public.

Regional scope: national, UK

Simulation horizon: 1980–2080

Sources: [50].

5. The Transition of Regional Energy Systems (TREES) model

Model purpose and policy insights: TREES takes a regional perspective and focuses on a decentralised energy transition. The model supports electric utility companies, technology developers and municipalities in testing and assessing strategies in the decentralisation of energy systems and captures the dynamic interaction between the diffusion of prosumers on the financing of the electricity distribution grid and corresponding tariff setting, as well as business strategies for companies to engage in the decentralisation trend. More concretely, TREES provides information for public policy for (i) different grid tariff designs and their impact on the diffusion of prosumer concepts, (ii) different support mechanisms for solar PV (photovoltaic), and (ii) derives business strategy recommendations for flexibility aggregators. The model was developed at the Zurich University of Applied Sciences as part of the Swiss Competence Center for Energy Research—Center for Energy, Society and Transition and profited from close collaborations with several industry partners.

Regional scope: Regional (e.g., applied to several supply areas of Swiss utility companies)

Simulation horizon: 2010–2035/2050

Sources: [51–55].

4. Results and Discussion

4.1. Model Reivew

This section summarises how the five evaluated SD models capture the desired STS energy transition features, including the following: (1) techno-economic details; (2) multi-dimensionality, systems perspective and interdisciplinarity; (3) path dependency, lock-in, inertia and self-reinforcement of change; (4) multiple actors and heterogeneous behaviours; (5) sustainability transition pathway dynamics; (6) open-endedness and uncertainty (see Section 2.2). Appendix A contains a detailed review of the selected models for each STS model feature. Importantly, SD models are generally purpose-driven and therefore do not aim to represent *all* features of sustainability transitions. That is, SD models are always abstractions and simplifications of sustainability transitions, and model builders generally choose to depict those characteristics relevant for the model purpose. While differences in included or excluded transition features across the models are described as a "limitation" of a particular model in this study, we wish to clarify that the Inclusion of all transition features is only relevant for realising an ideal, or a "blueprint" of a sustainability transition model.

First, we found several strengths with regard to the representation of the desired STS model features of the evaluated models that can be traced back to the SD methodology (see Section 3.1) rather than to an individual model. Firstly, all evaluated models provide a causal representation of relevant path dependency, self-reinforcement of change and other relevant mechanisms of the specific energy transition challenges addressed by the distinct models (STS model feature 3, see Section 2.2). Moreover, they adopt an interdisciplinary, holistic systems perspective and represent the structural complexity of (selected aspects of) energy transitions, including feedback effects, path dependency and reinforcement of change (STS model features 2 and 3).

Second, we found two main limitations of the evaluated SD models that are also mostly explained by the SD modelling methodology and not by the specific model focus. A common relevant limitation of the five models lies in the lack of the representation of multiple, heterogeneous agents (feature 4). That is, the evaluated models mostly represent macro-agents (e.g., one "aggregate" firm represents all firms of a sector or economy), but not multiple heterogeneous agents, such as thousands of firms that simulate the emergent dynamics of a firm sector. Moreover, with regard to the techno-economic structure, the evaluated models do not consider intermittency issues and are characterised by a lack of emergent behaviour representation, particularly at the niche level (e.g., emergence of new technologies, feature 1). These limitations are not necessarily a weakness but rather a result of the basic approach of SD in focusing on structural complexity and explaining the main mechanisms that cause a specific policy problem.

Third, the key foci of each of the five models vary considerably concerning the level of detail and the way they represent the desired STS features. In other words, while all models represent the desired STS features, the representation thereof may differ, particularly with regard to the incorporation of different sectors (feature 2), the techno-economic structure (feature 1) or path dependency or self-reinforcement of change (feature 3). To illustrate, while ERRE focuses on the wider feedback loops between the economy, the finance system and climate change, TREES focuses on the key feedback loops that explain the diffusion of decentralised, low-carbon energy technologies (see Appendix B for further details). These differences are due to the specific topic being studied and the need to provide tailored policy recommendations to the audience, as well as the related task.

4.2. Linking the Model to the Multi-Level Perspective Framework

In this section, we discuss the models' contributions to energy policy making by relating their policy recommendations in a cohesive narrative (MLP framework), which can inform the energy transition discourse.

Importantly, four of the models are not directly linked to established ST frameworks, such as the MLP, but employed other disciplinary frameworks as a starting point for model design. The exception thereof is TEMPEST that was based on a multi-layered, multi-theory model design, with a dynamic hypothesis about what causes changes in energy and emissions [50].

Figure 4 gives an overview of which levels of the MLP are mainly captured by the evaluated models, based on the model review (see Appendix B for details).

All of the models consider two or three levels of the MLP, highlighting the potential of SD models to capture STT processes. However, while the models cover the different levels, they do generally focus on a few aspects (e.g., with regard to sectors and actors) of these levels (see Appendix B). The most common linkage is between niches and regimes. With the exception of TEMPEST, the GIBM and EREE, landscape pressures were modelled as exogenous inputs.

A more detailed description of the model mechanisms structured (based on key examples) within the MLP framework can be found in Table 2.

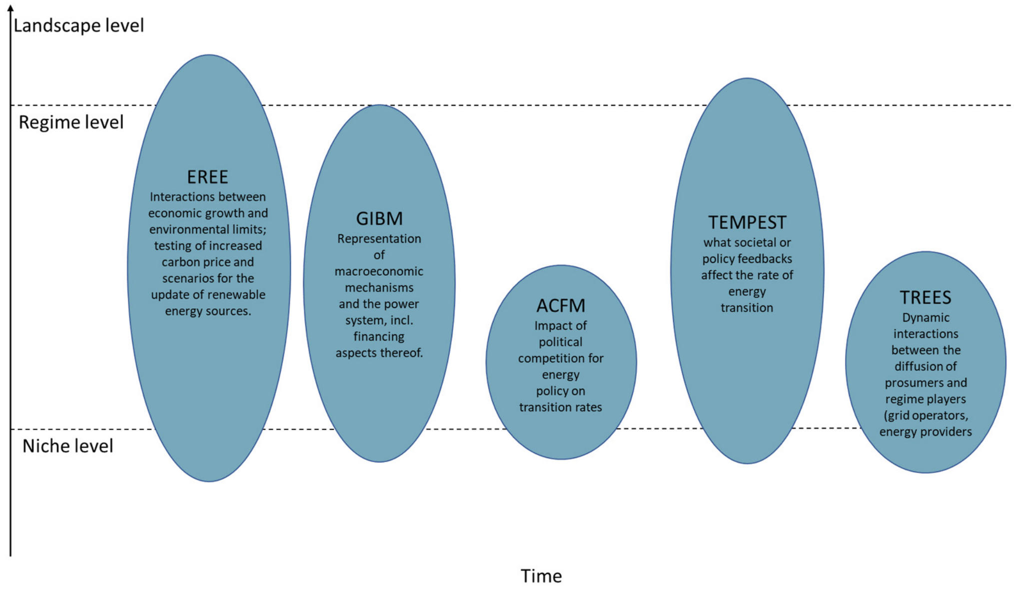

Figure 4. Key model mechanisms structured within the MLP framework.

Table 2. Positioning the evaluated SD models in the MLP framework (with examples).

	ERRE	GIBM	ACFM	TEMPEST	TREES
Landcape pressures	- Accounts for limits of fossil fuel reserves, land availability, and carbon emissions - Endogenous representation of climate change impacts - Exogenous changes in carbon taxes	- Exogenous changes in carbon taxes - Technical potential of renewable energy sources in the UK	- Climate change impacts are represented endogenously	- The landscape is climate science and international climate agreements that create mitigation targets.	- Considers different subsidy systems for solar PV and batteries and their impacts - Technology learning curves (exogenous)
Regime	- Price dynamics shift the demand from a source to another based on continuous pressures either from green tech growth or fossil fuel depletion. - Depletion of fossil fuels rises fossil prices - Green technology development (productivity) decreases cost of green tech - Biofuels work as intermediate product if green tech is slow	- Key Feedback loops in the economy - (Path-dependancy) of Decision mechanisms in the finance sector	- Fossil fuel industry resistance to renewable energy technologies - Special interest political lobbying competition for energy incentives – impacting price dynamics and capacity investments - Green energy advocates increase political lobbying efforts as climate change impacts increase	- Policy making (government), demand-side equipment regimes, and power sector technology and fuel regimes.	- Grid cost recovery - Solar potential scarcity effect - Various business dynamics of distributed flexibility solutions
Niches		- Decrasing LCOE of renewable energy technologies in the power sector due to (global and national) learning effects - Lock-in due to a lack of green finance and path-dependancy in energy-capacity investments	- Cost reduction effects on low-carbon technologies due to learning	- Niche innovations are new technologies, new behaviours, and new policies or societal responses.	- Peer effects - Incentives of grid cost recovery - Impacts of flexibility offers - Impacts of subsidy systems and technology learning curves

4.3. Linking the Policy Insights of the Reviewed Models to the Policy Intervention Points Framework

In this section, we summarise about which MLP levels and aspects the five SD models inform the current energy policy challenge. We do so by relating the specific policy interventions tested by the evaluated models against the policy intervention points developed within the [17] framework (see Section 2.3). We reiterate at this point that we use "policies" interchangeably with "governance measures". That is, the term policy describes all types of measures that aim to facilitate and accelerate sustainability transitions. In the following, we give an overview of the models' policy interventions mapped against the six policy intervention points [17]:

(1) Niche acceleration:

ERRE: Policy scenario: Green tech growth that expands above a 7% exponential growth rate over the time of the simulation.

GIBM: Policy scenarios for upscaling renewables.

TEMPEST: Support social movements and technology innovation that can increase public participation in the energy transition.

ACFM: Economic incentives for novel renewable energy technologies. Support is an aggregated mechanism represented by a Feed-in-Tariff.

TREES: Subsidy schemes for rooftop solar PV and home storage batteries (one-time investment grant, Feed-in-Tariff, net metering systems with different billing period, net purchase and sale system); business strategies for flexibility aggregators to cross the valley of death (the situation where they are too small to bid); co-benefits between PV, batteries and flexibility solutions.

(2) Regime destabilisation:

ERRE: Carbon taxes (ERRE is a global model and therefore it is a matter of interpretation whether changes in international carbon taxes are attributed to the regime or the landscape level. As it currently does not include single countries, we have attributed it to the regime level.

GIBM: Finance regulations: Systems approach that tackles key investment barriers (e.g., policy uncertainty, fiduciary duty or consideration of climate-related risks), and changes in the energy and climate policy framework, such as the removal of subsidies for high-carbon energy technologies or changes in the carbon tax level.

TEMPEST: Ensure there is sufficient public willingness to participate in the energy transition, through well-designed policies.

ACFM: Carbon tax and incentivising early retirement of fossil fuel electricity generation plants may be more effective than incentivising innovative renewable energy technologies.

TREES: Grid tariff designs (volumetric tariff, flat rate and capacity tariff) and its incentivising effects for prosumer concepts and cost-covering mechanisms for the distribution grid and tariffs for surplus PV.

(3) Address the broader implications of regime destabilisation:

TEMPEST: Pilot whole-system energy transition in specific regions, making use of unique local culture, geography, industry and infrastructure while providing benefits to local households and businesses.

(4) Multi-regime coordination:

TEMPEST: Manage the energy transition from a whole-system viewpoint by regularly observing the strength of the feedback driving the system transformation and the interactions between them.

(5) Landscape tilting:

TEMPEST: Ensure sufficient political capital is available to fuel the energy transition and reduce the likelihood of pushback or policy failures.

ERRE: Different policy scenarios for economic growth.

Figure 5 visualises the tested models' policy interventions against the STT policy intervention points introduced by [17].

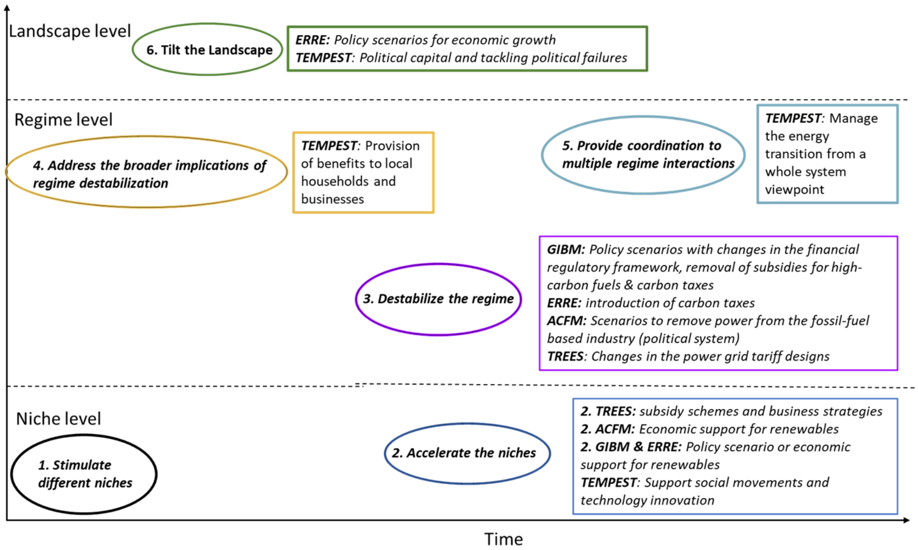

Figure 5. Overview of the policy intervention points of the evaluated SD energy transition models within the MLP framework and defined STT targets by [17]. Source: own elaboration based on [17].

The key insights from the policy intervention mapping exercise are summarised here. As the models focus mainly on the regime and niche levels of the MLP, the policies/leverage points from the models are similarly located mostly at the regime and niche level. This makes sense since the current state of low-carbon technologies, especially renewable energy technologies, are exhibiting falling costs due to increasing economies of scale, allowing for rapid expansion out of the niche and into the regime. However, such expansion often leads to resistance from incumbent technologies, making policy interventions at the regime level pertinent. Moreover, though different models address the same policy targets, their focus lies within different thematic aspects (i.e., industry vs. technology vs. markets vs. culture) of these intervention points, thus pointing towards the complementarity of the evaluated SD models with regard to policy testing. Furthermore, the policy intervention points "1. Stimulate different niches", "4. Address the broader implications of regime destabilisation" and "5. Providing coordination to multiple regime interactions" are not covered well by the models. This may be due to the limited scope of the models in purpose, or because those policy intervention targets are not by nature suitable for SD modelling. As renewables expand into the regime, multi-regime coordination and the broader impacts of regime destabilisation will likely become more critical as transition challenges associated with greater diffusion occur. Overcoming increased competition between renewable technologies, sector coupling and fossil fuel industry resistance due to shrinking high-carbon energy production are likely areas for future research.

Finally, we suggest that the mapping of the tested models' policy interventions against the six intervention points within the MLP framework equips policy makers and modellers alike with a toolbox containing policy recommendations (as tools) for tackling a particular energy transition challenge. Or in other words, when a decision maker aims to achieve a particular transition aim (e.g., to accelerate the niches or destabilise the regime), the undertaken mapping exercise informs on the tested tools (in the sense of policy interventions) suitable to reach the desired aim. In addition, the mapping overview indicates the readily available models that evaluate the suggested policy intervention and provide quantitative results on the policy implications. It goes beyond the scope of the current article how SDM should be applied alongside commonly applied models for the formulation of scientifically based policy decisions in dynamically complex transition challenges.

5. Conclusions

The decarbonisation of the energy system is increasingly considered a complex, multi-dimensional, long-term transition, leading to an increased need for energy models able to capture these characteristics (e.g., complexity, non-linearity and behavioural elements; see [2,3]. At the same time, a number of sustainability transition scholars—who have traditionally used qualitative frameworks for their research—have started to highlight the potential of quantitative modelling for studying sustainability transitions [10,11,27]. Finally, the growing number of (new) energy models makes it increasingly difficult for modellers and non-modellers (e.g., policy makers) alike to find the "right" model for their particular policy challenge.

In light of this background, we investigated (or confirmed) in this study the suitability of five system dynamics models to simulate socio-technical transitions, thus complementing the existing research [3,10,27]. The main research focus of this study was to investigate whether theoretical frameworks from the sustainability transition research strand can serve as an overarching framework to organise and position existing SD models and their gained policy insights, so that this linking of models/policies with theoretical transition frameworks can navigate non-modellers (e.g., policy makers) to the "right" model for specific purposes.

Our results of the review of five existing energy SD models show that these five models capture to a large extent the sustainability transition characteristics (e.g., dynamic complexity). The strengths of the different models with regard to the representation of the sustainability transition features are dependent on the specific model purpose. Further, by mapping the key mechanisms of the reviewed models against the MLP framework, we showed that most models focus on two levels of the MLP and cover different aspects of these levels. For example, while the GIBM or ACFM represent different renewables as niche technologies, TREES focuses on the representation of the corresponding new business models (e.g., prosumers). Finally, we related the policies tested by the reviewed models to a policy intervention framework that is based on the MLP and introduced by [17], demonstrating that the models again test policy interventions mainly at two levels of the MLP. In addition, the policy interventions derived by the evaluated models vary in terms of the type of the intervention or scenario tested, even though they may intend to achieve the same policy target.

We draw the following key conclusions. First, as the evaluated SD models capture desired energy transition model features, the sustainability transition research community as well as policy makers could benefit from using system dynamic models, such as the five evaluated models in this study, for the operationalisation of sustainability transitions and the testing of policy recommendations. Second, policy insights and recommendations of the evaluated SD models are mostly complementary, and therefore have the potential—when combined—to offer a more holistic and comprehensive knowledge base to the current policy debate. Finally, we find that mapping the policy interventions of models against a cohesive policy intervention framework, such as the one developed by [17], has the potential to provide policy makers and modellers alike with a policy intervention toolbox, helping them identify the right model and policy interventions given a particular policy target. We therefore encourage future research to do similar mapping exercises for other energy transition models.

Future Research

An integrative toolbox (e.g., via the theoretical sustainability transition frameworks) that links policy targets with already tested policy interventions and readily available energy models (tools) is highly relevant in the context of the increasing emergence of energy models. However, we see our work only as a first step towards this ambitious endeavour. The further development of such an integrative (multi-dimensional) policy intervention framework warrants future research, in particular with regard to the following aspects or objectives:

- **Relating policy interventions to results and insights**: The introduced toolbox (MLP framework, policy intervention framework by [17] links policy targets to policy interventions and models. However, policy makers are not only interested in policy interventions and models, but also in understanding the related policy implications and effectiveness. Therefore, we suggest that future research expand the current toolbox with additional dimensions, containing for example information on simulation results and policy effectiveness. Another possibility would be to apply the developed toolbox alongside a modelling platform that shows the results of various models, given specific parameter values and policies. The developed toolbox would allow for the comparison of policy targets across the included models. We highlight that this expansion should occur in conjunction with the increased effort to ensure model comparability, including transparency on the policy impact of models' assumptions and analytical frameworks [57,58].
- **Policy recommendations and tools for specific actors**: The transition of current high-carbon energy systems towards net zero emissions systems are governed by many different actors, including but not limited to governments and authorities at different levels, businesses, influencers or non-profit organisations. The development of actor-specific policy toolboxes would help to equip all relevant actors with tools to successfully achieve their actor-specific targets. In addition, we recommend a general overview that informs what energy governance aspects are covered or targeted by which actors, thus identifying exploitable synergies across actors.
- **Generalisation of the suitability of policy interventions and model results**: Energy models often differ with respect to aggregation level, regional scope, time scale and audience. For this reason, it is relevant to investigate under which conditions transferring the policy recommendations derived from one model can be transferred to other policy questions, possibly situated in a different context and time horizon.

Finally, we do not suggest that quantitative models could, or should, necessarily be the only tool informing policy makers on energy transitions; instead, we argue that robust qualitative tools and insights from various research fields could complement policy evidence drawn from quantitative energy transition models. It warrants further research to investigate how qualitative policy evidence and different quantitative modelling tools can be combined, evaluated and communicated more effectively to policy makers.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A.

Appendix A.1. Model Sample ERRE (Economic Risk, Resources and Environment Model)

The Economic Risk, Resources and Environment (ERRE) model is a globally aggregated model whose purpose is to analyse the financial pressures emerging from economic growth while coping with natural limits in both energy and agricultural systems.

Figure A1 shows the overall system boundaries of ERRE, highlighting the network structure among the nine sectors that compose the model. The general dynamics of the system imply that while the economy grows, the dynamics of economic activity accumulates depletion and scarcity of natural resources, in turn generating pressures that propagate from the real economy to the financial system. In such a context, the financial sector has the role of supplying money and controlling the interest rate for the whole economy. The government collects taxes from every economic activity and gives back the income via government transfer to households. Options for applying subsidies and tax changes are also considered.

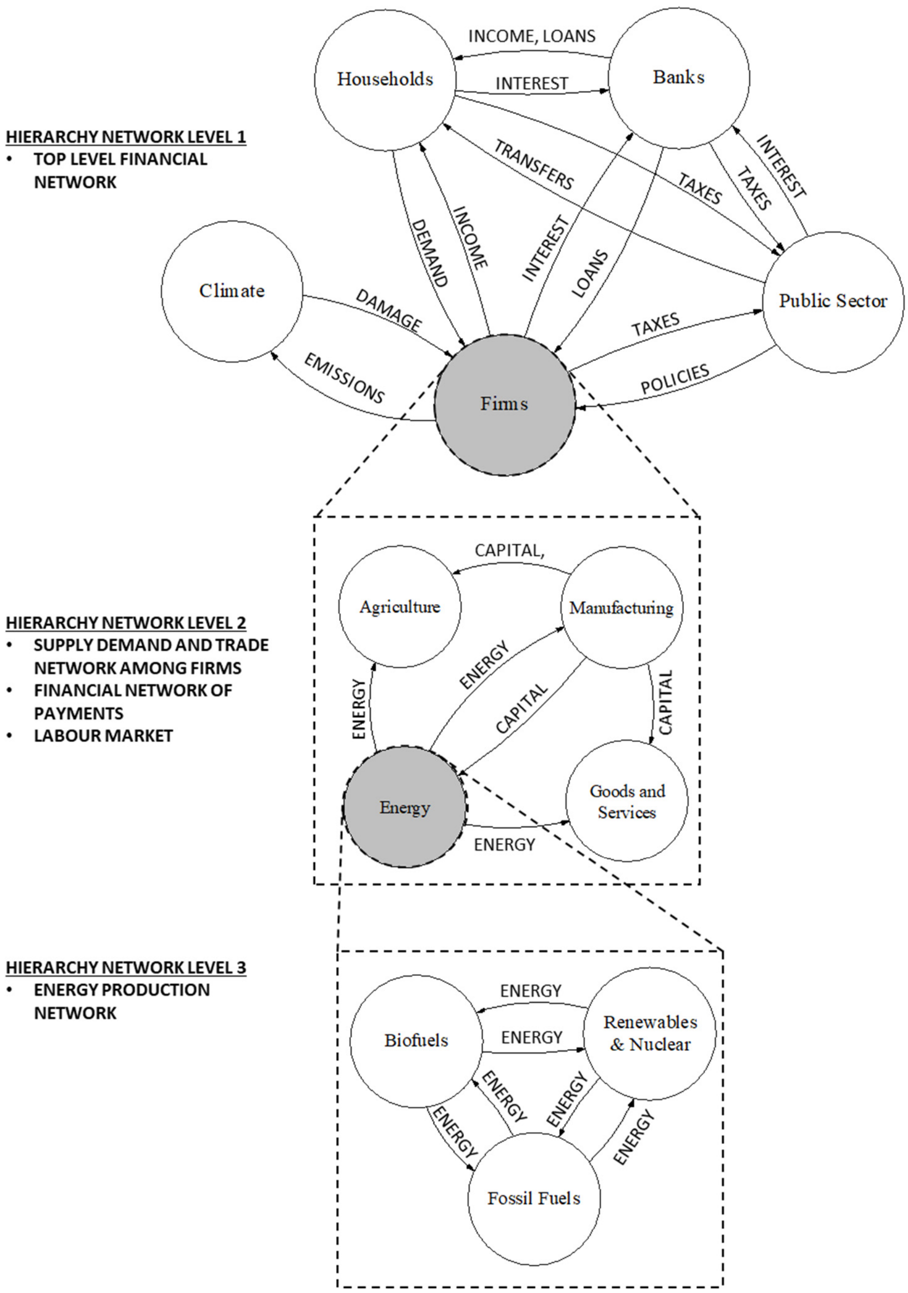

Figure A1. High-level overview of ERRE.

The dynamics of the energy transitions are played out with a mixture of reinforcing and balancing loops present in the energy production network (level 3 of Figure A1. This is further explained in Figures A2 and A3 below).

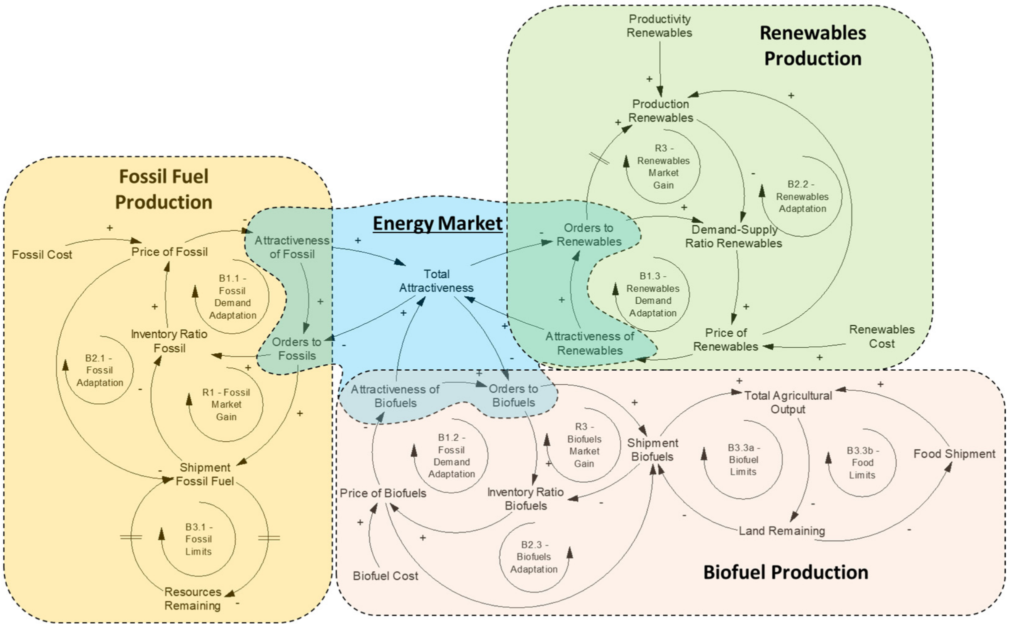

Figure A2. Key energy transition feedback loops in the ERRE model.

Figure A2 shows the interconnections and feedback loops existing between the three energy sectors (fossil fuels, renewables and biofuels) responsible for the energy transition. The energy market is modelled to determine a shift in demand in relation to the relative price change between the three energy types in comparison to initial conditions. As Figure A2 shows, all sectors present a similar structure of capacity adaptation and market competition dynamics. In particular, the feedback loops B1 and B2 represent the adaptation capacity based on the price dynamics of both the demand and supply for each sector. The reinforcing feedbacks R1, R2 and R3 determine the ability of each model to gain additional market shares during the transition, where a higher market share yields higher competitive capacity and price reduction.

Such market competition structures are also influenced by boundaries in terms of resource limits. In particular, two limits to growth feedback are considered in the fossil fuel and biofuel sectors. The lower the resources and land available, the stronger the constraint in production shifting towards higher prices, and the less the competition. In the case of renewables, no constraint is considered; rather, an exogenous productivity measure is considered to apply a scenario analysis based on the potential evolution of green tech in the future. A growth in green productivity would support higher supply, a decrease in prices and smooth market gains for the sector. On the other hand, reaching the limits of land and fossil resources would ultimately impact fossil and biofuel competitiveness, also supporting the transition towards renewables.

Energy prices are also influenced by the costs of production, which are endogenously modelled as being composed of asset charge rates (dependent on tax level, interest rate, inflation, depreciation and price), labour cost and energy cost, showing the resulting reinforcing loop linking energy cost with energy price for all sectors. These, linked to the feedback loops of Figure A3, determine the dynamics of the energy transition, which ultimately push towards a transition to renewables. Green productivity scenarios can be tested to address the maturity of green technology by the time fossil fuel energy depletes, with a subsequent impact on economic dynamics from collapse, crisis with recovery, and a smooth transition.

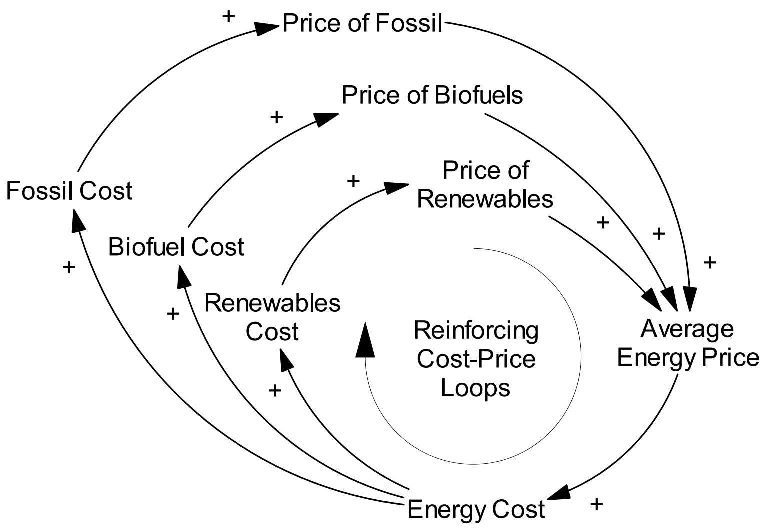

Figure A3. Reinforcing loop of energy cost and price in all sectors.

Model limitations and boundary: The ERRE model provides techno-economic analysis, but it currently lacks societal responses to climate or food scarcity (e.g., riots). In addition, technology growth in the model is assumed to be exogenous for most sectors, mostly influencing increases in production, with a reduction in cost and price as an effect.

Appendix A.2. GIBM (Green Investment Barrier Model)

The GIBM includes the main macroeconomic sectors (e.g., production, consumption or labour market), a public sector and a power supply sector (see Figure A9). The production sector endogenously simulates production, the demand for different production inputs and prices; the consumption sector simulates household consumption per industry and disposable income; the labour market sector determines employment and represents unemployment as the difference between labour demand coming from the production sector and the labour force. Moreover, the labour market simulates the wage level and includes a subsector that simulates the UK working population endogenously; the exchange and interest rate sector represents the exchange rate between the UK and its main trading partners, and the average interest rate of the UK; the public or government sector tracks public income and expenditure. Finally, the power supply sector includes a detailed representation of the electricity production capacity and determines annual energy produced in the UK. The power supply sector is differentiated by 12 electricity production technologies, including biomass, hydro, marine, onshore wind, offshore wind, solar, thermal and other renewable energies as renewable technologies, nuclear and CCS gas as other low-carbon technologies, and finally coal and gas as brown technologies.

Importantly, as an extension to previous energy economy models, the GIBM enables the testing of policy scenarios designed to close the green finance gap. Specifically, the power supply sector includes, when the respective scenario is chosen, a green finance gap, implying that there are not enough green investments for a low-carbon energy transition. In addition, the mark-ups of technology-specific interest rates for renewable power technologies are influenced by green investment barriers. The main data sources used to calibrate the initial conditions, for the UK economy and energy system in the year 2016, are from ONS, EUROSTAT and policy reports (e.g., National Grid reports, in the case of the energy system).

Figure A5 summarises the key feedback loops related to the energy transition in the GIBM.

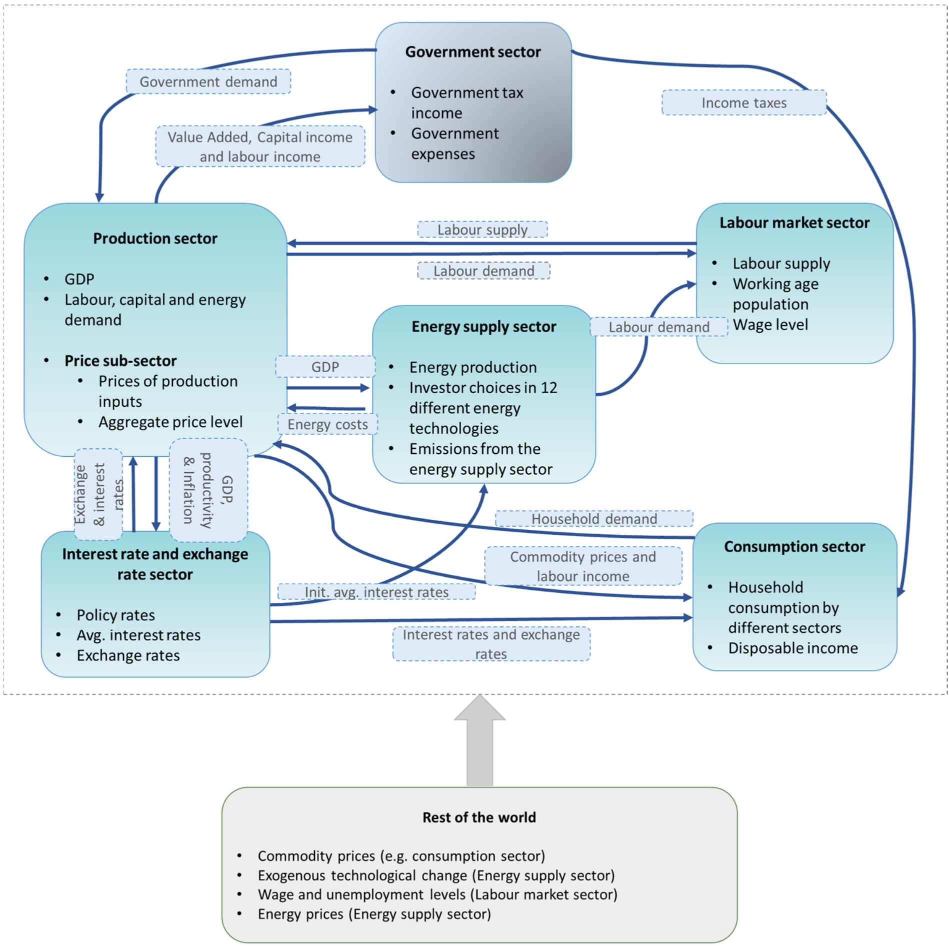

Figure A4. High-level overview of GIBM.

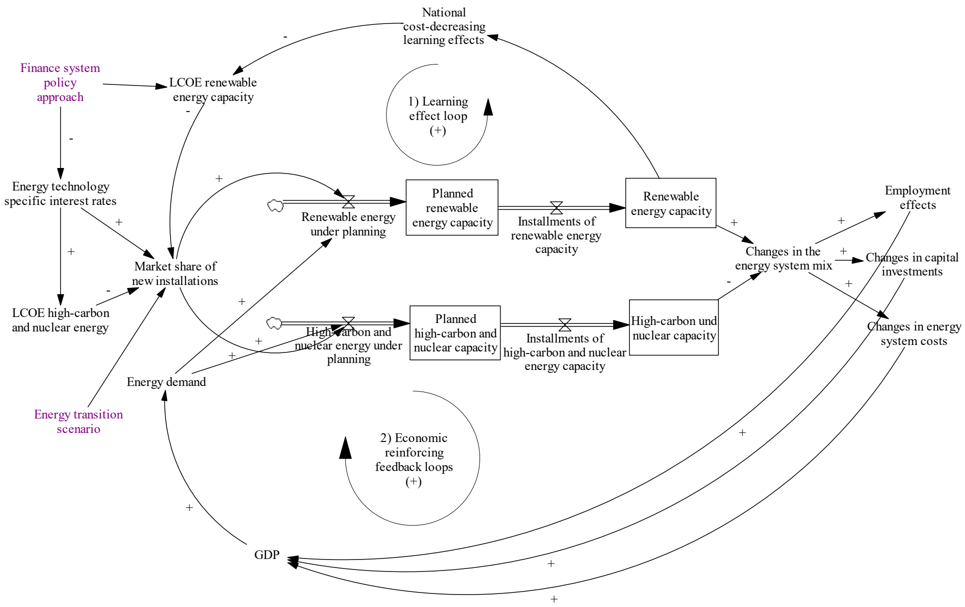

Figure A5. Overview of key feedback loops of the energy transition. Source: own elaboration.

In more detail, these feedback loops include the following:

1. **Learning effect loops in the power sector (+)**: This loop describes the link between the increasing capacity of renewable energy infrastructure and the decreasing costs in constructing related infrastructure (on national level). That is, the more renewable energy production capacity is constructed, the more learning experience within the UK is available, and therefore the less it costs. Importantly, the GIBM includes both national learning effects (modelled endogenously) and international learning effects (represented exogenously) on the capital costs of renewable energy.
2. **Economic (mostly) reinforcing feedback loops (+)**: Changes in the composition of energy production capacity in the electricity system have impacts on the economy via the following three channels: (1) a change in direct employment in the power system that subsequently leads to changes in overall employment in the economy. In the economy, for example, higher employment means increases in wage income, higher consumption, and therefore an increase in GDP. An increase in GDP leads to a further increase in employment; (2) changes in capital investments in energy capacity. For example, an increase in investments in energy capacity leads to an increase in aggregate demand, which means an increase in GDP. An increase in GDP leads in turn to higher investments due to the higher production requirements and finally (3) changes in the power system costs. An increase in the power system costs leads to an increase in the power prices (for consumer), which subsequently translates to higher average prices (CPI). This in turn leads to an increase in the wage level, as such that it has no or only a small impact on the expenditure of the rest of the economy. However, more importantly for changes in the economy, an increase in the average price level also leads to an increase in the interest rates, leading subsequently to an increased propensity for consumption and therefore to an increase in GDP, leading again to additional increases in consumption. The dynamics of the economics are also visualised in Figure A6.

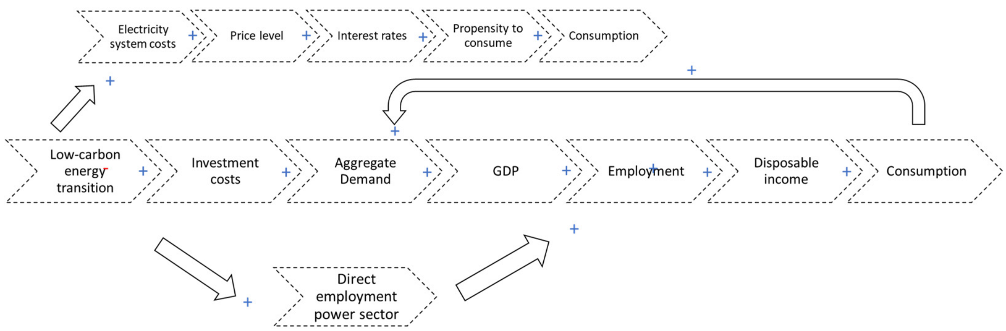

Figure A6. Visualisation of the economic dynamics within GIBM due to changes in the energy system.

Model limitations and boundary: The GIBM neglects intermittency and supply- and demand-balancing issues and represents the transport and heating system exogenously. In addition, the GIBM is a national model and therefore does not represent global dynamics, and the institutional setting is represented only to a limited extent.

Appendix A.3. ACFM (Advocacy Coalition Framework Model)

The ACFM extends previous electricity capacity expansion system dynamics models incorporating techno-economy feedback into investment decisions via a suite of available technologies. These models examine risk and profitability to determine the most appropriate technology to fill future needs. Renewable energy incentives or policy support are included in these as such support is still crucial to the success of an energy transition. However, policy formation is an inherently political process driven by stakeholders in a variety of domains seeking to improve business environments in their favour. The ACFM incorporates competition for energy policy into electricity capacity extension models. The competition is grounded in the Advocacy Coalition Framework Model, which models dynamics between pro-fossil and pro-renewable special interest groups. The pro-fossil groups are well-funded and attempt to repeal, curtail or shorten supportive policy for renewables through political lobbying. The pro-renewable coalition is underfunded and less capable of creating support for renewables. The dynamics between the two results in policy instability, driving up risk analyses and the cost of implementing renewables. Figure A8 gives an overview of the model.

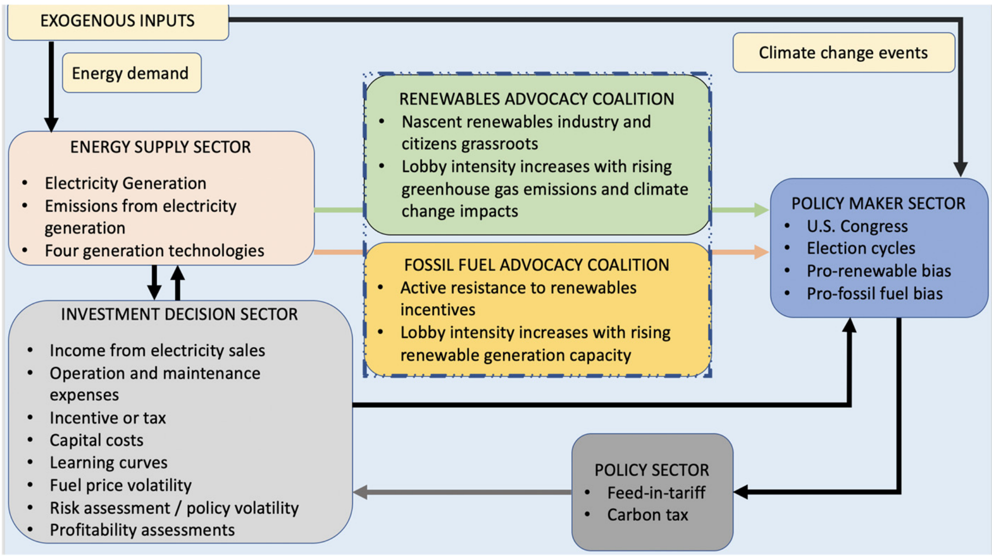

Figure A7. High-level overview of ACFM.

Figure A8 summarises the key feedback loops of the ACFM.

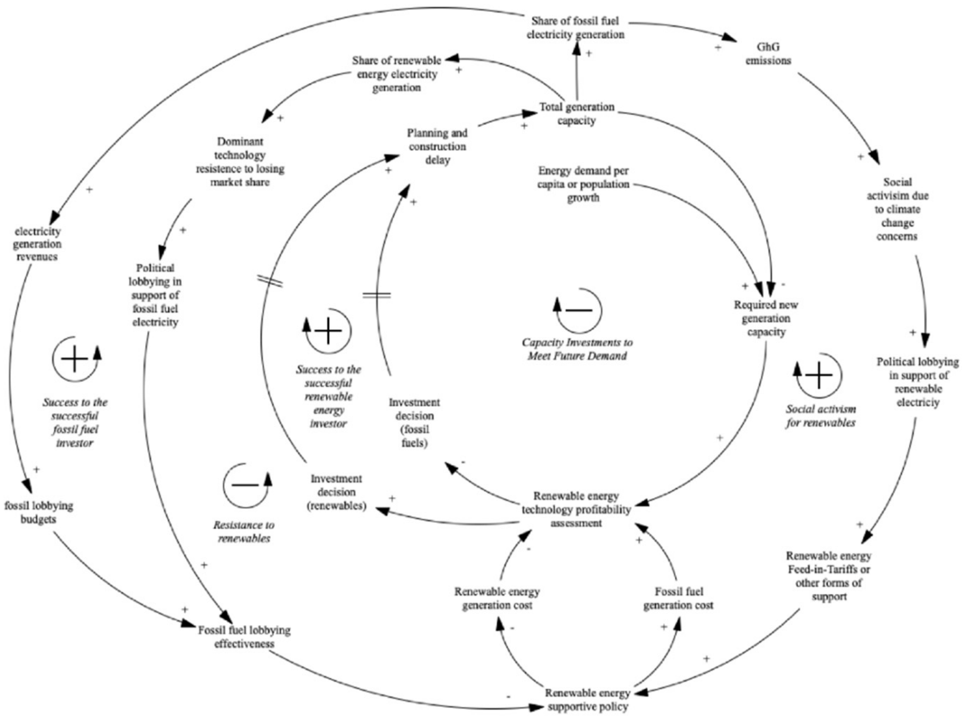

Figure A8. Key feedback loops of ACFM.

There are five key feedback loops driving the ACFM investment dynamics.

(1) **Capacity investments to meet future demand (−)**: This loop describes the basic investment decisions regarding the new electricity generation capacity required to address growing populations or increasing energy demand per capita. The profitability assessment of renewable energy technologies compared to incumbent technologies determines which technology is selected. There is then a planning and construction phase and new capacity is added to the existing stock, which reduces the need for future capacity. Reduced demand then drives down profitability assessments.
(2) **Success for the successful fossil fuel investor (+):** This reinforcing loop results in economic barriers to entry for renewables. In the absence of renewable incentives, the higher capital costs of renewables lessen their profitability assessment, leading to greater investments in fossil fuel technologies. Greater rates of fossil-fuelled electricity lead to greater revenues, which can be used to end lobbying efforts to inhibit renewable incentives from being enacted. This locks in fossil fuels and makes renewable incentives critical to diffusion.
(3) **Social activism for renewables (+):** This reinforcing loop begins with greater shares of fossil-fuelled electricity, resulting in greater GhG emissions. Higher emissions and the subsequent climate change events increase the intensity of green energy coalitions, empowering political lobbying for renewable incentives such as a Feed-in-Tariff. Once enacted, an incentive increases the profitability assessment of renewables, resulting in greater diffusion rates.
(4) **Success for the successful renewable energy investor (+):** This reinforcing loop represents the impact of supportive policies on economies of scale. As policies are enacted, they lower the price of renewables, increasing investments and added capacities. As more capacity comes online, learning curves or experience-by-doing further drop the price, driving more investments.
(5) **Resistance to renewables (−):** This balancing loop represents fossil fuel industry's resistance to higher capacities of renewable electricity generation. As greater shares of renewables come online, fossil fuel industry political lobbying intensifies, becoming more effective at rolling back renewable incentives. This changes the profitability assessment and results in higher rates of fossil fuel investment decisions.

Model limitations and boundary: A key limitation of the ACFM is the aggregation of behaviour for both policy makers and investors. The model is also validated for the governance structure of the United States and is not representative of other political systems.

Appendix A.4. TEMPEST (Technological Economic Political Energy Systems Transition)

TEMPEST is a system dynamics simulation model of the UK's socio-politically driven energy transition. In TEMPEST, mitigation measures that reduce CO_2 emissions are modelled along with political and social factors in energy transition. The scope of TEMPEST includes UK energy-related CO_2 emissions. It simulates historical energy, emissions and measured data in the period of 1980 to 2019 and models pathways towards net zero CO_2 emissions in a future period (2020 to 2080). Energy and CO_2 emissions data are calculated at the level of nation, sector, and mitigation measures; there are 39 mitigation measures across 5 sectors. Representatives from the UK government informed the model design and development through several meetings and a workshop.

The tasks involved in developing TEMPEST were (i) creating a multi-layered, multi-theory model design with a dynamic hypothesis about what causes change in the system metrics (energy and emissions). Relating the model to the MLP, the landscape is climate science and international climate agreements that create mitigation targets; the ST regimes are policy making (government), demand-side equipment regimes, and power sector technology and fuel regimes; niche innovations are new technologies, new behaviours and new policies or societal responses that reduce energy use and the carbon intensity of energy; (ii) analysing data on trends in energy, emissions, mitigation measures and policies in the historical period, and calculating changes in energy and emissions, assigned to the measures, against a baseline of 1980; data came from government sources[i] and the National Grid; (iii) developing a "measure typology" that allows for the simulation of the diffusion of measures without building a full economic model. The typology includes proxies for economic cost such as novelty and difficulty and user impacts; (iv) build the model in Vensim and carrying out basic tests for model robustness; (v) calibrating the model to match the historical data. The calibration process involves matching simulated and historical data for the 39 measures by adjusting inputs that define measure characteristics, adjusting calibration constants and refining equations in the variables; (vi) analysing uncertainty via sensitivity analysis of selected uncertainty variables in the future period.

TEMPEST simulates energy system changes through a structure of five-system feedback. The feedback is illustrated in Figure A9 as a causal loop diagram and explained as follows:

1. Loop 1 (balancing): mitigate while not at target: Emissions savings must be achieved until the distance to target reaches zero. Once the target is reached, the balancing loop ceases.

2. Loop 2 (balancing): measures in the mix are more difficult as target is approached. Much of the "low-hanging fruit" potential for emissions savings, such as LED light bulbs, has been realized. The remaining potential involves mitigation measures that are more novel and generally more technologically complex (e.g., carbon sequestration or hydrogen as an energy carrier) and/or more on the user side (e.g., heat pumps). This loop represents the increasing "average difficulty of implementing measures to reduce emissions" as we approach net zero.

3. Loop 3 (balancing): policy ambition uses up political capital. As policies are launched, available PolCap is used. PolCap can be influenced by drivers and barriers such as the international political economy and elections. The amount of PolCap available limits the ambition of policies that can be launched.

4. Loop 4 (balancing): pushback can affect political capital. Pushback in response to policies is affected by the measure difficulty and the strength of policy ambition. If a strong extrinsic imperative to act from policy occurs alongside insufficient PWP, then pushback can lead to poor policy outcomes. On the other hand, too little policy ambition could mean that not enough energy transition actions are taken. Loop 4 can run both ways; the success of policies can lead to an increase in PolCap. For example, building-mounted solar PV programmes have been popular and have increased public support for renewables.

5. Loop 5 (reinforcing): measure achievements reduce difficulty. Loop 5 represents learning by doing (LBD): *"the more something is made, the better it can be made"* [59]. LBD reduces mitigation measure costs over time due to economies of scale in production; it also enables the early-stage development of measures (pre-commercialisation). Measure deployment can eventually become self-sufficient through LBD, removing the need for policy support.

6. Interactions: The five loops interact in several ways, for example: (i) Loop 2 is counterbalanced by loop 5. If loop 5 reduces mitigation measure difficulty faster than the rate at which more difficult measures are required, then loop 2 will become insignificant, improving the whole energy transition. (ii) Loop 4 is counterbalanced by loop 5. As measure difficulty decreases, pushback decreases—or even becomes negative, increasing PolCap. (iii) Loop 5′s growth rate is limited by the availability of policy ambition in loop 3, which can be changed through drivers and barriers and through pushback from loop 4.

Model limitations and boundary: TEMPEST does not represent macroeconomic impacts or the financial cost of energy transition, and the level of detail on mitigation measures is less than in large energy-planning models.

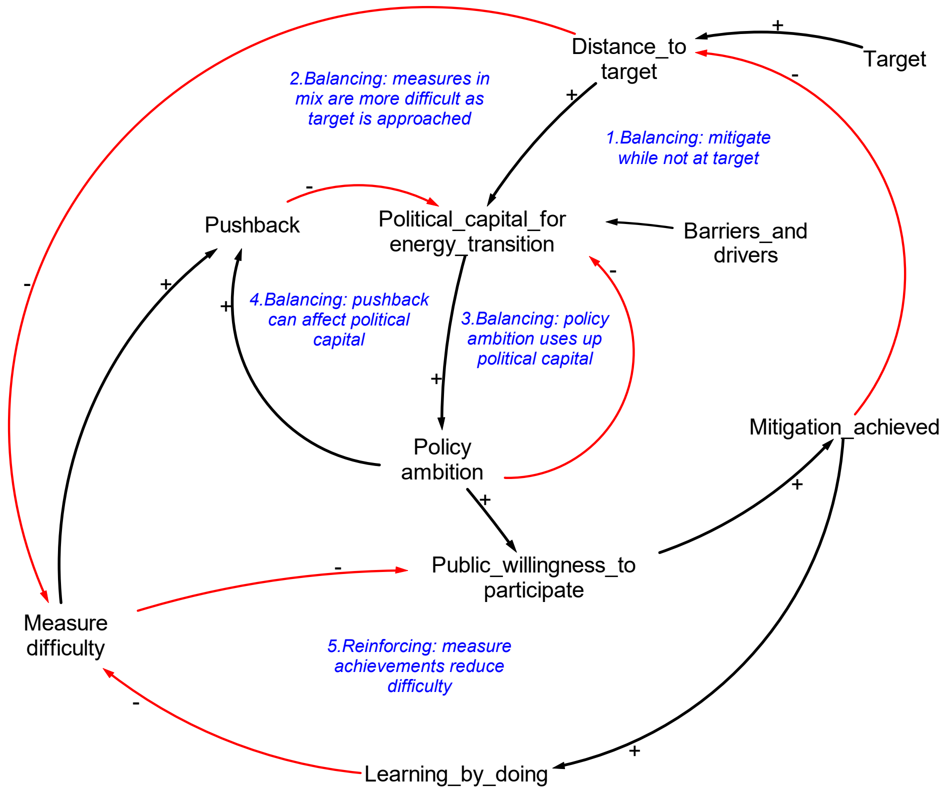

Figure A9. Overview of key feedback loops in TEMPEST.

Appendix A.5. TREES (Transition of Regional Energy Systems) Simulation Platform

The Transition of rEgional Energy Systems (TREES) simulation platform is designed to support electric utility companies, technology developers and municipalities in the decentralisation of energy systems. The model was developed at the Zurich University of Applied Sciences as part of the Swiss Competence Center for Energy Research—Center for Energy, Society and Transition and profited from close collaborations with several industry partners.

The core of the TREES model centres around the diffusion of prosumer concepts (prosumers are producers and consumers at the same time). The model captures the dynamic interaction between the diffusion of prosumers, the financing of the electricity distribution grid and the corresponding tariff setting, as well as business strategies for companies to engage in the decentralisation trend. The diffusion simulation is supported by the endogenous simulation of various feedback processes that govern the attractiveness of the prosumer concepts. The TREES model's foundation is grounded in network theory, applied to the decentralisation dynamics of energy systems [55]. The model was applied to various case studies and validated in a workshop series with industry experts [22]. The TREES model has a strong regional focus. The typical application scope for case studies is the supply area of a utility company.

The model allows for the analysis of the impacts of different grid tariff designs and provides policy recommendations. For this purpose, the model has been applied to several municipalities and the supply area of Swiss utility companies [51]. Later versions of the TREES model also allow for a strategy analysis for different business models. The model was expanded to analyse prosumer communities as a strategic partner and future business field in decentralised energy systems [60]. Further, the business dynamics of flexibility aggregation were analysed with an advanced TREES model [54], for which in-depth strategy analysis was performed for the business cases of a battery swarm, a district battery and a multi-energy flexibility solution. Strategy analyses typically centre around the dynamics interplay between demand side developments, revenue stream combinations and cash flows, tariff design and consumer levels, as well as impacts on grid financing (see Figure A10).

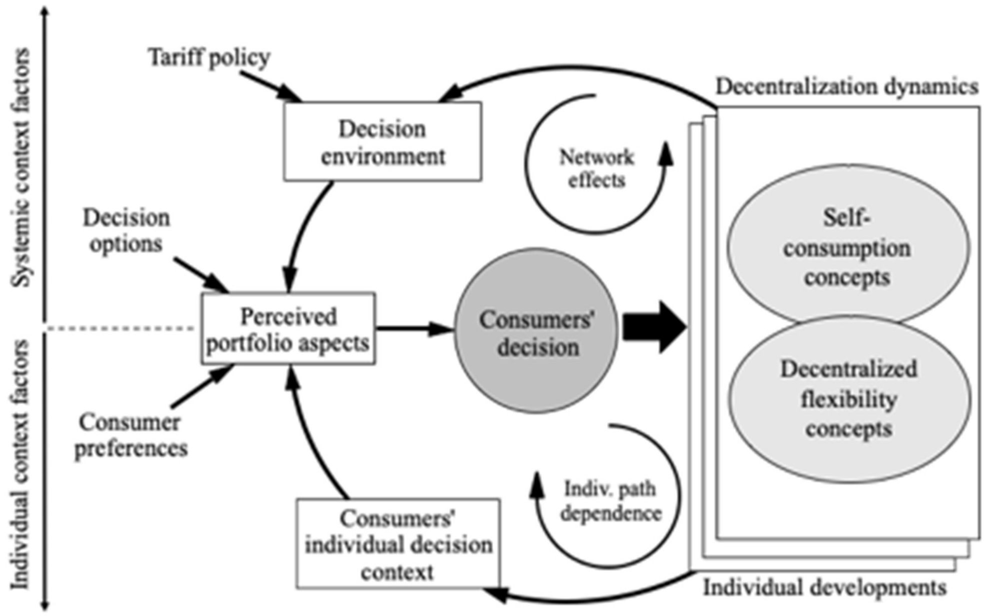

Figure A10. Overview of key feedback loops of the TREES model.

Model limitations and boundary: The TREES model applies an annual perspective to energy flows, which is sometimes perceived as a limitation since the seasonal effects of self-consumption systems are neglected. The model could be expanded in various areas, of which the technical implications on the electricity grid would be of interest to some stakeholders. Regarding the simulation of balancing power markets, an endogenous perspective on the market price dynamics and competition by further providers was beyond the scope of the study but could have relevant effects.

Appendix B. Detailed Model View

1. Techno-economic details: All the selected SD models have a good representation of the techno-economic details. Specifically, ERRE represents primary energy in three globally aggregated sectors (fossil fuels, biofuels and renewables) to study a price-driven energy transition in relation to (i) fossil fuel depletion, (ii) green technology development and (iii) the impacts of energy transition on food output. All sectors are fully endogenous, including demand, supply, capital accumulation vintage structure, asset value, prices, wages, labour and dividends/interest rates, among others. Both the GIBM and ERRE capture the macroeconomic implications of different centralised energy scenarios. The GIBM represents the electricity supply sector endogenously, by simulating the investment decisions of energy firms based on the LCOE of 12 different power production technologies. The LCOE are endogenously adjusted due to learning-by-doing effects by the simulation model. The GIBM captures the technical constraints of renewables and constraints related to the availability of finance for investment in electricity projects. It further uses exogenous scenarios for the electricity demand of the heating and transport sector and endogenously simulates the demand for electricity from the rest of the economy. The ACFM represents new generation capacity investment decisions in California's electricity supply sector. Using exogenous data on electricity demand prospects, the model considers risk calculations, learning curves, renewable incentives/carbon taxes and fossil fuel volatility to determine the profitability of a portfolio of technologies. TEMPEST simulates energy consumption (electricity and non-electric fuels), carbon intensity of energy and emissions from energy use ($MtCO_2$) across the whole economy (five sectors). In total, 39 mitigation measures that save energy or reduce the carbon intensity of fuels are modelled to simulate the time-dependent impact over time to achieve energy transition targets. The TREES model considers for rooftop solar and battery systems the adoption and business model perspective of prosumers and energy providers (e.g., with regard to financial advantages or individual non-financial preferences) within a transition to decentralised renewable electricity.

With regard to the representation of techno-economic details, all models make a simplification with the choice of relatively large simulation time steps. This choice does not allow for the modelling of daily electricity load and generation. The ERRE model has a time step of 11 days, and the other selected SD models use a time step of 3 months or a year. As a consequence, the evaluated models neglect intermittency issues that occur at time steps of less than a year. This means that the effects of storage or demand management technologies on grid management cannot be analysed at a high time resolution and technical perspective by the evaluated models (however, the TREES model does simulate the diffusion of storage solutions; see for example [33], where TREES simulates the diffusion of home storage solutions and their effect on self-consumption and grid financing, or [34] for an analysis of a battery swarm as a business model for decentralised flexibility). See Table A1 for an overview.

Table A1. Overview of how the evaluated SD models account for techno-economic details.

ERRE	*Captures the macroeconomic implications of low-carbon energy transitions. Endogenously represents the market dynamics of fossil fuels, green energy and biofuels and its relative impact on food stability. Addresses the dynamics of a centralised power transition.*
GIBM	*Represents the costs and carbon intensity of a portfolio of eleven electricity production technologies. Captures the technical and financial constraints of renewable power diffusion Addresses the dynamics of a centralised power transition.*
ACFM	*Represents the costs of a portfolio of electricity technologies—natural gas, PV, coal and oil. Addresses the dynamics of a centralised power transition.*
TEMPEST	*Represents energy consumption (electricity and non-electric fuels), carbon intensity of energy and emissions from energy use (MtCO2) across the whole national economy (5 sectors), and the implementation of 39 mitigation measures that save energy or reduce the carbon intensity of fuels. Considers centralised energy transitions.*
TREES	*Represents the costs of a portfolio of decentralised electricity prosumers and production technologies. Addresses the dynamics of a decentralised power transin.*

2. Multi-dimensionality, systems perspective and interdisciplinary: The evaluated SD models are all characterised by multi-dimensionality (i.e., they represent different sectors and different parts of society), a systems perspective and interdisciplinarity. Indeed, SD as a methodology is well suited to capture these features (see Section 2.1). In more detail, ERRE adopts the widest systems perspective in the sense that it covers a closed (global) system economy, modelling households, government, the financial sector and firms, and their interactions with global resource limits and greenhouse gas emissions. The GIBM represents the key macroeconomic sectors and the power supply sector. In addition, the GIBM in particular adopts an interdisciplinary systems perspective with regard to its consideration of the green investment barriers, deterring the green finance gap from closing (i.e., it shows not only barriers within the energy system, but also biased risk perception, policy uncertainty or lack of ESG data as key investment barriers). The ACFM, TEMPST and TREES focus on the representation of the energy sector and do not represent macroeconomic dynamics. They apply interdisciplinary knowledge and a systems perspective in the following ways: representing policy competition dynamics (ACFM), bridging the sectors of consumer decisions, grid financing, policy design and businesses (TREES), and the dynamics of feedback between three layers in the model—the national level of politics, the governance of mitigation policies and the implementation of mitigation measures (TEMPEST).

Overall, this feature is well captured by the evaluated system dynamics models, which can also be explained due to the fact that system dynamics is a methodology well suited to capture key mechanisms of multi-dimensional, complex systems. Further details on how the specific models capture this feature are summarised in Table A2 below.

Table A2. Overview of how the evaluated SD models account for multi-dimensionality, a systems perspective and interdisciplinary.

ERRE	Covers a closed-system economy, modelling households, government, the financial sector and firms, and their interactions with global resource limits and greenhouse gas emissions.
GIBM	Covers key macroeconomy sectors (e.g., production, consumption, labour market, interest rates, etc.) and a power supply sector with investment decisions of energy firms. It addresses a green finance gap, including key investment barriers deterring it from closing. The interdisciplinary perspective is enriched by expert knowledge and empirical data from interviews.
ACFM	Examines political competition dynamics linked with economics and a technology change perspective by modelling pro-renewable and pro-fossil coalition attempts to influence policy making. The model includes endogenous behaviour changes of both coalition groups linked with capacity dynamics of renewable electricity technologies.
TEMPEST	Includes feedback between three layers in the model—the national level (political), the governance of mitigation (policy) and the implementation of mitigation measures (market?). Uses concepts from social sciences, including political capital, social capital and public acceptance. Design partly based on the meta-theoretical framework from Cherp et al. (2018) [6].
TREES	The model integrates empirical insights from research on technical aspects (costs, sizing and technology learning curves), decision making, consumer preferences, finance and the business model literature. Knowledge has also been included from practitioners in participatory modelling workshops.
All models	Model building is based on the relevant literature from different fields, including, but not limited to, behavioural economics, energy economics studies and political science. All models include various sectors and their interrelated feedback loops from a systems perspective.

3. Multiple actor network and behavioural aspects: The evaluated SD models capture feature 3 in different ways. First, the core structure of ERRE can be represented as a three-layer hierarchical network model in more detail, all sectors are modelled as boundary objects, each responding to a demand generated endogenously by the other sectors of the model, thus forming networks. Networks can be found in many forms including (i) energy trade network, (ii) capital trade network, (iii) labour mobility network, (iv) money supply and distribution network (see Appendix A for further details)), where (i) the firm sector interacts at the top level with climate, government, households and financial sector and can be broken down as nodes of an entire supply chain, and (ii) which further represent energy as composed of three primary energy sectors (biofuel, fossil and green energy sources). Second, the GIBM represents macro-actors such as firms, consumers, workers, energy firms (investing in grid and energy production infrastructure) and financial investors. In both ERRE and the GIBM, macro-agents generally have decision mechanisms based on micro-founded decision feedback structures, drawing on bounded rationality, imperfect information and non-linear cognitive capabilities. Third, the ACFM includes both pro-fossil and pro-renewable coalitions, each attempting to influence policy maker's decisions. These special interest groups hold opposing perceptions, pursue conflicting policy goals and attempt to influence the rate at which the transition occurs. Fourth, TEMPEST represents the political domain via the concept of "political capital", which is the "fuel" needed for policy making that drives energy transition and represents policy making with a policy choice engine that assigns policy ambition to measures. TEMPEST represents societal responses to policies with the concept of "public willingness to participate" (PWP), which indicates the likelihood that expected outcomes of policies will be achieved through actions from the energy sector and the rest of society. Fifth, the interplay between consumers, the grid operator and providers of flexibility solutions are captured in the TREES model. Indeed, a particular strength of the TREES model is the empirically substantiated modelling of consumer decisions, allowing for the simulation of realistic adoption scenarios of low-carbon energy technologies.

A key limitation of all SD models is that the representation of heterogeneity in agent populations is limited. That is, while system dynamics can represent groups of different types of agents (e.g., consumers or firms), it is less suitable for capturing the effects of multiple interactions between thousands of agents, in which case agent-based modelling is more appropriate. Further details on the evaluated models are summarised in Table A3.

Table A3. Overview of how the evaluated SD models account for actor network and behavioural aspects.

ERRE	*The core structure of ERRE is defined as a three-layer network with the relationships between the macro-actors "households", "banks", "government" and "firms".*
GIBM	*Represents macro-actors such as firms, consumers, workers, energy firms (investing in grid and energy production infrastructure) and financial investors.*
ACFM	*Includes both pro-fossil and pro-renewable coalitions, each seeking to influence the decisions of policy makers. These interest groups hold opposing views, have conflicting political agendas and seek to enact policies that favour their agendas, thus influencing the speed of the transition.*
TEMPEST	*Represents the political domain through the concept of "political capital", which is the "fuel" needed for policy making that drives the energy transition, and represents policy making with a policy choice engine that assigns policy ambition to measures. TEMPEST represents societal responses to policies with the concept of "public willingness to participate" (PWP), which indicates the likelihood that expected policy outcomes will be achieved through actions from the energy sector and the rest of society.*
TREES	*Represents three consumer groups—single family houses, multi-family houses and commercial consumers, the grid operator, and providers of flexibility business models. Consumer decisions are modelled based on empirical data, in particular using results from a conjoint analysis, allowing for the simulation of a realistic adoption of decentralised technologies* (Kubli (2020) [33] describes how conjoint data can be integrated effectively into an SD model reducing the uncertainty in the simulation).
All models	*Importantly, actors in all models are governed by behavioural aspects (e.g., preferences, perceived rather than actual values) and apply heuristics (as opposed to cost optimisation).*

4. ***Path dependency, lock-in, inertia and self-reinforcement of change:*** System dynamics is a modelling tool particularly well suited to capture path dependency, lock-in, inertia and self-reinforcement of change (see Section 2.2). The following examples indicate how the evaluated models capture this feature: ERRE and the GIBM include various feedback loops within the economy (e.g., Keynesian multipliers). ERRE further includes important feedback loops between the economy and the natural resource limits (e.g., hot house effect on climate, resource depletion and land availability). The GIBM also represents path dependency in the power supply sectors both through the energy firms' preference for certain technologies, and because installing energy infrastructure leads to learning effects of the installed technology, driving a reduction in price. The ACFM examines both path-dependent and lock-in dynamics through fossil fuel coalition resistance to renewables moving out of the niche, intensifying lobbying efforts as the market share of renewables increases. Self-reinforcement is included by intensifying green advocacy coalition efforts to manipulate policy making as climate change impacts rise. TEMPEST includes a combination of reinforcing loops driving mitigation progress (learning by doing), and balancing loops limiting progress (societal pushback against strong policy pushes). Both inertia and self-reinforcement of change are represented, and the combination of all feedback loops determines the rate of mitigation. TREES focuses on different constellations of electricity self-consumption concepts. Consumer decisions are modelled on their individual decision context explicitly representing individual path dependency. The self-reinforcing feedback loop of the grid cost-recovery effect on prosumer diffusion is a central part of the model. Several further feedback loops govern the diffusion of the prosumer concepts: peer effects, investor roof match probability and the scarcity effect. For flexibility aggregators, the lock-in effect of being "too small to bid" (Kubli and Canzi, 2021 [34]) is captured, which turns into a self-reinforcing process once it has been overcome.

Also, TREES considers additional feedback loops that evolve around the flexibility premium and the impact of flexibility provision, both dependent on the bidding success in balancing power markets (see Table A4).

Table A4. Overview of how the evaluated SD models account for path dependency, lock-in, inertia and self-reinforcement of change.

ERRE	*Includes various feedback loops within the economy (e.g., Keynesian multipliers). It also includes important feedback loops between the economy and the natural resource limits (e.g., climate change impacts and economy).*
GIBM	*Includes various feedback loops within the economy (e.g., Keynesian multipliers). It also represents path dependency in the power supply sector as the energy firms' decisions are dependent on individual preferences or because installed energy infrastructure leads to learning effects of this particular technology, and therefore contributes to lowering the costs of this technology.*
ACFM	*Examines path-dependent and lock-in dynamics through fossil fuel coalition resistance to renewables moving out of the niche, intensifying lobbying efforts as the market share of renewables increases. Self-reinforcement is included by intensifying green advocacy coalition efforts to manipulate policy making as climate change impacts rise.*
TEMPEST	*Includes a combination of reinforcing loops that drive mitigation progress such as learning by doing, and balancing loops that limit progress, such as the possibility of societal pushback against strong policy pushes. The combination of all feedback loops determines the rate of mitigation.*
TREES	*Models consumer decisions respecting their individual decision context. By doing so, the individual path dependency is explicitly represented in the model. The self-reinforcing feedback loop of the grid cost-recovery effect on prosumer diffusion is a central part of the model. Further feedback loops are included for the simulation of flexibility business models.*
All models	*The representation of feedback loops is a key feature of system dynamics and thus also of the evaluated models. Depending on the type of feedback loops their interlinkages, feedback loops explain path dependency, lock-in and self-reinforcement of change.*

5. Sustainability transition pathway dynamics*:* All of the evaluated SD models apply a long-term simulation period (ranging from a 15-year modelling horizon (TREES) to a 100-year period (TEMPEST, ERRE)). All models evaluate normative (policy) goals, including emissions reduction (TEMPEST, GIBM), installed capacity of electricity generation technologies (ACFM, TREES), the share of self-consumed electricity (TREES), distributional effects (TREES), key macroeconomic impacts (GIBM, ERRE) and impacts on land use (ERRE) (see Table A5).

Table A5. Overview of how the evaluated SD models account for sustainability transition pathway dynamics.

ERRE	100-year modelling horizon; evaluates transition using different sustainability indicators, such as emissions, GDP, unemployment, changes in prices or impacts on land use.
GIBM	50-year modelling horizon; evaluates transition using different sustainability indicators, such as emissions, GDP, unemployment, generated direct employment, changes in electricity prices or power system costs.
ACFM	30-year modelling horizon; evaluates transition rate based on installed capacity of renewable energy source electricity generation.
TEMPEST	40-year historical period (1980 to 2019), and 60-year modelling horizon (2020 to 2080 or the year of achieving net zero emissions); evaluates the success of energy transition on the basis of cumulative emissions staying within a carbon budget, and the year of reaching net zero being close to the target of 2050.
TREES	15/35-year modelling horizon, with historical period of 5–10 years (from 2010 to 2015/2020); evaluates transition using different sustainability indicators, such as share of solar power, share of self-consumed energy and grid costs, as well as distributional effects (see [31]).

6. Open-endedness and deep uncertainty: Importantly, related to the methodology of System dynamics, deep uncertainty is represented in all of the evaluated models in the sense that model agents do not possess perfect information about the future and that sensitivity testing is generally undertaken. In more detail, the ACFM, TREES and TEMPEST employed Vensim's Monte Carlo sensitivity analysis, and the GIBM, ERRE and TREES compared various scenarios for sensitivity analysis. Pasqualino and Jones (2020) [46] show, based on ERRE, an extreme fat tail systemic risk analysis, addressing three risk scenarios (i.e., (i) the effect of climate change on the food system, (ii) extreme risk effect of climate on food system and (iii) the possibility of fossil fuel depletion and the economy assuming a peak of energy production around 2070) and the limits of the potential solutions via three additional scenarios (i.e., rise of green tech, application of carbon taxes and the combination of both). However, system dynamics models, including the five models that we evaluated, embed numerous assumptions about the future. Using scenario analysis, it is only to some extent possible to test them. In addition, SD models are more static with regard to the model structure in comparison to agent-based models. Finally, models and theories per se are not suitable to include the "unknown unknowns" aspects of deep uncertainty. See Table A6 for an overview.

Table A6. Overview of how the evaluated SD models account for open-endedness and uncertainty.

ERRE	Compares various scenarios for sensitivity analysis (see [2,56] for guidelines on model validation and sensitivity testing for system dynamics models).
GIBM	Compares various scenarios for sensitivity analysis.
ACFM	Compares various scenarios for sensitivity analysis and employs Vensim's Monte Carlo sensitivity analysis.
TEMPEST	Employs Vensim's Monte Carlo sensitivity testing for uncertainty analysis based on varying exogenous conditions.
TREES	Compares various scenarios for strategy analysis and employs Vensim's Monte Carlo sensitivity analysis.
All models	Model agents only have access to current information (no forward-looking agents) and model outcomes are tested by changing the exogenous assumptions via scenario analysis.

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