International Journal of Sustainable Energy Planning and Management Vol. 36 2022 33–52

International Journal of
Sustainable Energy Planning and Management

A review of social aspects integration in system dynamics energy systems models

Alaize Dall-Orsoletta[a] , Mauricio Uriona-Maldonado[b] , Géremi Dranka[a,c], and Paula Ferreira[a]

[a]ALGORITMI Research Center/LASI, University of Minho, Campus Azurém, 4800-058 Guimarães, Portugal
[b]Deparment of Industrial and Systems Engineering, Federal University of Santa Catarina (UFSC), Campus Universitário – Trindade, 88040-900 Florianopolis, Brazil
[c]Department of Electrical Engineering, Federal University of Technology – Paraná (UTFPR), Via do Conhecimento km 1, 85503-390 Pato Branco, Brazil

ABSTRACT

The problem of techno-economic approaches to evaluating energy transition pathways has been constantly reported in the literature, while existing research recognises the critical role played by social aspects in energy systems models. System dynamics (SD) has been pointed out among modelling techniques as a suitable tool to evaluate the interdisciplinary nature of energy transitions. This paper explores how energy system-related SD models have incorporated social aspects through a literature review. Models were assessed based on their geographical resolution, time horizon, methodological approach, and main themes: supply-demand, energy-economy-environment (3E), energy-transport, water-energy-food (WEF) nexus, and consumer-centric and socio-political dynamics. Social aspects considered include behaviour and lifestyle changes, social acceptance, willingness to participate, socio-economic measures, among others. As expected, the representation of social aspects was not standard among the papers analysed. Socio-economic aspects were most commonly included in supply-demand and 3E models. Energy-transport and WEF models mainly incorporated changes in travel and consumption habits, respectively. The last theme had a more diverse approach to social aspects that deserves further attention, especially for energy access and justice issues. Other research lines include modelling approaches combination, enhanced participatory and transparent processes during model development, and use of SD models in policy-aiding and stakeholders' information processes.

Keywords

System dynamics;
Energy systems models;
Social aspects;
Energy transition;
Causal loop diagrams;

http://doi.org/10.54337/ijsepm.7478

1. Introduction

Considering the urgent need to reduce CO_2 emissions and achieve a net-zero economy, consumption patterns, energy technologies and manufacturing processes must change toward sustainable practices. As energy systems are at the core of the global economy, producing energy from low-emission sources, consuming it more efficiently, and lowering demand are key aspects of a successful transition. Nevertheless, the complexity of energy systems has required quantitative modelling techniques to support decision-makers in the challenging task of developing short and long-term transition pathways. Thanks to computational capabilities, the number of energy system models (ESMs) and the complexity captured by them has increased significantly over the last decades [1]. Likewise, review works of

---

*Corresponding author – e-mail: alaize.orsoletta@gmail.com

ESMs have assessed and categorised developed models while aiding modellers and decision-makers in selecting appropriate tools.

One of the most common classifications separates models into bottom-up and top-down models. Bottom-up or engineering models stress the technical characteristics of energy systems, whereas top-down approaches focus on price and market influences [2]. Models can also be classified according to their modelling technique [2], spatial (regional, national, and global) and time dimension (short, medium, and long-term) [3]. They also have different purposes (e.g., forecasting, exploring, or backcasting) and require or include combinations of quantitative, qualitative, disaggregated, or aggregated data elements [4]. Another category of models that has become popular to inform large-scale and global climate mitigation pathways [5] is the Integrated Assessment Models (IAMs). IAMs have been used in the Intergovernmental Panel on Climate Change (IPCC) [6] and European Commission's [7] assessments and include a wider set of modules than energy systems models alone, such as land use, agriculture, energy, industry, forestry, and climate modules [8].

Regarding underlying methodology, Lopion et al. [9] differentiated ESMs in optimisation, simulation, and hybrid models. Optimisation models refer to all linear, mixed-linear and non-linear programming, and equilibrium models solved to optimality (e.g. [10,11]). On the other hand, simulation models consist of dynamic and stochastic approaches that do not seek optimality [9] but are concerned with representing overall systems structure and generating insights from policy scenario analysis. On the differences between simulation and optimisation archetypes, Lund et al. [12] compared the two approaches in technical, decision-making, and political terms. The authors argued that optimisation models are well-suited for forecasting and prescribing the optimal future, whereas simulation models are fit for backcasting and debating the desired future. Hybrid models combine optimisation and simulation methodologies. Some works also classify as "hybrid" those models that integrate bottom-up and top-down models [1] or use more than one modelling technique (e.g., macro-economic modelling, general economic equilibrium, linear optimisation, partial equilibrium, and system dynamics (SD)) [2].

Concerning previous review studies, Prina et al. [1] reviewed bottom-up ESMs and classified them as short-term or long-term models, while Kotzur et al. [13] and Ridha et al. [14] reviewed ESMs in terms of their complexity. Ringkjøb et al. [15] reviewed and classified modelling tools for energy systems with a large share of renewable energy sources (RES). Connolly et al. [16] considered 68 and further analysed 37 computer tools used to evaluate the integration of RE into energy systems. Later, the same methodology was employed in Chang et al. [17], who surveyed similar review studies and 54 ESMs, including models' application aspects. Alternatively, Fodstad et al. [18] took a different approach as it reviewed modelling frameworks according to the main challenges faced by ESMs, namely, (i) the handling of several energy carriers, (ii) the integration of different time and spatial scales, (iii) uncertainty, and (iv) the integration of energy transition dynamics.

Also, Fattahi et al. [19] analysed nineteen IAMs used at national levels and unfolded an interesting discussion on current and future low-carbon energy system modelling challenges and how to address them. Moreover, this last work also recognized how social aspects are commonly neglected in ESMs, given their predominant techno-economic nature [19]. The latter aspect was also highlighted by Süsser et al [20] who argued for the relevance of integrating social and environmental factors into energy models. The authors showed how ignoring these aspects could lead to misleading policy recommendations in terms of the speed of the energy transition and technological options.

Particularly, SD is a simulation-based modelling technique that has been successfully used for energy system modelling [21] since the seminal works of Sterman [22] and Fiddaman [23]. In contrast with linear models, SD captures the complex dynamics of energy systems through feedback loops and endogenously models system behaviours commonly absent from other modelling techniques [2]. SD modelling can account for market failures, delays in feedback loops, the absence of complete information and deal with several uncertainties present in energy systems, such as human behaviour and perceptions [24]. Reddi et al. [25] reviewed SD modelling on RES and combined heat and power generation. Leopold [26] extensively reviewed energy-related SD models from 2000 to 2015 in terms of their general purpose, time horizon, regional frame, and main conclusion. The author underscored that SD models have been applied to diverse situations within the energy sector, but gaps in transformation processes and transition research through consumer-centric perspectives remained [26].

Nonetheless, Papachristos [27] emphasised the potentiality of SD simulations for the study of socio-technical energy transitions (STET) as a way to catalyse learning and decision making in complex systems. Also, Li et al. [28], when reviewing STET models, stated that, even though agent-based models (ABMs) are the most employed when it comes to incorporating the heterogeneity of actors, dynamics simulation approaches seem to be as successful as ABMs in representing key characteristics of socio-technical systems. Additionally, Bolwig et al. [21] stressed the potential of SD to "capture the co-evolution of economic, policy, technology, and behavioural factors over sufficiently long periods, which is necessary for the analysis of transition pathway dynamics". The authors also presented how SD models integrate sustainable transition concepts, such as strategic niche management (SNM) [29], learning effects, consumer behaviour and values [21].

A broad number of frameworks and theories have been used to conceptualise the social processes behind the energy transition, such as Multi-Level Perspective (MLP), the Technological Innovation System (TIS), SNM, and Transition Management (TM), with some of these frameworks being well represented in SD models [30]. Moreover, recent debates on just energy transitions and energy justice have shed light on the preoccupation of how to transition to a low-carbon system without reinforcing current socio-economic inequalities but rather diminishing them. This leads to the question of how to incorporate social aspects and metrics into quantitative ESMs appropriately, which has contributed to the development of frameworks and indicators within a trend towards further incorporation of social sciences into energy analysis [20]. Even though this is not a new problematic, as social metrics have been a source of discussion since the rise of sustainability and welfare concepts, it is still subject to improvement. Krumm et al. [31], for instance, reviewed how different types of energy models (i.e., IAMs, ABMs, ESMs, and computable general equilibrium models) represent social factors. The authors concluded that 13 out of the 23 reviewed energy models incorporated social aspects, mainly public acceptance, and behavioural and lifestyle choices, being ABMs the only ones to partially address public participation and the heterogeneity of actors [31]. However, none of the reviewed models consisted of SD models.

From this background on ESMs reviews, SD, and the incorporation of social aspects into modelling, the present work aims to identify how SD energy system-related models incorporate social aspects without placing a particular focus on the literature about STET. To the best of the authors' knowledge, this is the first work in the literature to approach this gap. A review of energy-system related SD models available in the peer-reviewed literature was conducted and main social aspects incorporated in models were identified. Within 'social aspects', it was considered socio-economic, demographics, behavioural, socio-political, wellbeing, and social acceptance aspects, as described in Section 2.2. Henceforth, these aspects are simply referred to as "social" for the sake of simplicity. Ultimately, we aim to contribute to the research on social perspectives of energy transitions and a better representation of social dynamics in SD models.

2. Methodological approach

This work was based on a literature review of SD energy system-related models conducted in three databases, Scopus, Science Direct, and Web of Science, on the 12th of September 2022. The search string consisted of a combination of the words "energy system", "model" or "modelling", and "system dynamics". Considering works published after 2012, this search string led to 240, 92 and 73 results on Scopus, Science Direct, and Web of Science databases, respectively. Books, book chapters, conference papers, review articles, and documents other than research articles, as well as non-English documents, were excluded. After abstract screening and duplicates removal in the reference manager Mendeley, 69 works remained. Most works excluded in the abstract screening stage consisted of research on power control systems. In the full-paper screening stage, only papers that (i) could be retrieved, (ii) contained a representation of the SD model (e.g., model structure, causal loop diagrams (CLD), stock and flow diagrams (SFD)), (iii) applied the model to real case studies, and (iv) made future simulations were considered. This led to the exclusion of 24 other works and a final portfolio containing 45 works. The literature review process is presented in Figure 1.

2.1. Main themes of models

The final collection of 45 works was assessed based on the location of case studies, geographical resolution, time horizon, methodological approach, and main themes. Concerning main themes, supply-demand

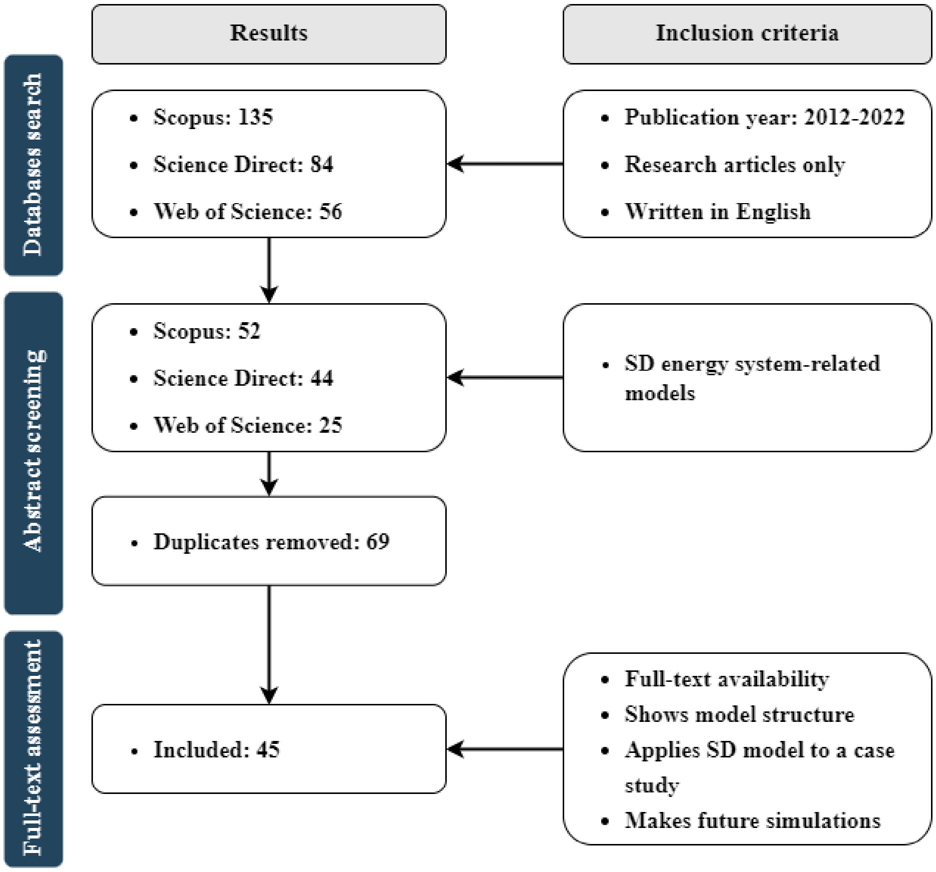

Figure 1: Literature review process.

models were concerned with representing the feedback processes that affect production, mainly from specific sources (e.g., natural gas, hydrogen, biomass), and energy consumption. Models in the energy-economy-environment (3E) topic were concerned mainly with macro-economic aspects, energy production, and emissions, and include IAMs (e.g., [32]). Energy-transport models integrated energy and transport sectors. The water-energy-food nexus (WEF) evaluated the dynamics across the water, energy, and food spheres. Sometimes, the analysis was restricted to two aspects (e.g., water-energy [33]) or extended to others (e.g., society [34]). Finally, consumer-centric and socio-political dynamics models were more diverse and mostly incorporated feedback focused on consumer behaviour, technology adoption, and household-level dynamics.

2.2. Social aspects

As it is beyond the scope of this study to systematically review energy-related social aspects, we framed as 'social aspects' the concepts commonly linked to the energy transition. Since 'Limits to growth' [35], economic and biophysical models have underscored the dangers of unstoppable economic and population growth [36]. This motivated us to consider population and gross domestic product (GDP) growth in the search for socio-economic aspects representation. Next, given concerns over a just energy transition [37] and the dynamics of job creation and destruction from fossil fuels phase out [38], employment and income were also pondered. Particularly, employment impacts can be perhaps deemed as the socio-economic aspect most commonly incorporated in ESMs, regardless of the modelling approach (e.g., [39,40]). Behavioural aspects have also been commonly investigated in energy research [41], and include individual consumption habits, socio-cultural preferences, and lifestyle changes [42].

Social acceptance and perception of renewable energy (RE) and energy efficient technologies are also key determinants of the adoption of alternative technologies and the pace of low-carbon transition [43–45], being linked to levels of public awareness [46]. There is also reference to the public participation and ownership of energy transitions, and the potential of inclusive perspectives [47]. When not taken into consideration, the absence of these aspects can negatively affect investments in RE, especially in rural communities [48]. Next, there are socio-political factors such as institutional structures [49], trust in infrastructures and services, as well as the heterogeneity of actors involved in energy systems [31].

Last but not least, we looked into well-being issues in light of how energy systems affect people's lives. These include quality of life and health and environmental hazards as a result of technology choices and consumption habits [50]. Given the growing concern on achieving Sustainable Development Goal 7 (SDG7), energy justice, and these effects on socio-economic development, we also assumed energy access as a social aspect [51]. These aspects are represented in Figure 2. Therefore, by assessing models' structures and looking for the aforementioned aspects, it was possible to identify which and how they were modelled in SD. Main social dynamics that included these social aspects were then represented in CLDs for each modelling theme. CLDs were chosen as a visualisation tool because, together with SFDs, they are the most common and easiest way to visualise SD models and represent feedback processes [52]. Nonetheless, it is worth having in mind that presented CLDs are simple representations of much more complex models.

2.3. Limitations

The literature review process was not based on the review of SD models themselves, being entirely based on secondary information published in the peer-reviewed literature. Therefore, even though the most relevant feedback loops and variables were commonly discussed in papers, identifying social aspects and describing dynamics could be different. Different search strings would have different results (e.g., "energy" AND "system" instead of "energy system"). However, an overlapping 'system dynamic' concept in the electric and electronic fields required initial search restrictions to avoid a large number of unrelated works. The search string and inclusion criteria were used to filter a diverse and broad literature on the topic that is far from being extensively reviewed in this paper. However, this is not considered an impediment to fulfilling this research's objectives. While the location, geographical resolution, time horizon, and methodological approach are objective classifications, works could have been grouped into different main themes. Nonetheless, we carefully considered the identified problems and hypotheses mentioned in the studied models to select appropriate categories aligned with existing literature.

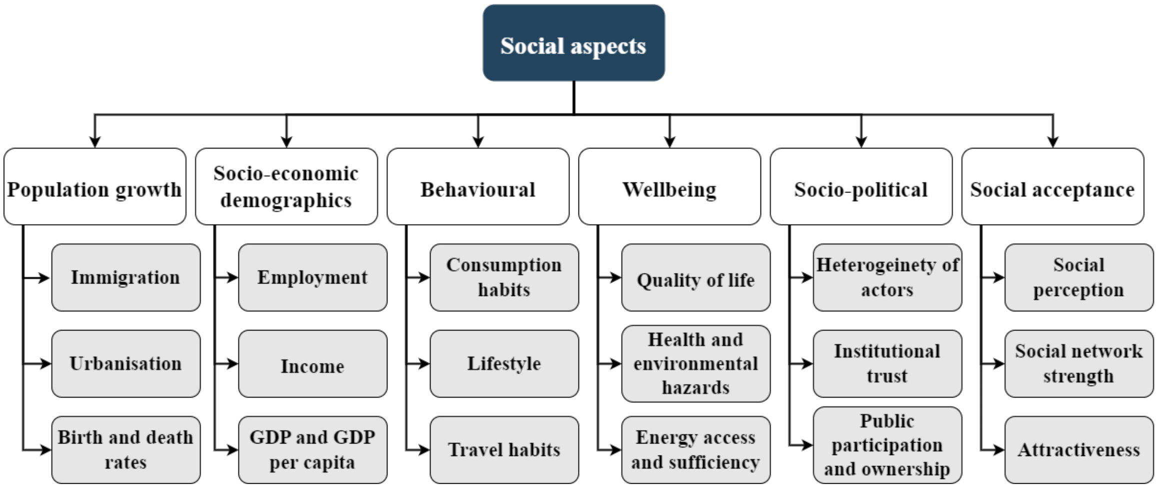

Figure 2: Social aspects related to the energy transition.

3. Descriptive results

Concerning the methodological approach, out of the 45 reviewed works, two [53,54] combined SD with a Geographic Information System (GIS) in order to evaluate results both temporally and spatially. In Pakere et al. [54], the GIS model provided data on land suitable for wind turbines, which was used as a limiting input in the SD model. In Wu and Ning [53], GIS software was used to visually analyse the results of the SD model representing Beijing's districts. Five other works [55–59] combined SD to multi-objective optimisation modelling to evaluate supply-demand and 3E dynamics. Among them, the ANEMI model [60] consists of an integrated optimisation-simulation model that solves an optimal allocation problem within each simulation time step without considering future projections (i.e., it generates an endogenous path for energy supply). Also, Daneshzand et al. [58], Wu and Xu [56], and Eker et al. [61] considered multi-objective optimisation methods to find optimal values of policy variables. Karunathilake et al. [59] employed a fuzzy optimisation approach to find optimal energy mixes according to different performance objectives, which were used as input in their life-cycle-based SD model. Lastly, Blanco et al. [62] bidirectionally soft-linked the SD model PTTMAM of the passenger transport sector with TIMES to simulate the development of fuel cell vehicles in Europe. The remaining 37 works employed pure SD models.

In terms of spatial resolution, one model was global [55], three papers [43,53,54] evaluated a group of countries, 27 models had a national scope, and nine other papers analysed regions within countries. Most models were simulated up to 2050, given the year's relevance for climate action plans as a landmark for achieving a net-zero global economy [38]. Regarding model development, only Blumberga et al. [65] and Strapasson et al. [66] mentioned the performance of workshops to gather insights on systems structures and stakeholders' expectations. Concerning the employment of models to aid policy-making, only Blumberga et al. [65] reported on the development of an open Internet-based policy-aiding tool.

4. Social aspects and dynamics

This section brings which and how social aspects have been incorporated in SD models concerning energy systems according to the main identified themes. First, social aspects found in models are synthesized in tables for each theme, after, the ways by which these aspects were influenced in the models are discussed along with visual representations in simplified CLDs. In CLDs, variables are related by causal links (arrows). Links can have positive (+) or negative (-) polarity that shows how the dependent variable changes with the dependent one. A positive link means that if the cause increases, the effect also increases; and if the cause decreases, the effect also decreases. On the other hand, a negative link means that if the cause increases, the effect decreases; and if the cause decreases, the effect increases [52]. Particularly, CLDs do not differ between stocks (i.e., accumulations in the system), flows (i.e., rates of change in and out stocks), and converters, which are all components of SD models. Important feedback loops are also shown in CLDs, and they can be denoted as balancing or reinforcing. Balancing or negative loops counteract a change, pushing in the opposite direction. Conversely, reinforcing or positive loops sustain and "reinvest" in a change. In terms of behaviour, balancing feedback loops bring stability to the system, while reinforcing feedback loops produce behaviours such as exponential growth.

4.1. Supply-demand

Table 1 displays the works reviewed in this category, their investigation topic, and considered social aspects. Models targeted RE, natural gas, electricity generation and flexibility, and whole energy systems. Economic and population related aspects were most commonly included in models, followed by income and employment, social acceptance of technologies and human health.

While some models incorporated different social concepts through exogenous and endogenous variables and policy levellers, other technology-based models did not include any social aspects [67,72]. These models were very technical and considered exogenous energy demand projections together with technological availability, efficiency, energy sources, and associated costs in the supply side. GDP and population growth were represented as drivers of energy demand in [64,68,70]. Residential energy demand, in particular, was calculated through exogenous urbanisation rates and household income [58]. From a technological perspective, demand was also influenced by the share of energy efficient and inefficient consumers [65]. Energy efficiency interventions are presented in Figure 3 as a

Table 1: Supply-demand thematic and considered social aspects.

Reference	Topic	GDP	Population growth	Urbanisation rates	Income	Employment	Social acceptance	Environmental awareness	Human health	Consumption habits
[67]	RE development									
[68]	Electricity generation	x								
[57]	Bioenergy						x			
[69]	Bioenergy		x			x				
[70]	Natural gas	x	x							
[71]	Bioenergy	x				x			x	
[58]	Natural gas	x	x	x	x					
[59]	RE development	x	x				x		x	
[72]	Electricity generation									
[64]	Electricity generation and flexibility	x						x		
[73]	Hydrogen production									
[65]	Energy system	x	x							x

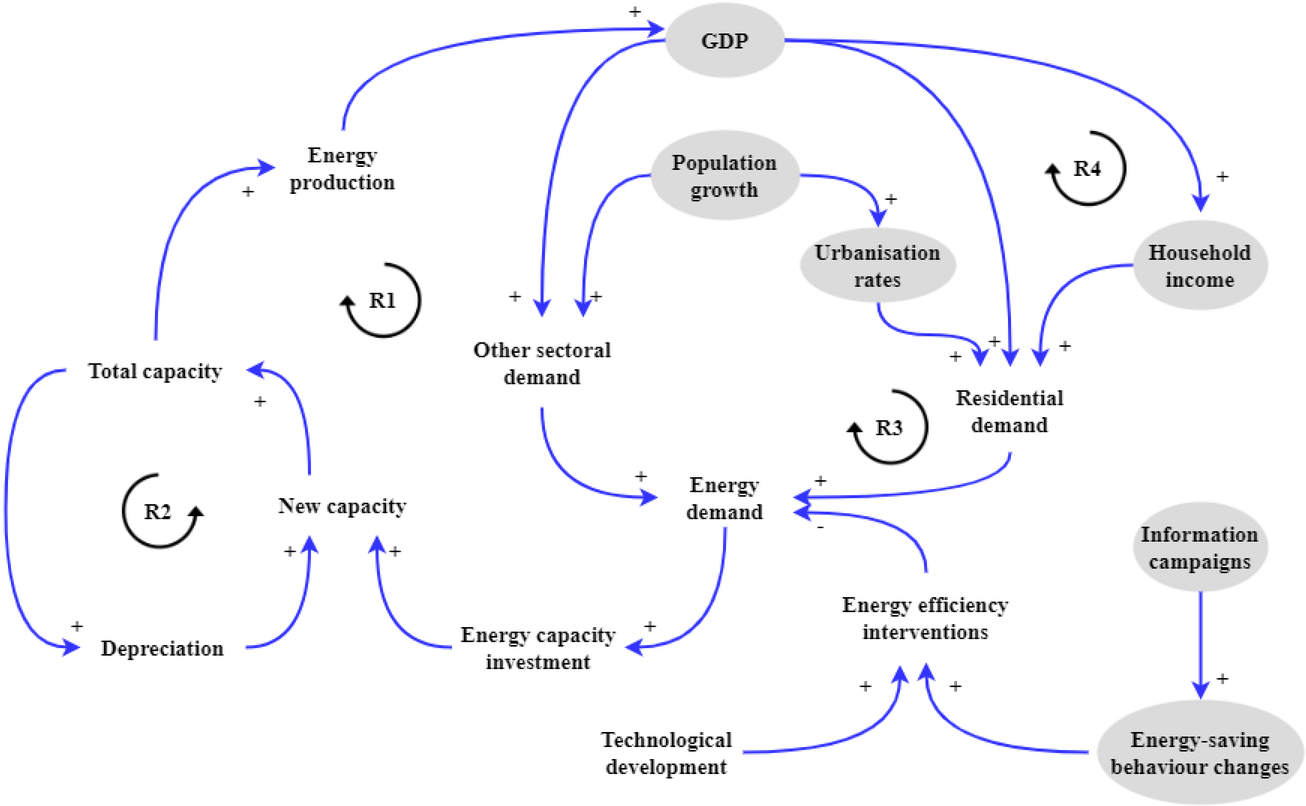

Figure 3: Representative CLD of social dynamics influencing energy demand in supply-demand models (R – reinforcing loop). Adapted from: [58,65,67,72].

result of technological development and behaviour changes [65]. Information campaigns influenced the latter. As it can be seen, social aspects were commonly represented exogenously. There are four reinforcing (R) feedback loops in Figure 3. R1 and R3 demonstrate how higher GDP levels lead to higher energy demand, investment, and production, which in turn positively affect GDP growth [70]. R2 represents the relationship between energy capacity depreciation and new installed capacity [72], while R4 indicates the cause-and-effect relationship between GDP, household income, energy demand, up to energy production. Variables in a grey ellipse indicate social aspects.

Moreover, given the pursuit of a less carbon-intense energy matrix, overall energy demand was commonly split into fossil fuel and RES. RE development was dependent on the social acceptance of technologies [57] and the effects of policies [69], whereas RE project suitability was seen as a consequence of lifecycle impacts on human health and emissions [59]. Increasing energy demand requires a matching production capacity, which can offer employment opportunities across project lifecycles [71]. If RE capacity increases, a reduction in CO_2 emissions is expected, which can be linked to the social cost of carbon (i.e., non-commercial impacts of emissions on health and the environment) and consequent savings [71], as shown in Figure 4. The reinforcing feedback loops, R1 and R2, link GDP and energy demand to investment in fossil fuels and RE, respectively. The other two reinforcing feedback loops, R3 and R4, refer to how investment in RE can reduce emissions and lead to more RE investment while reducing health and environmental hazards through the social cost of carbon.

4.2. Energy-economy-environment

Commonly, 3E models observed socio-economic aspects, as it can be seen in Table 2. The relative absence of other social aspects can be explained by the underlying purpose of these models in representing top-down system structures and their particular concern with emissions resulting from energy systems and other sectors. In particular, 3E-SD models that did not emphasise any social dynamics [63,74] were again technical-based models concerned with the investments

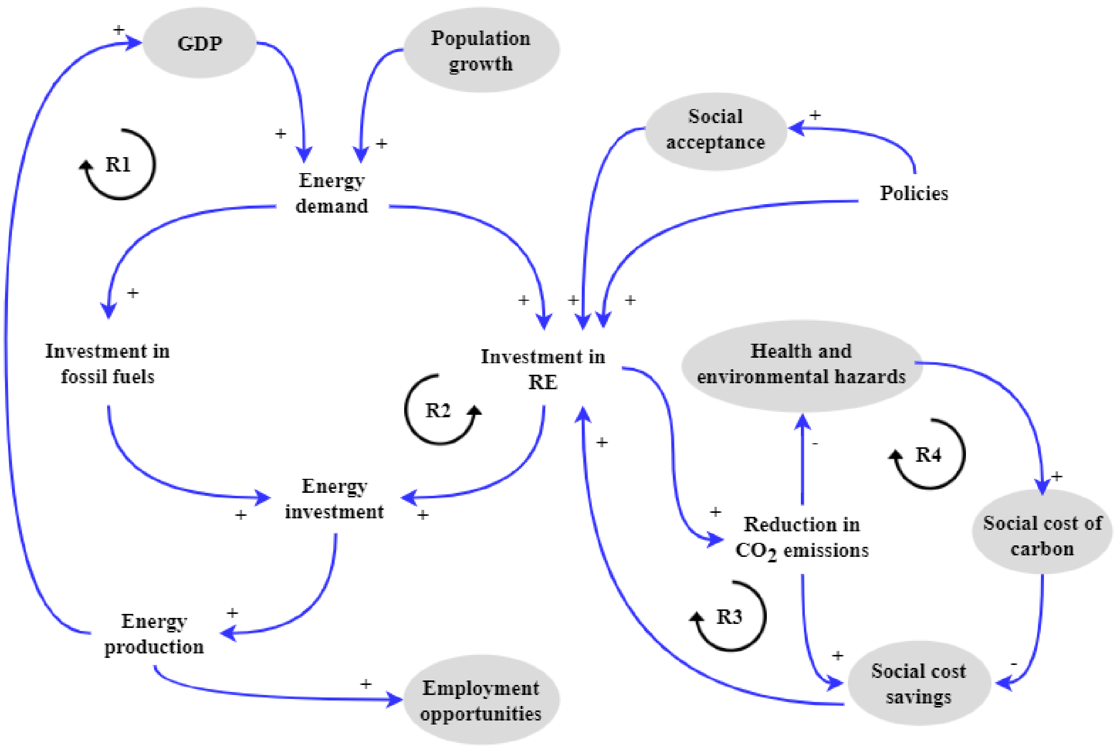

Figure 4: Representative CLD of social dynamics influencing RE in supply-demand models (R – reinforcing loop). Adapted from: [57,59,69,71].

Table 2: 3E thematic and considered social aspects.

Reference	Topic	GDP	Population growth	Income	Employment	Consumption habits	Life expectancy
[55]	Climate-biosphere-economy-energy	x	x	x	x	x	x
[56]	Energy-economy-emissions	x	x				
[75]	Energy-economy-emissions	x	x				
[63]	Energy-emissions						
[76]	Energy-economy-emissions	x			x		
[53]	Energy system	x	x				
[77]	Climate-biosphere-economy-energy	x	x				
[78]	Development scenarios	x	x				
[32]	IAM	x	x				
[62]	Energy-economy-emissions	x	x	x		x	
[74]	Energy system						

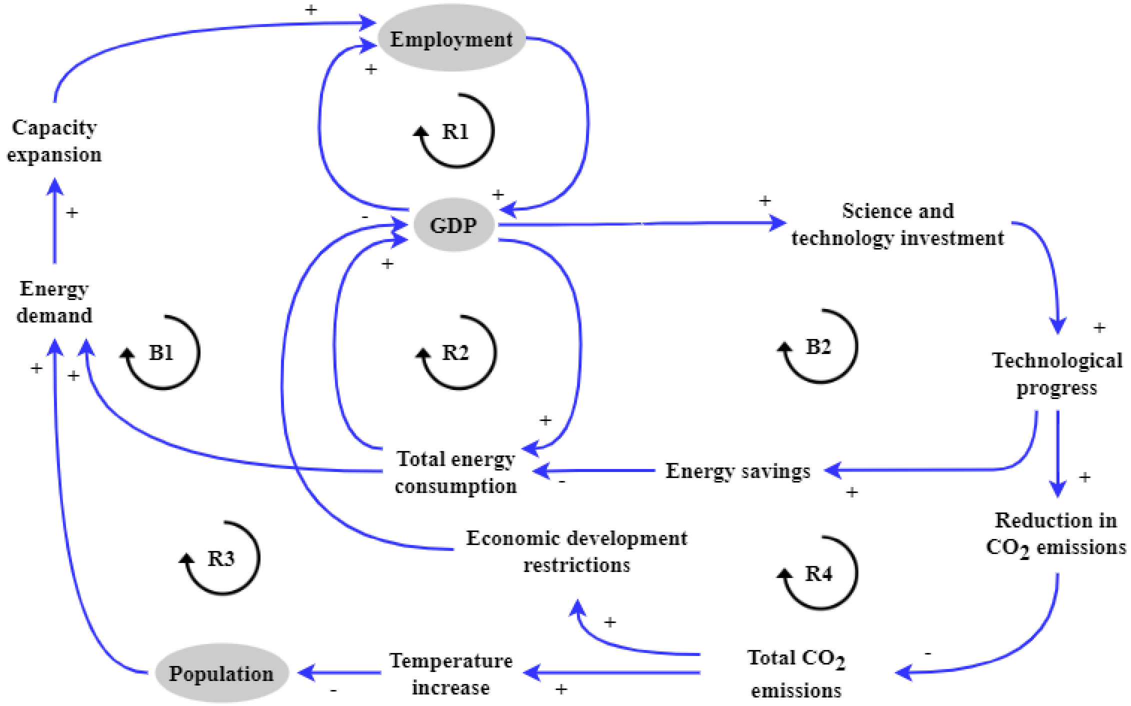

Figure 5: CLD representing the relationship between GDP, employment, emissions, and energy consumption. (R – reinforcing loop; B – balancing loop). Source: Adapted from [55,56,74,77,79].

and depreciation of capacities under different policy scenarios.

Similar to supply-demand models, 3E systems considered population growth and economic development as drivers of energy demand. Distinctly, population growth was modelled endogenously as a result of fertility and death rates resulting from climate change in the ANEMI model [55,77]. Economic development was also linked to employment opportunities [76]. In some cases, labour dynamics were understood as a demand-supply feedback, in which households provided labour to the market, and the resulting household income led to an average consumption of goods [55,62,77]. In another approach, Laimon et al. [74,79] considered employment

Table 3: Energy-transport thematic and considered social aspects.

Reference	Topic	GDP	Population growth	Travel demand	Social acceptance	Heterogeneity of actors
[81]	Low-carbon transport development	x	x	x		
[82]	Alternative fuels market	x	x	x		
[83]	Alternative fuels market	x	x	x	x	
[84]	Supply-push strategies for biofuel vehicles	x	x	x		
[85]	Cost-effectiveness of low-carbon transport	x	x	x		
[86]	Hydrogen and electricity fuelled vehicles	x	x	x		
[8]	Soft-linking SD transport and optimization-based energy systems			x		x
[80]	Geothermal electricity production and transport demand	x	x	x		

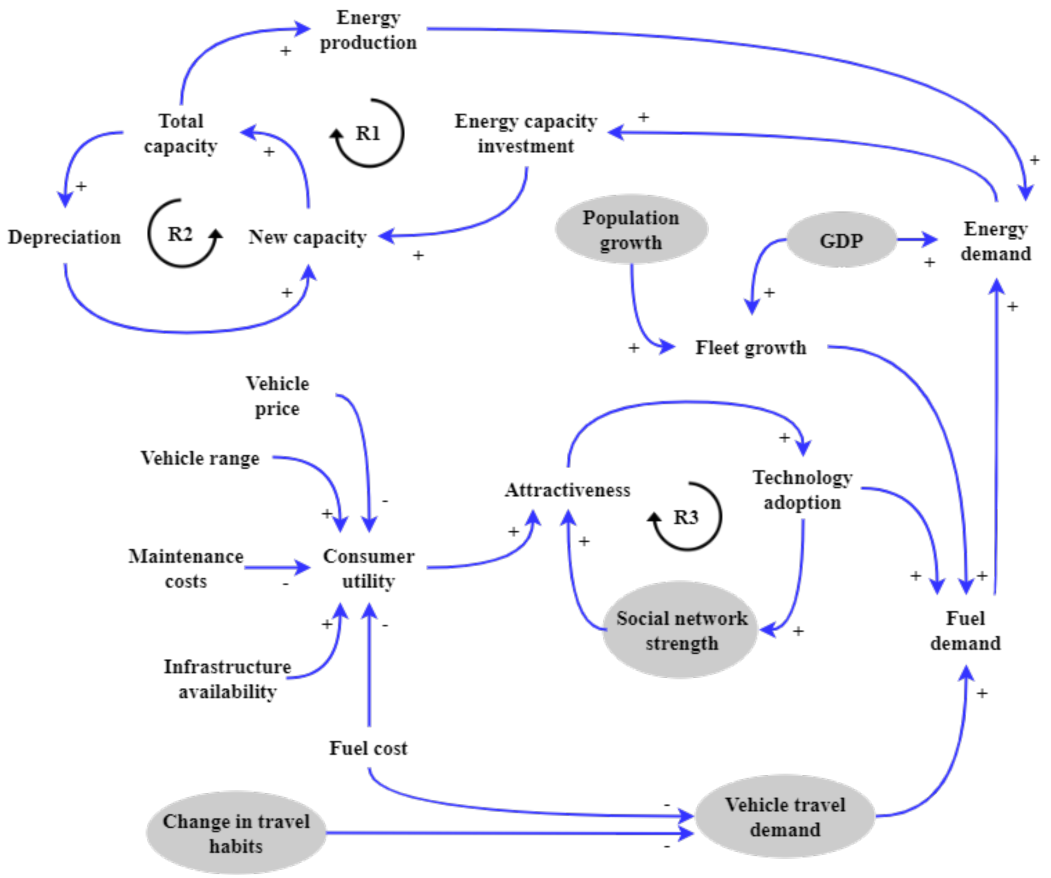

Figure 6: CLD representing the relationship between change in travel habits and vehicle adoption (R – reinforcing loop). Source: Adapted from [80,83].

opportunities generated by increasing energy production capacity as a driver of immigration and, therefore, population growth. Population growth drove energy demand and, consequently, energy production, creating a reinforcing feedback loop.

Moreover, conflicting objective functions have been reported, in which there is no common solution for maximising GDP or minimising energy consumption, pollution and emissions [53,56]. Figure 5 represents the aforementioned 3E dynamics together with four reinforcing (R1, R2, R3, and R4) and two balancing feedback loops (B1 and B2). B1 and B2 refer to how GDP growth leads to higher investment in science and technology, resulting in technological progress towards more efficient technologies. This reduces energy consumption linked to GDP in B2 and to energy demand, capacity expansion, employment, and GDP in B1. R1 indicates that GDP growth brings employment opportunities and, R2, higher energy consumption. R3 links GDP and population through emissions and global temperature, while R4 shows how GDP growth can be reinforced through investment in more efficient technologies even when economic development restrictions are in place.

4.3. Energy-transport

Table 3 summarizes the social aspects within energy-transport SD models. GDP and population were modelled exogenously as drivers of energy and transport demand [80]. Behavioural aspects, such as vehicle use (i.e., travel demand) and the social acceptance of alternative options, were also commonly considered.

Seven out of eight works on energy-transport dynamics were based on the UniSyD model [87]. This model incorporates social aspects related to consumers' travel behaviour and perceived utility of a particular modal choice and alternative fuel vehicles. Shafiei et al. [83] particularly pointed to assessing social network strength on consumers' consumption and further technological adoption but did not consider its effects in the modelling. These aspects can be seen in Figure 6, where three reinforcing loops (R1, R2, and R3) are identified. Besides R1 and R2 linking energy production and capacity, there is a potential loop (R3) between the social network strength, the attractiveness of a particular technology, and its actual adoption. Especially, Blanco et al. [62] softly linked PTTMAM [88], a simulation model that considers the major stakeholders (i.e., users, authorities, infrastructure providers, and manufacturers) in the light-duty passenger transport, to TIMES [89], a widely known optimisation model. Therefore, the heterogeneity of actors was also incorporated into the SD model (i.e., socio-political-technical).

4.4. Water-energy-food nexus

WEF models were concerned with the macro-economic and population dynamics driving water, energy, and food demands, and how changes in consumption habits and lifestyle could impact these demands. In two instances, quality of life [33] and environmental awareness [33,34] were also considered, as shown in Table 4.

Within WEF models, economic and population growth influenced the demand for food, energy, and water [90]. The relationship between these resources supply and demand was labelled as 'security' [91] or 'shortage' [34]. Water, energy, and food shortages influenced the population's environmental awareness [34]. Food security affected agricultural development, the area under cultivation and, consequently, food supply. The cultivated area also impacted the amount of water needed for agriculture, which, along with urban, industrial, and energy sector demand for water, composed the water demand variable. While agricultural water demand is also linked to energy requirements in irrigation systems, water is also required for hydroelectric energy generation. Life quality was modelled as a result of water, energy, and water-energy end uses in urban systems [33]. Quality of life, in turn, affected population growth, which then impacted demand for energy and water along with pressure to reduce consumption. Behavioural aspects were also considered through diet habits [66], more specifically, meat consumption and overall calories. The latter was represented in Figure 7 through 'lifestyle and consumption changes' along with the main dynamics influencing social aspects in the WEF nexus.

Table 4: Water-energy-food thematic and considered social aspects.

Reference	Topic	GDP	Population growth	Consumption habits	Quality of life	Environmental awareness
[33]	Water-energy		x	x	x	x
[66]	Energy-food-climate-land		x	x		
[90]	Energy-food	x	x	x		
[91]	WEF	x	x	x		
[34]	Water-energy-food-society	x	x	x		x

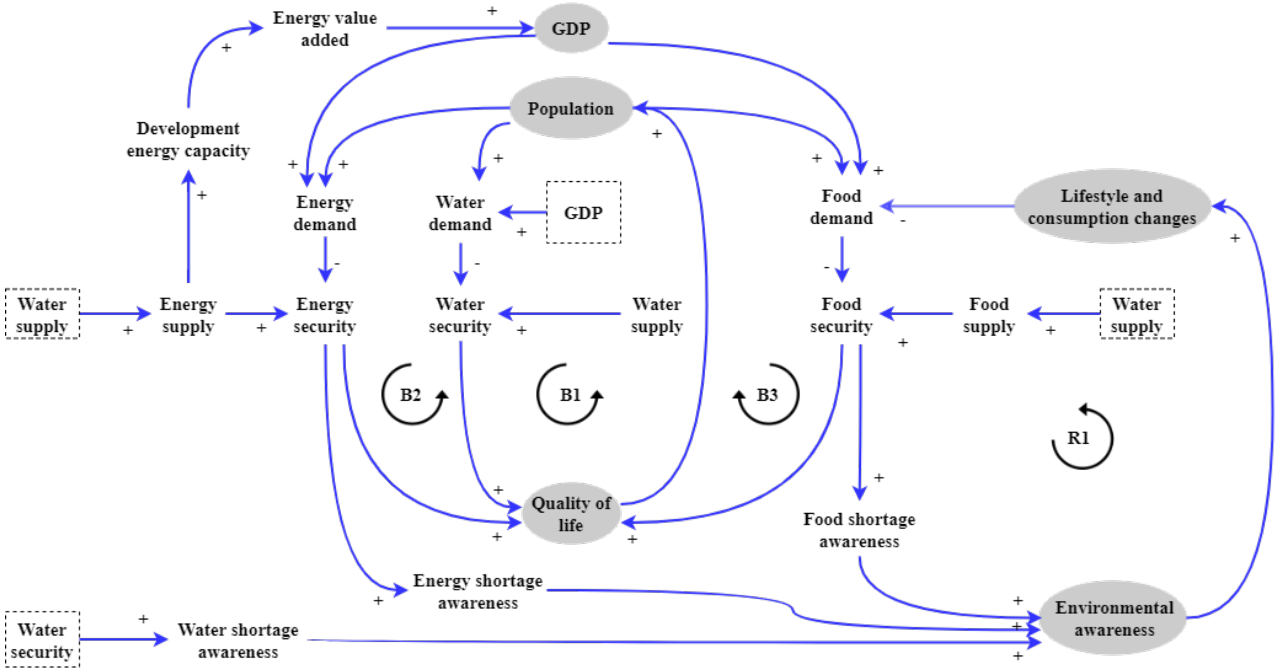

Figure 7: CLD representing the relationship between economic and population growth and WEF demand. Source: Adapted from [33,90].

In Figure 7, we can notice the following feedback loops. In R1, lifestyle and consumption habits change with environmental awareness, decreasing food demand, and raising food security and awareness. The other three balancing feedback loops, B1, B2, and B3, show how population growth increases demands for water, energy, and food, respectively, which decreases security indicators. Lesser life quality lowers population growth levels.

4.5. Consumer-centric and socio-political dynamics

In general, models within this category incorporated the largest number of social aspects given their underlying representation of consumer-centric and socio-political dynamics, as it can be seen in Table 5.

Clean and RE technology adoption at household levels was represented through the Bass innovation diffusion model [52] in [92,96,99], where, besides reinforcing feedback loops (R1 and R2) among adopters (Figure 8), external influences included environmental awareness and social acceptance of technologies [92]. Concerning effects on demand, energy efficiency takes place through technological development and more efficient technologies, which are influenced by investment in R&D, and behaviour changes in energy consumption [95]. This can be affected by the level of consumers' environmental awareness and social acceptance [95]. These two aspects could be influenced by information campaigns and governmental policies, which could also affect inconvenience costs [97], describing social aspects affecting production costs, such as lack of knowledge and trust in RE technologies.

Inconvenience costs of RE technology expansion were also included as ‘public awareness’ influencing consumers’ reliance on contractors [98] and perceived utility [94]. Moreover, demand for more sustainable technologies was represented as a result of several other aspects, such as income, educational levels, socio-cultural differences and preferences, household size, urban-rural adoption, environmental and health hazards, and cost subsidies [99]. Notably, there is a reinforcing effect on education, income, and socio-economic impacts represented by R3 (Figure 8). The further installing and RE expansion capacity processes was modelled as influencing employment opportunities and rural-urban migrations [98]. Considering the heterogeneity of actors involved in the energy transition, socio-political factors’ influence on the feasibility of the UK’s carbon budgets was also represented using SD in [96]. Social political factors included political capital, policy ambition, public

Table 5: Consumer-centric and socio-political dynamics and considered social aspects.

Reference	Topic	GDP	Population growth	Urbanisation rates	Income and Employment	Environmental awareness	Human health	Social perception	Consumption habits	Willingness to participate	Heterogeneity of actors	Energy sufficiency
[92]	Technology adoption					x						
[93]	Electricity savings	x			x				x	x		
[94]	Distributed generation					x		x				
[95]	Building renovation					x		x	x		x	
[51]	Energy sufficiency		x	x								x
[96]	Socio-political-technical feedbacks							x		x	x	
[97]	RE development							x		x	x	
[98]	Distributed generation				x							
[99]	Technology adoption			x	x		x	x	x			

willingness to participate, and pushbacks. Pushback is an information feedback that notifies governments about the public acceptance of governance and influences the political capital for the energy transition and the ambition of policies [96].

Consumer behaviour choices were also modelled as a result of the willingness to undertake energy efficiency measures, environmental awareness, electricity and income ratio, and changes in consumption habits as a result of the use of electrical appliances [93]. This is shown in Figure 9, along with a balancing loop (B1) between electricity consumption and changes in habits and appliances. Low- and high-income households were considered given different perceptions, consumption behaviours, and disposable income [93]. Apart from behavioural and socio-economic aspects, the concept of 'energy sufficiency' was also defined and modelled to evaluate urban and rural household electricity provision in Sub-Saharan Africa [51]. Energy sufficiency corresponds to "a maximum desired amount of energy per capita to be produced and consumed" and is linked to energy justice and SDG7 [51].

5. Main findings and conclusion

As pointed by Lund et al. [12] when reviewing simulation versus optimisation models, each modelling approach has its own advantages and disadvantages. Therefore, each problem must be carefully evaluated before a methodological choice is made. In any case, challenges will follow. Particularly, this paper reviewed how flexible and resourceful SD energy system-related models are, as they have been applied to a diverse range of topics and case studies from regional to global levels. These results are in agreement with those obtained by Bolwig et al. [21]. Additionally, different actors (e.g., households, infrastructure investors and providers, energy suppliers, and governments) and sectors (e.g., residential, industrial, and agricultural) were represented in the models, which highlights the potential of SD models to incorporate the heterogeneity of actors in the energy transition [31]. Nevertheless, as Blumberga et al. [65] discusses, it is necessary to pay attention to the political dimension of models and policy processes. Still, the underlying top-down approach of SD as a

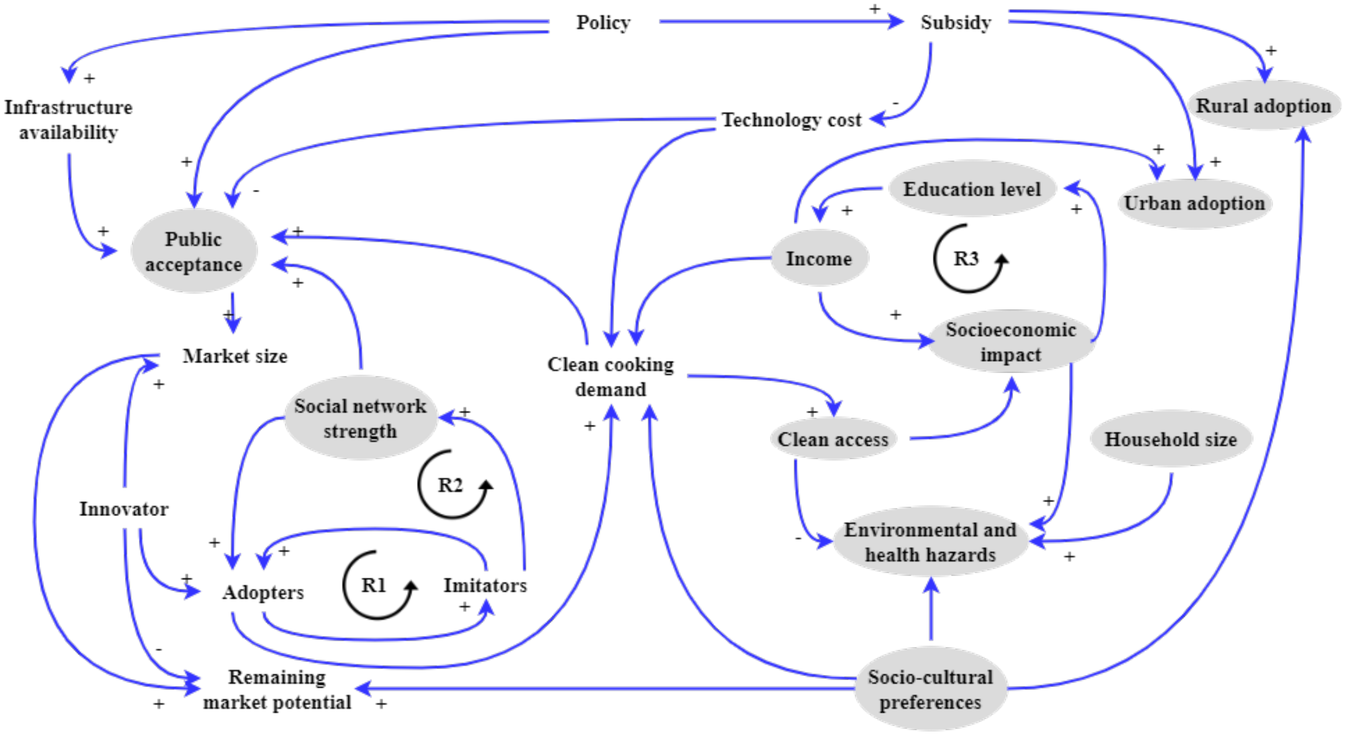

Figure 8: CLD representing the relationship between policy effects and clean cooking demand (R – reinforcing loop). Source: Adapted from [99].

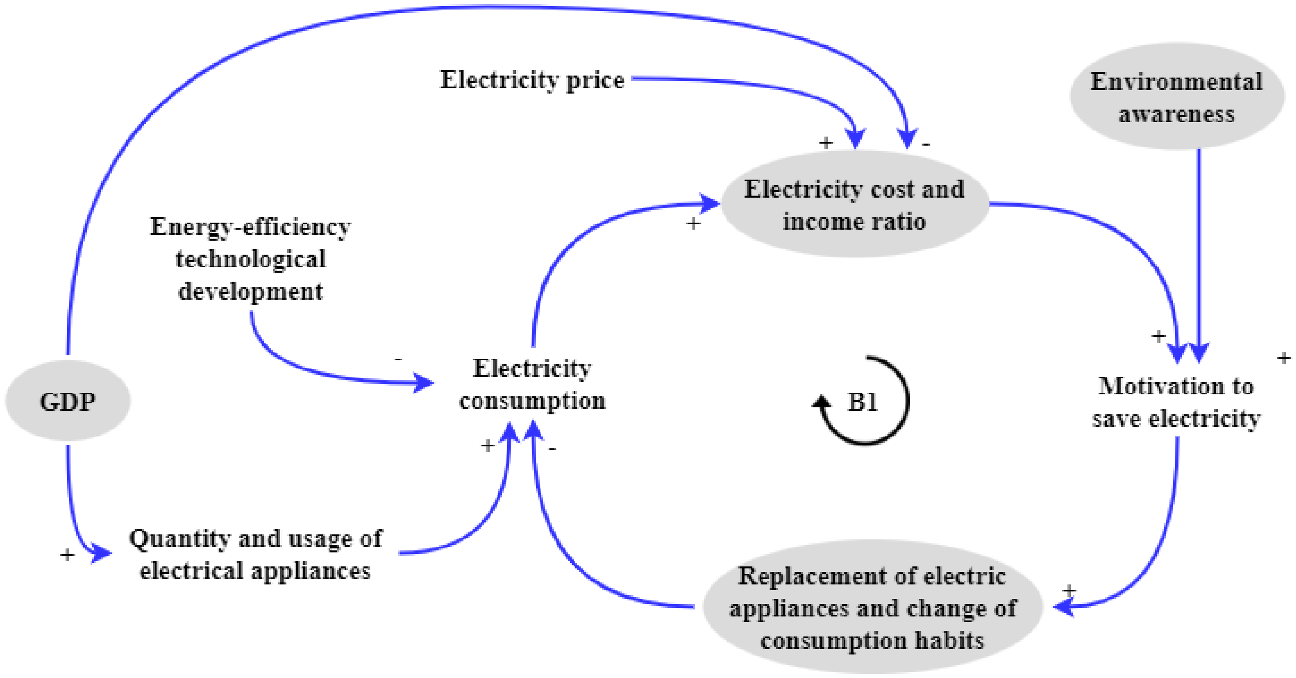

Figure 9: CLD representing the relationship between GDP and electricity consumption parameters (B – balancing loop). Source: Adapted from [93].

simulation model seems also fit to represent the socio-environmental-energy nexus and approach the problem of integrated sustainability [100].

The combination of SD with other modelling techniques, even though minority, seemed capable of symbiotically approaching the energy transition from more than one front: bottom-up and top-down, geographically and timely, simulation and optimisation. The potential of methodological combinations has been already highlighted in the literature as they forward to overcome some of the obstacles in the path towards more realistic quantitative modelling of transitions [21]. The participatory development of models considered in a few works [65,66] and the conversion of models into accessible policy-aiding tools [65] can help develop inclusive pathways and enhance the public sense of ownership and participation while acknowledging the variety of actors affecting and affected by the energy transition. Even though minority, participatory development and decision-making approaches could contribute to co-creation initiatives [100], reducing the chances of atomistic approaches leading to increased social inequality and environmental injustice [101].

Regarding social dynamics incorporated in SD models, supply-demand models have mainly integrated GDP, population, and the social acceptance of technologies. 3E models focused on population and economic growth, labour and consumption aspects, whereas energy-transport models included behaviours in relation to travel and the utility of vehicle choices. WEF models considered population and GDP as food, energy, and water consumption drivers, while environmental awareness and lifestyle changes balanced it. In consumer-centric and socio-political models, many social aspects were considered, including urbanisation rates, household income and employment, social acceptance, willingness to participate, environmental awareness, and behavioural aspects. In contrast with socio-economic factors, well-being aspects (e.g., environmental and health hazards, quality of life) were less often considered, which can be explained by the challenges of representing social welfare and well-being and its various dimensions through quantitative metrics [102]. The incorporation or not of social aspects remains subject to the modellers' choice of how to approach a certain problem within each model's purpose and focus.

As for future avenues of research in SD modelling, we would like to highlight (i) the combination of SD with other modelling techniques and (ii) the participatory development of models and conversion of models into accessible policy-aiding tools. Our review indicated that incorporating social metrics in SD energy systems models is far from being standard, as also concluded by Krumm et al. [31] when reviewing other types of energy-related models. Selecting appropriate social indicators and shifting from a techno-centric perspective remains a challenge in quantitative energy modelling but indeed a requirement for successful transitions [20]. We underpin the importance of further and bridging research on social and engineering sciences as well as socio-technical transitions.

The array of models targeting consumer-centric dynamics and the different incorporated social variables suggest there are research opportunities on the use of SD models to quantitatively assess the impacts of energy access and the (in)justice of energy transitions. Moreover, the offset of job opportunities from fossil fuels to renewables as a result of the energy transition could be further explored through SD models as well as dynamics involving disposable income, energy prices, and energy poverty issues. Given the richness of models and topics, we argue for further and in-depth reviews of SD models in each one of the main identified themes so conclusions about the real influence of social aspects and their exogenous or endogenous nature can be captured.

Acknowledgements

This work has been supported by FCT – Fundação para a Ciência e Tecnologia within the R&D Units Project Scope: UIDB/00319/2020.

References

[1] M.G. Prina, G. Manzolini, D. Moser, B. Nastasi, W. Sparber, Classification and challenges of bottom-up energy system models - A review, Renew. Sustain. Energy Rev. 129 (2020) 109917. https://doi.org/10.1016/j.rser.2020.109917.

[2] N. Spittler, G. Gladkykh, A. Diemer, B. Davidsdottir, Understanding the current energy paradigm and energy system models for more sustainable energy system development, Energies. 12 (2019). https://doi.org/10.3390/en12081584.

[3] S.C. Bhattacharyya, G.R. Timilsina, A review of energy system models, Int. J. Energy Sect. Manag. 4 (2010) 494–518. https://doi.org/10.1108/17506221011092742.

[4] T. Nakata, D. Silva, M. Rodionov, Application of energy system models for designing a low-carbon society, Prog. Energy Combust. Sci. 37 (2011) 462–502. https://doi.org/10.1016/j.pecs.2010.08.001.

[5] M. Nilsson, A. Dzebo, G. Savvidou, K. Axelsson, A bridging framework for studying transition pathways – From systems models to local action in the Swedish heating domain, Technol. Forecast. Soc. Change. 151 (2020) 119260. https://doi.org/10.1016/j.techfore.2018.04.003.

[6] I.P.O.C.C. IPCC, Working Group III Report:“Mitigation of Climate Change,” (2008).

[7] E. Commission, Energy roadmap 2050, Publications Office of the European Union, 2012.

[8] H. Blanco, J.J. Gómez Vilchez, W. Nijs, C. Thiel, A.A.A. Faaij, J.J.G. Vilchez, W. Nijs, C. Thiel, A.A.A. Faaij, J.J. Gómez Vilchez, W. Nijs, C. Thiel, A.A.A. Faaij, Soft-linking of a behavioral model for transport with energy system cost optimization applied to hydrogen in EU, Renew. Sustain. Energy Rev. 115 (2019) 109349. https://doi.org/10.1016/j.rser.2019.109349.

[9] P. Lopion, P. Markewitz, M. Robinius, D. Stolten, A review of current challenges and trends in energy systems modeling, Renew. Sustain. Energy Rev. 96 (2018) 156–166. https://doi.org/10.1016/j.rser.2018.07.045.

[10] M.G. Prina, D. Moser, R. Vaccaro, W. Sparber, EPLANopt optimization model based on EnergyPLAN applied at regional level: The future competition on excess electricity production from renewables, Int. J. Sustain. Energy Plan. Manag. 27 (2020) 35–50. https://doi.org/10.5278/ijsepm.3504.

[11] J.C. Osorio-Aravena, A. Aghahosseini, D. Bogdanov, U. Caldera, E. Muñoz-Cerón, C. Breyer, Transition toward a fully renewable-based energy system in Chile by 2050 across power, heat, transport and desalination sectors, Int. J. Sustain. Energy Plan. Manag. 25 (2020) 77–94. https://doi.org/10.5278/ijsepm.3385.

[12] H. Lund, F. Arler, P.A. Østergaard, F. Hvelplund, D. Connolly, B.V. Mathiesen, P. Karnøe, Simulation versus optimisation: Theoretical positions in energy system modelling, Energies. 10 (2017) 1–17. https://doi.org/10.3390/en10070840.

[13] L. Kotzur, L. Nolting, M. Hoffmann, T. Groß, A. Smolenko, J. Priesmann, H. Büsing, R. Beer, F. Kullmann, B. Singh, A. Praktiknjo, D. Stolten, M. Robinius, A modeler’s guide to handle complexity in energy systems optimization, Adv. Appl. Energy. 4 (2021) 100063. https://doi.org/10.1016/j.adapen.2021.100063.

[14] E. Ridha, L. Nolting, A. Praktiknjo, Complexity profiles: A large-scale review of energy system models in terms of complexity, Energy Strateg. Rev. 30 (2020) 100515. https://doi.org/10.1016/j.esr.2020.100515.

[15] H.K. Ringkjøb, P.M. Haugan, I.M. Solbrekke, A review of modelling tools for energy and electricity systems with large shares of variable renewables, Renew. Sustain. Energy Rev. 96 (2018) 440–459. https://doi.org/10.1016/j.rser.2018.08.002.

[16] D. Connolly, H. Lund, B. V. Mathiesen, M. Leahy, A review of computer tools for analysing the integration of renewable energy into various energy systems, Appl. Energy. 87 (2010) 1059–1082. https://doi.org/10.1016/j.apenergy.2009.09.026.

[17] M. Chang, J.Z. Thellufsen, B. Zakeri, B. Pickering, S. Pfenninger, H. Lund, P.A. Østergaard, Trends in tools and approaches for modelling the energy transition, Appl. Energy. 290 (2021) 116731. https://doi.org/10.1016/j.apenergy.2021.116731.

[18] M. Fodstad, P. Crespo del Granado, L. Hellemo, B.R. Knudsen, P. Pisciella, A. Silvast, C. Bordin, S. Schmidt, J. Straus, Next frontiers in energy system modelling: A review on challenges and the state of the art, Renew. Sustain. Energy Rev. 160 (2022) 112246. https://doi.org/10.1016/j.rser.2022.112246.

[19] A. Fattahi, J. Sijm, A. Faaij, A systemic approach to analyze integrated energy system modeling tools: A review of national models, Renew. Sustain. Energy Rev. 133 (2020) 110195. https://doi.org/10.1016/j.rser.2020.110195.

[20] D. Süsser, N. Martin, V. Stavrakas, H. Gaschnig, L. Talens-Peiró, A. Flamos, C. Madrid-López, J. Lilliestam, Why energy models should integrate social and environmental factors: Assessing user needs, omission impacts, and real-word accuracy in the European Union, Energy Res. Soc. Sci. 92 (2022). https://doi.org/10.1016/j.erss.2022.102775.

[21] S. Bolwig, G. Bazbauers, A. Klitkou, P.D. Lund, A. Blumberga, A. Gravelsins, D. Blumberga, Review of modelling energy transitions pathways with application to energy system flexibility, Renew. Sustain. Energy Rev. 101 (2019) 440–452. https://doi.org/10.1016/j.rser.2018.11.019.

[22] J. Sterman, The Energy Transition and the Economy: A System Dynamics Approach, Massachusetts Institute of Technology, 1981.

[23] T.S. Fiddaman, Feedback Complexity in Integrated Climate-Economy Models, Massachusetts Institute of Technology, 1997.

[24] M. Mutingi, C. Mbohwa, V.P. Kommula, System dynamics approaches to energy policy modelling and simulation, Energy Procedia. 141 (2017) 532–539. https://doi.org/10.1016/j.egypro.2017.11.071.

[25] K.R. Reddi, W. Li, B. Wang, Y. Moon, System dynamics modelling of hybrid renewable energy systems and combined heating and power generator, Int. J. Sustain. Eng. 6 (2013) 31–47. https://doi.org/10.1080/19397038.2012.689781.

[26] A. Leopold, Energy related system dynamic models: a literature review, Cent. Eur. J. Oper. Res. 24 (2016) 231–261. https://doi.org/10.1007/s10100-015-0417-4.

[27] G. Papachristos, System dynamics modelling and simulation for sociotechnical transitions research, Environ. Innov. Soc. Transitions. 31 (2019) 248–261. https://doi.org/10.1016/j.eist.2018.10.001.

[28] F.G.N. Li, E. Trutnevyte, N. Strachan, A review of socio-technical energy transition (STET) models, Technol. Forecast. Soc. Change. 100 (2015) 290–305. https://doi.org/10.1016/j.techfore.2015.07.017.

[29] J. Schot, F.W. Geels, Strategic niche management and sustainable innovation journeys: Theory, findings, research agenda, and policy, Technol. Anal. Strateg. Manag. 20 (2008) 537–554. https://doi.org/10.1080/09537320802292651.

[30] N. Martin, C. Madrid-López, L. Talens-Peiró, D. Süsser, H. Gaschnig, J. Lilliestam, Observed trends and modelling paradigms on the social and environmental aspects of the energy transition. Deliverable 2.1. Sustainable Energy Transitions Laboratory (SENTINEL) project (1.0), (2020). https://dx.doi.org/10.5281/zenodo.4917183.

[31] A. Krumm, D. Süsser, P. Blechinger, Modelling social aspects of the energy transition: What is the current representation of social factors in energy models?, Energy. 239 (2022) 121706. https://doi.org/10.1016/j.energy.2021.121706.

[32] I. Perissi, G. Martelloni, U. Bardi, D. Natalini, A. Jones, A. Nikolaev, L. Eggler, M. Baumann, R. Samsó, J. Solé, Cross-validation of the MEDEAS energy-economy- environment model with the integrated MARKAL-EFOM system (TIMES) and the long-range energy alternatives planning system (LEAP), Sustain. 13 (2021) 1–27. https://doi.org/10.3390/su13041967.

[33] S. De Stercke, A. Mijic, W. Buytaert, V. Chaturvedi, Modelling the dynamic interactions between London's water and energy systems from an end-use perspective, Appl. Energy. 230 (2018) 615–626. https://doi.org/10.1016/j.apenergy.2018.08.094.

[34] Y. Zeng, D. Liu, S. Guo, L. Xiong, P. Liu, J. Yin, Z. Wu, A system dynamic model to quantify the impacts of water resources allocation on water–energy–food–society (WEFS) nexus, Hydrol. Earth Syst. Sci. 26 (2022) 3965–3988. https://doi.org/10.5194/hess-26-3965-2022.

[35] D.H. Meadows, D.L. Meadows, J. Randers, W.W. Behrends, The limits to growth, Universe Books, New York, 1972. https://doi.org/10.1016/B978-0-444-63768-0.00630-2.

[36] M. Dale, S. Krumdieck, P. Bodger, Global energy modelling — A biophysical approach (GEMBA) part 1: An overview of biophysical economics, Ecol. Econ. 73 (2012) 152–157. https://doi.org/10.1016/j.ecolecon.2011.10.014.

[37] P. García-García, Ó. Carpintero, L. Buendía, Just energy transitions to low carbon economies: A review of the concept and its effects on labour and income, Energy Res. Soc. Sci. 70 (2020) 101664. https://doi.org/10.1016/j.erss.2020.101664.

[38] IEA, Net Zero by 2050: A Roadmap for the Global Energy Sector, 2021.

[39] H. Lund, J.Z. Thellufsen, P. Sorknæs, B.V. Mathiesen, M. Chang, P.T. Madsen, M.S. Kany, I.R. Skov, Smart energy

Denmark. A consistent and detailed strategy for a fully decarbonized society, Renew. Sustain. Energy Rev. 168 (2022). https://doi.org/10.1016/j.rser.2022.112777.

[40] H. Lund, F. Hvelplund, The economic crisis and sustainable development: The design of job creation strategies by use of concrete institutional economics, Energy. 43 (2012) 192–200. https://doi.org/10.1016/j.energy.2012.02.075.

[41] O.K. Bishoge, G.G. Kombe, B.N. Mvile, Energy consumption efficiency knowledge, attitudes and behaviour among the community, Int. J. Sustain. Energy Plan. Manag. 31 (2021) 175–188. https://doi.org/10.5278/ijsepm.6153.

[42] F. Clora, W. Yu, GHG emissions, trade balance, and carbon leakage: Insights from modeling thirty-one European decarbonization pathways towards 2050, Energy Econ. 113 (2022) 106240. https://doi.org/10.1016/j.eneco.2022.106240.

[43] B.J. Rygg, M. Ryghaug, G. Yttri, Is local always best? Social acceptance of small hydropower projects in Norway, Int. J. Sustain. Energy Plan. Manag. 31 (2021) 161–174. https://doi.org/10.5278/ijsepm.6444.

[44] R. Menges, G. Beyer, Underground cables versus overhead lines: Do cables increase social acceptance of grid development? results of a contingent valuation survey in Germany, Int. J. Sustain. Energy Plan. Manag. 3 (2014) 33–48. https://doi.org/10.5278/ijsepm.2014.3.4.

[45] P. Roddis, S. Carver, M. Dallimer, P. Norman, G. Ziv, The role of community acceptance in planning outcomes for onshore wind and solar farms: An energy justice analysis, Appl. Energy. 226 (2018) 353–364. https://doi.org/10.1016/j.apenergy.2018.05.087.

[46] B.P. Koirala, Y. Araghi, M. Kroesen, A. Ghorbani, R.A. Hakvoort, P.M. Herder, Trust, awareness, and independence: Insights from a socio-psychological factor analysis of citizen knowledge and participation in community energy systems, Energy Res. Soc. Sci. 38 (2018) 33–40. https://doi.org/10.1016/j.erss.2018.01.009.

[47] H.M. Marczinkowski, Rethinking Islands and their Models in Sustainable Energy Planning: How Inclusive Local Perspectives Improve Energy Planning Globally, Int. J. Sustain. Energy Plan. Manag. 33 (2022) 7–18. https://doi.org/10.5278/ijsepm.6970.

[48] A.I. Butu, P. Strachan, Navigating Pathways for Community Renewable Electricity in Rural Areas: Stakeholders' Perspectives on the Shape Community Project, Nigeria, Int. J. Sustain. Energy Plan. Manag. 33 (2022) 19–34. https://doi.org/10.5278/ijsepm.6813.

[49] S. Selvakkumaran, E.O. Ahlgren, Understanding the local energy transitions process: A systematic review, Int. J. Sustain. Energy Plan. Manag. 14 (2017) 57–78. https://doi.org/10.5278/ijsepm.2017.14.5.

[50] S. Samarakoon, A justice and wellbeing centered framework for analysing energy poverty in the Global South, Ecol. Econ. 165 (2019) 106385. https://doi.org/10.1016/j.ecolecon.2019.106385.

[51] G. Gladkykh, B. Davíðsdóttir, A. Diemer, When justice narratives meet energy system models: Exploring energy sufficiency, sustainability, and universal access in Sub-Saharan Africa, Energy Res. Soc. Sci. 79 (2021). https://doi.org/10.1016/j.erss.2021.102075.

[52] J.D. Sterman, Business dynamics: Systems thinking and modeling for a complex world, McGraw-Hill Companies, 2000.

[53] D. Wu, S. Ning, Dynamic assessment of urban economy-environment-energy system using system dynamics model: A case study in Beijing, Environ. Res. 164 (2018) 70–84. https://doi.org/10.1016/j.envres.2018.01.029.

[54] I. Pakere, M. Kacare, A. Grāvelsiņš, R. Freimanis, A. Blumberga, Spatial analyses of smart energy system implementation through system dynamics and GIS modelling. Wind power case study in Latvia, Smart Energy. 7 (2022). https://doi.org/10.1016/j.segy.2022.100081.

[55] M.K. Akhtar, J. Wibe, S.P. Simonovic, J. MacGee, Integrated assessment model of society-biosphere-climate-economy-energy system, Environ. Model. Softw. 49 (2013) 1–21. https://doi.org/10.1016/j.envsoft.2013.07.006.

[56] Z. Wu, J. Xu, Predicting and optimization of energy consumption using system dynamics-fuzzy multiple objective programming in world heritage areas, Energy. 49 (2013) 19–31. https://doi.org/10.1016/j.energy.2012.10.030.

[57] S. Eker, E. van Daalen, A model-based analysis of biomethane production in the Netherlands and the effectiveness of the subsidization policy under uncertainty, Energy Policy. 82 (2015) 178–196. https://doi.org/10.1016/j.enpol.2015.03.019.

[58] F. Daneshzand, M.R. Amin-Naseri, M. Asali, A. Elkamel, M. Fowler, A system dynamics model for optimal allocation of natural gas to various demand sectors, Comput. Chem. Eng. 128 (2019) 88–105. https://doi.org/10.1016/j.compchemeng.2019.05.040.

[59] H. Karunathilake, K. Hewage, T. Prabatha, R. Ruparathna, R. Sadiq, Project deployment strategies for community renewable energy: A dynamic multi-period planning approach, Renew. Energy. 152 (2020) 237–258. https://doi.org/10.1016/j.renene.2020.01.045.

[60] M.K. Akhtar, J. Wibe, S.P. Simonovic, J. MacGee, Integrated assessment model of society-biosphere-climate-economy-energy system, Environ. Model. Softw. 49 (2013) 1–21. https://doi.org/10.1016/j.envsoft.2013.07.006.

[61] S. Eker, E. van Daalen, A model-based analysis of biomethane production in the Netherlands and the effectiveness of the subsidization policy under uncertainty, Energy Policy. 82 (2015) 178–196. https://doi.org/10.1016/j.enpol.2015.03.019.

[62] S. Hafner, A. Jones, A. Anger-Kraavi, Economic impacts of achieving a net-zero emissions target in the power sector, J. Clean. Prod. 312 (2021) 127610. https://doi.org/10.1016/j.jclepro.2021.127610.

[63] A. Blumberga, D. Lauka, A. Barisa, D. Blumberga, Modelling the Baltic power system till 2050, Energy Convers. Manag. 107 (2016) 67–75. https://doi.org/10.1016/j.enconman.2015.09.005.

[64] S. Sheykhha, R. Madlener, Flexibility scores for energy transition pathways: Integrating socio-technical factors in a long-term energy market model, Energy Convers. Manag. 258 (2022). https://doi.org/10.1016/j.enconman.2022.115327.

[65] A. Blumberga, A. Gravelsins, D. Blumberga, Deliberation platform for energy transition policies: How to make complex things simple, Energies. 15 (2022). https://doi.org/10.3390/en15010090.

[66] A. Strapasson, J. Woods, J. Meessen, O. Mwabonje, G. Baudry, K. Mbuk, EU land use futures: modelling food, bioenergy and carbon dynamics, ENERGY Strateg. Rev. 31 (2020) 100545. https://doi.org/10.1016/j.esr.2020.100545.

[67] A. Aslani, P. Helo, M. Naaranoja, Evaluation of renewable energy development in power generation in Finland, J. Renew. Sustain. Energy. 5 (2013) 063132. https://doi.org/10.1063/1.4855095.

[68] H. Qudrat-Ullah, Understanding the dynamics of electricity generation capacity in Canada: A system dynamics approach, Energy. 59 (2013) 285–294. https://doi.org/10.1016/j.energy.2013.07.029.

[69] N. Szarka, J. Wolfbauer, A. Bezama, A systems dynamics approach for supporting regional decisions on the energetic use of regional biomass residues, Waste Manag. Res. 36 (2018) 332–341. https://doi.org/10.1177/0734242X18757626.

[70] A. Aslani, S. Akbari, S. Tabasi, The Robustness of Natural Gas Energy Supply: System Dynamics Modelling, Int. J. Syst. Dyn. Appl. 7 (2018) 57–71. https://doi.org/10.4018/IJSDA.2018070103.

[71] E. Jin, G.P. Mendis, J.W. Sutherland, Integrated sustainability assessment for a bioenergy system: A system dynamics model of switchgrass for cellulosic ethanol production in the U.S. midwest, J. Clean. Prod. 234 (2019) 503–520. https://doi.org/10.1016/j.jclepro.2019.06.205.

[72] N. Spittler, B. Davidsdottir, E. Shafiei, A. Diemer, Implications of renewable resource dynamics for energy system planning: The case of geothermal and hydropower in Kenya, Energy Policy. 150 (2021). https://doi.org/10.1016/j.enpol.2020.111985.

[73] J.G. Insuasty-Reina, J.C. Osorio-Gómez, D.F. Manotas-Duque, A System Dynamics Model for the Analysis of CO_2 Emissions Derived from the Inclusion of Hydrogen Obtained from Coal in the Energy Matrix in Colombia, Int. J. Energy Econ. Policy. 12 (2022) 72–82. https://doi.org/10.32479/ijeep.12538.

[74] M. Laimon, T. Mai, S. Goh, T. Yusaf, System dynamics modelling to assess the impact of renewable energy systems and energy efficiency on the performance of the energy sector, Renew. Energy. 193 (2022) 1041–1048. https://doi.org/10.1016/j.renene.2022.05.041.

[75] X. Liu, G. Mao, J. Ren, R.Y.M. Li, J. Guo, L. Zhang, How might China achieve its 2020 emissions target? A scenario analysis of energy consumption and CO_2 emissions using the system dynamics model, J. Clean. Prod. 103 (2015) 401–410. https://doi.org/10.1016/j.jclepro.2014.12.080.

[76] S.H. Roberts, B.D. Foran, C.J. Axon, B.S. Warr, N.H. Goddard, Consequences of selecting technology pathways on cumulative carbon dioxide emissions for the United Kingdom, Appl. Energy. 228 (2018) 409–425. https://doi.org/10.1016/j.apenergy.2018.06.078.

[77] M.K. Akhtar, S.P. Simonovic, J. Wibe, J. MacGee, Future realities of climate change impacts: An integrated assessment study of Canada, Int. J. Glob. Warm. 17 (2019) 59–88. https://doi.org/10.1504/IJGW.2019.096761.

[78] H. Wu, D. Peng, L. Wang, Model for sustainable development based on system dynamics and energy–economy–environment coordination: A case study of Beijing, China, Energy Sci. Eng. 9 (2021) 828–842. https://doi.org/10.1002/ese3.837.

[79] M. Laimon, T. Mai, S. Goh, T. Yusaf, Energy Sector Development: System Dynamics Analysis, Appl. Sci. 10 (2019) 134. https://doi.org/10.3390/app10010134.

[80] N. Spittler, B. Davidsdottir, E. Shafiei, J. Leaver, E.I. Asgeirsson, H. Stefansson, The role of geothermal resources in sustainable power system planning in Iceland, Renew. Energy. 153 (2020) 1081–1090. https://doi.org/10.1016/j.renene.2020.02.046.

[81] E. Shafiei, B. Davidsdottir, J. Leaver, H. Stefansson, E.I. Asgeirsson, Potential impact of transition to a low-carbon transport system in Iceland, Energy Policy. 69 (2014) 127–142. https://doi.org/10.1016/j.enpol.2014.03.013.

[82] E. Shafiei, B. Davidsdottir, J. Leaver, H. Stefansson, E.I. Asgeirsson, Simulation of Alternative Fuel Markets using Integrated System Dynamics Model of Energy System, Procedia Comput. Sci. 51 (2015) 513–521. https://doi.org/10.1016/j.procs.2015.05.277.

[83] E. Shafiei, B. Davidsdottir, J. Leaver, H. Stefansson, E.I. Asgeirsson, Comparative analysis of hydrogen, biofuels and electricity transitional pathways to sustainable transport in a renewable-based energy system, Energy. 83 (2015) 614–627. https://doi.org/10.1016/j.energy.2015.02.071.

[84] E. Shafiei, B. Davidsdottir, J. Leaver, H. Stefansson, E.I. Asgeirsson, D.R. Keith, Analysis of supply-push strategies governing the transition to biofuel vehicles in a market-oriented renewable energy system, Energy. 94 (2016) 409–421. https://doi.org/10.1016/j.energy.2015.11.013.

[85] E. Shafiei, J. Leaver, B. Davidsdottir, Cost-effectiveness analysis of inducing green vehicles to achieve deep reductions in greenhouse gas emissions in New Zealand, J. Clean. Prod. 150 (2017) 339–351. https://doi.org/10.1016/j.jclepro.2017.03.032.

[86] E. Shafiei, B. Davidsdottir, J. Leaver, H. Stefansson, E.I. Asgeirsson, Energy, economic, and mitigation cost implications of transition toward a carbon-neutral transport sector: A simulation-based comparison between hydrogen and electricity, J. Clean. Prod. 141 (2017) 237–247. https://doi.org/10.1016/j.jclepro.2016.09.064.

[87] J.D. Leaver, K. Gillingham, A. Baglino, System Dynamics Modelling of Pathways to a Hydrogen Economy in New Zealand: Final Report, 2012.

[88] J.R. Centre, I. for Energy, Transport, G. Harrison, L. Jones, C. Thiel, Powertrain Technology Transition Market Agent Model (PTTMAM), Publications Office, 2016. https://doi.org/doi/10.2790/719385.

[89] W. Nijs, P. Ruiz Castello, 01_JRC-EU-TIMES Full model, Eur. Comm. Jt. Res. Cent. (n.d.). http://data.europa.eu/89h/8141a398-41a8-42fa-81a4- 5b825a51761b (accessed September 24, 2022).

[90] M. Mobaseri, S.N. Mousavi, M.H. Mousavi Haghighi, Causal effects of population growth on energy utilization and environmental pollution: A system dynamics approach, Casp. J. Environ. Sci. 19 (2021) 601–618. https://doi.org/10.22124/cjes.2021.5088.

[91] M.J. Keyhanpour, S.H. Musavi Jahromi, H. Ebrahimi, S.H.M. Jahromi, H. Ebrahimi, System dynamics model of sustainable water resources management using the Nexus Water-Food-Energy approach, Ain Shams Eng. J. 12 (2021) 1267–1281. https://doi.org/10.1016/j.asej.2020.07.029.

[92] A. Toka, E. Iakovou, D. Vlachos, N. Tsolakis, A.-L. Grigoriadou, Managing the diffusion of biomass in the residential energy sector: An illustrative real-world case study, Appl. Energy. 129 (2014) 56–69. https://doi.org/10.1016/j.apenergy.2014.04.078.

[93] G. Bažbauers, U. Bariss, L. Timma, D. Lauka, A. Blumberga, D. Blumberga, Electricity saving in households due to the market liberalization and change in the consumer behaviour, Energetika. 61 (2015) 108–118. https://doi.org/10.6001/energetika.v61i3-4.3251.

[94] M. Kubli, S. Ulli-Beer, Decentralisation dynamics in energy systems: A generic simulation of network effects, Energy Res. Soc. Sci. 13 (2016) 71–83. https://doi.org/10.1016/j.erss.2015.12.015.

[95] A. Blumberga, E. Cilinskis, A. Gravelsins, A. Svarckopfa, D. Blumberga, Analysis of regulatory instruments promoting building energy efficiency, Energy Procedia. 147 (2018) 258–267. https://doi.org/10.1016/j.egypro.2018.07.090.

[96] R. Freeman, Modelling the socio-political feasibility of energy transition with system dynamics, Environ. Innov. Soc. Transitions. 40 (2021) 486–500. https://doi.org/10.1016/j.eist.2021.10.005.

[97] I. Pakere, M. Kacare, A. Grāvelsiņš, R. Freimanis, A. Blumberga, Spatial analyses of smart energy system implementation through system dynamics and GIS modelling. Wind power case study in Latvia, Smart Energy. 7 (2022). https://doi.org/10.1016/j.segy.2022.100081.

[98] M. Eftekhari Shahabad, A. Mostafaeipour, H. Hosseini Nasab, A. Sadegheih, H. Ao Xuan, A new model to investigate effects of subsidies for home solar power systems using system dynamics approach: A case study, Sustain. Energy Technol. Assessments. 49 (2022) 101706. https://doi.org/10.1016/j.seta.2021.101706.

[99] B.E. Shari, M.O. Dioha, M.C. Abraham-Dukuma, V.O. Sobanke, N. V. Emodi, Clean cooking energy transition in Nigeria: Policy implications for Developing countries, J. Policy Model. 44 (2022) 319–343. https://doi.org/10.1016/j.jpolmod.2022.03.004.

[100]F. Cappellaro, R. Chiarini, C. Meloni, C. Snels, Smart community co-creation: The case of centocelle project, Int. J. Sustain. Energy Plan. Manag. 24 (2019) 155–162. https://doi.org/10.5278/ijsepm.3339.

[101]S.S. Qarnain, M. Sattanathan, B. Sankaranarayanan, Analysis of social inequality factors in implementation of building energy conservation policies using fuzzyanalytical hierarchy process methodology, Int. J. Sustain. Energy Plan. Manag. 29 (2020) 153–170. https://doi.org/10.5278/ijsepm.3616.

[102]S. Scott, B. Nolan, T. Fahey, Formulating environmental and social indicators for sustainable development, The Economic and Social Research Institute, Dublin, 1996.