Pre-print for Energy, Volume 239, Part A, 2022, 121706, ISSN 0360-5442, https://doi.org/10.1016/j.energy.2021.121706.

# Modelling social aspects of the energy transition: What is the current representation of social factors in energy models?

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## Abstract

Computer-based models provide decision-makers with techno-economic insights into transition pathways for decarbonising energy systems. Such models focusing mainly on techno-economic aspects and do not adequately represent the social aspects of the energy transition, although there is broad consensus that non-technical factors are important drivers and constraints. To map the current integration and identify perspectives for future research, we ask: Which model types are particularly good at integrating social aspects? What social aspects are represented in energy models? How are these social aspects integrated? We analysed publications applying these models to investigate the integration within three main modelling steps: (i) storyline, scenario, and input parameter, (ii) optimisation/simulation process, and (iii) model output discussion. Results show that social aspects are mainly integrated through exogenous assumptions and output discussions. We also identify models that go beyond technical potential and pure cost optimisation/simulation. All model types integrate behaviour and lifestyle; some address public acceptance, but not transformation dynamics. Only agent-based models integrate heterogeneity of actors and public ownership. We conclude that there is a need for a better representation of social aspects in energy models, and that there is a high potential to improve this by combining different model types and conducting interdisciplinary research.

**Keywords:** energy modelling, social science, social aspects, energy policy

**Highlights**

- Review of energy model studies about what and how models integrate social aspects
- Models represent social aspects mainly as exogenous assumptions or output discussion
- Approaches exist that go beyond pure cost optimisation/simulation
- Techno-economic model design remains, except for agent-based models
- Interdisciplinary research can enhance linking of energy modelling and social science

Pre-print for Energy, Volume 239, Part A, 2022, 121706, ISSN 0360-5442, https://doi.org/10.1016/j.energy.2021.121706.

# 1 Introduction

Achieving EU's commitments under the European Green Deal, the Energy Union Strategy, and the Paris Agreement requires a significant transformation of current energy systems into carbon-neutral and renewables-based systems. To facilitate this transformation in a socially, economically and politically accepted way is crucial, and 'just transition' has become a central term for the envisioned change to a sustainable and climate-neutral economy, leaving no one behind [1].

Models can assist policy- and decision-makers to explore possible energy futures and transition pathways to climate neutrality [2], [3]. Policy- and decision-makers increasingly use such computer-based energy modelling tools – hereafter referred to as models – and they also influence the modelling [2]. Models are becoming increasingly capable of describing technological and techno-economic developments, and partially policy assumptions (e.g., [4], [5]). However, they often do not adequately represent social aspects[1] of the energy transition, although there is broad consensus that non-technical factors are important drivers and constraints of the transition, influencing the dynamics of the transition in various ways (e.g., [6]–[9]). For example, on the one hand, citizens can play a facilitating role as prosumers and co-owners of community energy projects, by benefitting from on-site energy projects [10]–[12]. On the other hand, public opposition towards renewable energy (RE) projects, such as onshore wind farms and accompanying transmission grids, slows down the energy transition [13]–[15]. Neglecting these social aspects in modelling could result in erroneous policy decisions. Therefore, techno-economic modelling needs to be re-examined to better reflect the social realities of the energy transition [16], including societal actors, socio-political dynamics and the "co-evolving nature of society and technology" [17]. This would allow for a better and more realistic analysis of energy system trajectories [18].

Combining socio-technical research and modelling approaches is a topic currently high on the research agenda, not at least because it can broaden the perspective on and understanding of energy transitions and real-world developments [18]–[21]. A better representation of social aspects in energy models is essential to understand the effects of drivers and constraints of renewable energy technologies, including the effects of societal paradigm changes, on the speed of the transition and redesign of the energy system. To improve their integration, societal assumptions in existing models must be mapped and assessed [21]. So far, current literature and model reviews do not systematically assess the integration of social aspects in energy models but rather focus on certain aspects or theories or staying within a discipline (e.g., [17], [20], [22]). Therefore, we take this research gap as a starting point to investigate if, what and how social aspects are currently represented in modelling applications of key energy modelling tools. Our research questions are: Which model types are particularly good at

[1] We define social aspects of the energy transition as all aspects that concern the people, their interactions, and relationships within the energy system. We use the term as a synonym to social dimension and social factors.

integrating social aspects? What social aspects are represented in energy models? How are these social aspects integrated?

To answer these research questions, we conduct a systematic analysis focusing on open-source energy modelling tools of the EU Horizon 2020 projects SENTINEL[2], and openENTRANCE[3]. We choose these two modelling projects because they include a diversity of open modelling tools, ranging from energy demand and system design to economic models. Specifically, we analyse up to five scientific publications that apply the models to understand the integration of social factors along these different modelling steps: (i) storyline, scenario and input parameter, (ii) optimisation/simulation process, and (iii) model output discussion.

With this research, we provide an overview of state-of the art approaches for integrating social aspects into energy models, which offers a starting point for dialogue among scholar from different fields and the right model selection for interdisciplinary studies. Furthermore, our results help modellers and decision-makers to find appropriate model types for specific research questions and scenarios linking techno-economic and social perspectives. Last, we identify future research and development needs for energy modelling.

# 2 Background on energy modelling and social science

## 2.1 Energy models, an overview

There is a rapidly growing variety of energy models that address specific energy challenges, and along with this, scholars use different model categorisations depending on the purpose of the study [5], [20], [23], [24]. We classified the models to fit our analysis (following [20], [23]), meaning that the purpose is to analyse what model types are suitable for integrating social aspects and how it is done. Therefore, in this study, we classify energy models into energy system models (ESM), integrated assessment models (IAM), agent-based models (ABM), and computable general equilibrium (CGE) models.

ESMs are usually bottom-up models or hybrid models that are cost-oriented and calculate prices endogenously. They are often used to provide information on the energy system of specific sectors with a great technological detail [24]–[26]. Optimisation and simulation are common underlying methodologies of energy models in general and ESMs in particular (cf. [5]). ESMs provide least-cost economic solutions by capturing technological and economic dynamics as realistically as possible [24], [26]. However, they have limited representation and realism of microeconomic processes and social aspects, e.g. behaviour and lack macroeconomic completeness [24].

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2 https://sentinel.energy/

3 https://openentrance.eu/

IAMs analyse the impact of policies in the long-term by including both human and nature dimension components and provide insights into systematic change. Cost and technological constraints are the basis for simulations and optimisations. One of the strengths of the model is the recognition of feedbacks between the global economy and the climate system [27]. Therefore, IAMs are usually applied at a spatially large scale and work with a single agent representation [25], [28]. They express cultural and social change and future uncertainties through exogenous assumptions, historical data and estimates of future developments. Therefore, these models are based on exogenous assumptions, e.g. about lifestyle, preferences, and technological changes [23], [25].

In contrast, ABMs place more emphasis on the agents' decision-making about renewable energy technologies and analyse the behaviour of complex social systems [23], [29]. This implies in particular behavioural aspects of the represented agents as well interactions between the agents and actor heterogeneity. ABMs are very well suited to represent social phenomena at microeconomic-level; although the energy system can only be represented to a limited extent [23], [25]. They are often based on social scientific theory, socio-psychological theory, game theory etc., and not on optimisation [25].

CGE are macroeconomic models that often combine or complement energy models. They are top-down models and assess the impacts of policies on economic, social, and environmental parameters. Furthermore, they analyse macroeconomic effects and the linkages between different economic sectors with real world (exogenous) data [24], [30]. For example, CGE models assess the impact of policy or economic shocks by comparing an initial general equilibrium and a recomputed equilibrium after changing parameters of the exogenous data to mimic policy interventions [24], [30]. CGE models assume optimal behaviour by economic agents. They use exogenous data, scenarios and sensitivity analyses to account for changing parameters [24].

For each of the four categories, we analyse different models with respect to the current and possible integration of social aspects.

## 2.2 Social aspects of the energy transition

There is an increasing awareness that societies are critical for the success of the energy transition (e.g., [31]–[33]). Analysing energy transitions through the lenses of socio-technological systems enables to put more emphasis on the role of society within the transition process and its outcomes [33]. Previous studies have focused on drivers and barriers (e.g., [6]–[9]), social benefits and challenges (e.g., [10], [34], [35]), of the energy transition (e.g., [36]). These studies address different geographical scales and levels of organisational behaviour and performance. This implies that some researchers rather investigate socio-demographics factors and societal patterns, such as lifestyle and social movements. Others analyse behavioural changes and aspects of social attitudes, including the acceptance of energy technologies and energy citizenships. Last, others study social innovations and experimentations, which can evolve and lead to new system configurations. Different levels and inherent social aspects are highly interlinked and interact.

It is not our intention to structurally review various social aspects. Instead, we recognise that different social aspects exist, and we place a particular emphasis on social and behavioural factors that scholars identified as relevant to socio-technical transitions and, therefore, where energy models need to be improved. In doing so, we refrain from looking at political and regulatory aspects to focus on the social and behavioural factors, although it should be noted that these aspects are linked to the social factors we are looking at. Recent transition literature identifies five strongly interrelated factors that are important for the energy transition:

- Behaviour and lifestyle [20], [21], [23], [25], [36]
  The aspect concerns the behaviour and lifestyle of all types of actors in transformations and the influence on the dynamic and pathways of the energy transition [21], [23], [25]. This includes aspects like material and non-material needs, values, norms, and preferences [21]. Changes in the behaviour of actors affect the prediction of trajectories significantly as this implies changes in demand and, thus, influences the necessary development and allocation of renewable energy.
- Heterogeneity of actors [20], [21], [23]
  The aspect is linked to the concept of agency and "heterogeneity across and within societies" as there are many different actors involved in the energy transition [21], [23]. The heterogeneity of the diverse actor groups (e.g., consumers and producers) in different states of the energy transition and the behaviour of the actors in the group influences the dynamics of the speed of the energy transition [23]. This includes contextual and environmental factors, distributional impacts of environmental change and policies, socio-economic conditions, and presence of incumbents and innovators [21].
- Public acceptance and opposition [20], [21], [36]–[38]
  The aspect considers public acceptance and opposition towards energy infrastructure that influences the speed of the renewable energy deployment. Acceptance is "a favourable or positive response relating to a proposed or in situ technology or socio-technical system, by members of a given social unit" [37]. Wüstenhagen et al. [38] conceptualise three dimensions of social acceptance: (i) socio-political acceptance refers to the general acceptance of the public on the energy transition; (ii) community acceptance describes the approval of the local population by specific landscape decisions, and (iii) market acceptance entails the reaction of the market to innovations. Furthermore, this social aspect accounts for jobs and local (economic) development that influences the people's attitude towards the energy transition [39].
- Public participation and ownership [10], [40], [41]
  Especially community acceptance is based on public participation and ownership. This is

considered to be a main driver of the energy transition as it allows people to influence and actively participate in the local energy transition [40]. Participation can be financial, e.g. through money transfers of local wind farms to citizens in the surrounding area. Alternatively, the participation of the population in project implementation and the processes of infrastructure measures, e.g. citizen assemblies referendum based on citizens' decision.

- Transformation dynamics [21], [23]
  The aspect concerns transformation dynamics at and across different scales and in time, which includes speed of transformations, path dependencies and the quality of different system states [21], [23]. This refers to the non-linear and polycentric (e.g., multiple actors and temporal scales) process of the transition and the societal system within [23].

## 2.3 Current approaches for linking social science and computer-based modelling

Quantifying and integrating social aspects into energy models is still one of the key modelling challenges [22], [28]. Research groups use different approaches for addressing social aspects in energy modelling, mainly analysing socio-economic impacts and using economic theory, such as social costs (e.g., [42]–[46]). Current models tend to treat the social dimension of the energy transition as an exogenous narrative, or "broader societal factor" [47]. However, differences exist between modelling approaches, and especially ABMs are able to simulate heterogeneous agents' behaviour and interactions, and thus, advance our understanding of societal phenomena (e.g., [48], [49]). They can provide a suitable framework for analysing adoption decisions for renewable energy technologies, demand flexibility and smart grids [29], [50].

Modelling can provide different benefits to social science and transition research: Interdisciplinary modelling can provide explicit, clear and systematic system representations that induce learning and facilitate communication about the target system [51]. Furthermore, modelling allows us to make inferences about dynamics in complex systems and generate emergent phenomena from underlying elements and processes. Lastly, the use of models can facilitate systematic experiments (ibid). Hence, combining social science and modelling can enhance interdisciplinary learning, increase realism, and support finding solutions to energy and climate challenges [21].

Trutnevyte *et al.* [21] differentiate between three strategies for linking models and insights from social sciences: bridging, iterating and merging strategy. The different strategies imply different levels of linkage between models and social science. In bridging, models and social science research are carried out in parallel and sometimes build 'bridges' for exchange between each other, especially with regard to common concepts and theories. The iterating strategy can be seen as "story and simulation" approach, where exogenous narratives defined by social sciences are "translated into quantitative input assumptions used by the models", and outputs may be used for revisiting the narratives. Merging implies an in-depth integration, assuming that "at least the key societal factors can be modelled", and leading to a structural modification of existing models, or creation of completely new models (Trutnevyte *et al.*, 2019:424-425). Trutnevyte et al. [21] state that mapping and assessment exercise of societal assumptions in energy models focusing on specific dynamics and societal change exist (e.g., [19], [23], [52], [53]). For example, De Cian et al. [25] focus on the depiction of actors, decision-making, and institutions in models by analysing their current implementation and possible further model development of four models (two IAMs, one ESM, and one ABM). They explain that achieving a lower degree of integration of these factors is already possible with existing modelling frameworks, whereas a higher degree of integration requires further model development. However, Trutnevyte et al. [21] argue that these mapping exercises either remain more generic and do not look how the representation influence the model outcome or remain "outside the modelling community" so that the findings are not used by the modelling community.

Thus, we conduct a systematic analysis of the representation of social aspects in open-source energy models by focusing on the modelling process. We build on the mentioned research by combining the knowledge gained from social science, the energy model community, and current interdisciplinary research to assess the potential of integrating social aspects in detailed modelling steps and model types.

# 3 Research Design

Different energy models can integrate or represent the five classified social factors (Section 2.2) along different modelling steps. **Figure 1** illustrates our framework of integration along three modelling steps: (i) storyline, scenario, and input parameter, (ii) optimisation/simulation process, and (iii) discussion of model output. The modelling steps are based on the framework by Trutnevyte et al. (2019) (see section 2) and, thus, the three strategies for linking social science and modelling can be found in the steps. By defining the steps, we delve deeper into the modelling process by breaking it down to the individual steps of modelling exercises and identify within potentials for integrating social aspects in models.

The first step constitutes of the linking process by developing exogenous storylines and translating them into input parameter, which become part of the scenarios. The softest integration happens via the "bridging" where concept and theories from modelling and social science are brought together. If an "iterating" approach is applied, empirical data are used to equip the input assumptions with more details on social aspects. Similar to that, "merging" can even go a step further by jointly developing or adapting a model with corresponding input parameters. In the simulation/optimisation process, an integration means that the aspects are found in the mathematical formulations, and, thus, structurally defines the model. This is only the case in the "merging" strategy. The last step in our framework is the model output discussion. This step involves an exogenous discussion of the model results in context of a social aspect, e.g. what the output means for the expansion of wind energy in residential areas. This is the only potential of integration in the framework that does not have an impact on the actual model results, however, impacts the way the results are interpreted and discussed. Beyond, the output discussion could also lead to the adjustment of the storylines if needed ("iterating" and "merging" strategy).

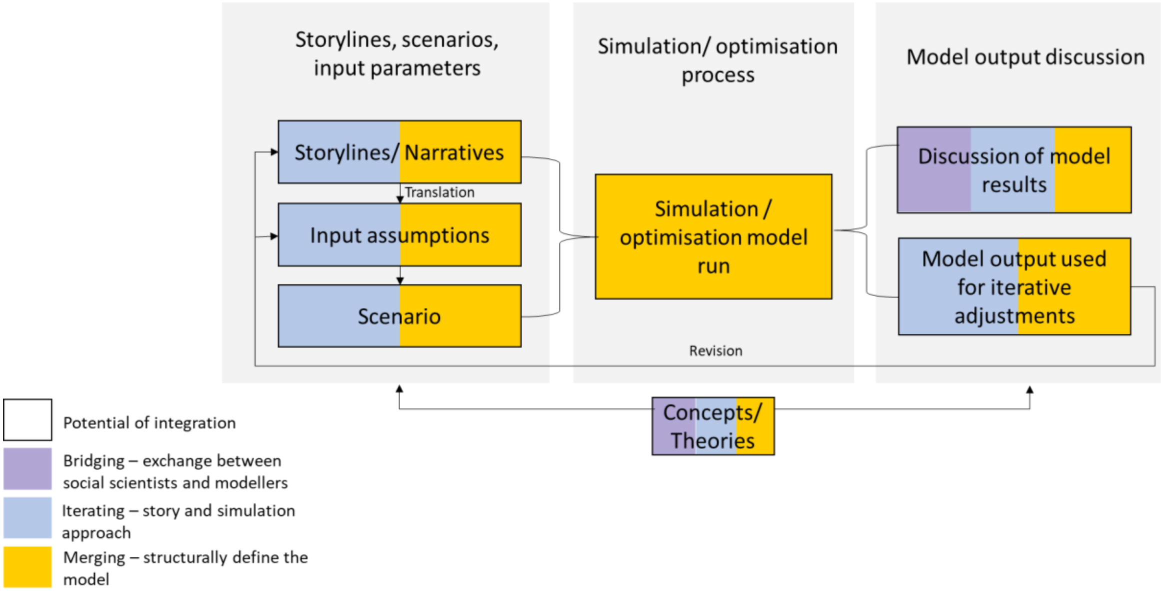


**Figure 1:** Potential of integration (based on: Turnheim et al., 2015; Trutnevyte et al., 2019; Hirt et al., 2020)

Depending on the model characteristics, different levels of representation are possible. To account for the model type characteristics, we apply the model classification described in Section 2 (ESMs, IAMs, ABMs, and CGE models). Within each type, we examine different energy model application to find the current levels of integration of social aspects by distinguishing between different ways of linking social science and energy modelling. We focus on model application to analyse how modelling teams currently integrate social aspects in scientific model publications. By focusing on these publications, we can also assess whether the scientist used theory or data from social science and if the work was done in an interdisciplinary way. We analysed scientific publications that apply or describe the energy models and use published model descriptions for indicating model specification, e.g. input and output parameters.

To explore what and how social factors are integrated into energy models, we analysed scientific publications models that are included in the modelling projects openENTRANCE and SENTINEL. We chose these models because (i) the modelling projects provide a diversity of models (from energy demand and system design to economic models) and (ii) the models are mainly open-source, which eases the analysis and future integration of new features. We found the selection to be appropriate for the – at least European – energy modelling landscape as these projects specifically aim for becoming major energy modelling suites in Europe. Between September and December 2020, we conducted a systematic literature search, to identify relevant publications that apply the models. This procedure provided "a comprehensive, unbiased and replicable summary of the state of knowledge" [54], [55]. We only considered scientific publications (exclusion of news feed, non-scientific magazine, encyclopaedia, and newspapers), published from 2015 onward, because model advancements may have changed the model design. For this, we used the ProQuest and Web of Science[4] search engines, because these are well-established databases that cover a broad range of scientific literature databases, and the model websites.

The search string we used to find relevant publications consists of three components connected via the logical operator AND (see **Figure A 1**). The first component consists of the short and long model names connected with the logical operator AND. The second component comprises the social factors: To identify whether publications address social aspects, we have identified and used keywords that are describing the nature of the social aspects using social science theory as well as existing linkage approaches. We used a brainstorming process based on the literature on social aspects among the authors to identify the social keywords and discussed them informally with scholars working in the field of socio-technical transitions. The social keywords are connected with the logical operator OR. The last component encompasses words such as energy, heat, transport etc. to limit the search to publications in the field of energy transition.

The first phase comprises the search for publications of models that we include in our detailed analysis. The two projects openENTRANCE and SENTINEL contain 28 models (see **Figure 2** for the distribution of model types in the projects). We applied the search string for each of the 28 models resulting in 28 search strings. The initial search for all models resulted in 823 publications. We screened the abstracts to determine whether the publications applied the model that is stated in the search string and included social aspects in one of the modelling steps of our framework. We included the publication if the following criteria were fulfilled: (i) the publication contains an application of the model (that can also include a detailed description of the model), and (ii) includes the integration of a social aspect in one of the potential integration ways of our framework. For this, we used the social keywords to find the relevant passages. We excluded publications if a social keyword was not mentioned in connection with any of the potential of integration. For example, if we only found a social keyword in the introduction, e.g. to explain the importance of climate change, we did not include the paper as this is not a potential of integration as defined by us. Based on this screening, we found publications for 13 models that met the inclusion criteria and excluded 15 models because the search did not reveal any relevant publications for our analysis. **Figure 2** shows (a) the distribution of model types in the two projects and b) the models included in our analysis.

[4] In ProQuest, we did not limit the search to title, abstract and keywords, as social drivers and barriers can also be found only partially within the paper, e.g. as a part of the discussion. Our search in WebofScience focused on the first component of the search term as the database searches only in the abstract and title

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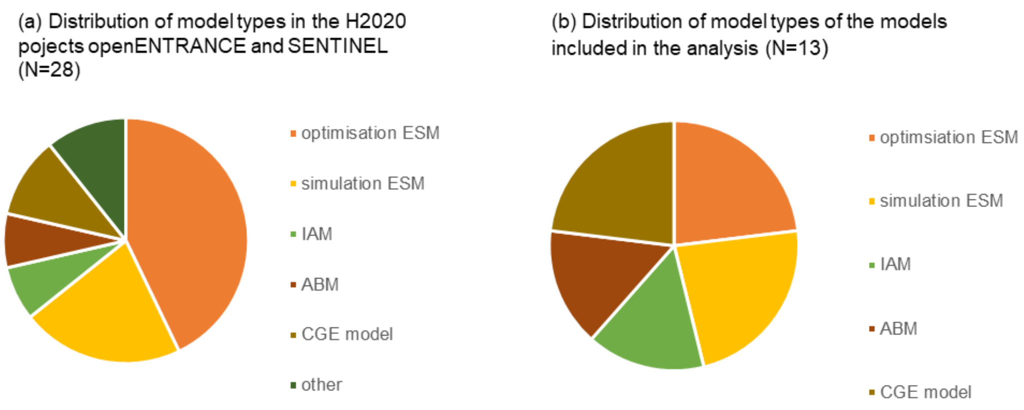


**Figure 2:** Overview of model types (a) all models in openENTRANCE and SENTINEL and (b) models included in the analysis

For the 13 models, we included up to five relevant publications in our analysis that we identified in the screening process, as this provides a manageable amount of documents to analyse. We defined relevance in terms of the extent to which the respective research took social aspects into account. This resulted in 29 publications for the detailed analysis (**Table A 1-A 6** present an overview of all models and publications). We complemented the scientific publications with model documentations that provided further insights into the models.

In a second phase, we examined the publications by applying our analytical framework, to identify what and how modellers integrate social aspects in their models. We read the publications and marked relevant text passages using the social keywords, and sorted them according to the three modelling steps in **Figure 1**.

# 4 Results – Representation of social factors

Out of 28 reviewed models, we present the result of the analysis of 13 modelling tools that incorporate social aspects to different extends. We investigated *what* social aspects and *how* social aspects have been integrated in the application of the energy-modelling frameworks. **Table A 1- Table A 5** provide short model descriptions, and summarise the findings regarding input and output parameters, information on the simulation/optimisation processes, and the publications which are included in the analysis of the integration of the social aspects.

## 4.1 Energy system models

We analyse the optimisation ESMs and the simulation ESMs separately, as they have a distinctly different mathematical approach and thus different analysis objectives.

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### 4.1.1 Optimisation ESMs

We find that three out of 12 optimisation ESMs, deal with social aspects in scientific publications: Calliope, GENeSYS-MOD, and FRESH:COM (see **Table A 1**). **Table 1** provides an overview of the included social aspects and how they are integrated in the models sorted along to the potential of integration. The social aspects 'behaviour and lifestyle', and 'public acceptance and opposition' are represented mainly in storylines, scenarios, and input parameter, as well as in the output discussion. However, we also find integration efforts of the aspects 'behaviour and lifestyle', and 'public acceptance and opposition' in the optimisation process.

**Table 1**
Representation of social factors in optimisation ESMs analysed.

| Social aspect | Potential of Integration | Description of the integration into models | Model and publications |
|---|---|---|---|
| Behaviour and lifestyle | Storyline, scenario, and input parameter | - Household sizes, habits and meal behaviour, %-out-of-home meal, and consumption assumptions to account for behaviour and preferences | Calliope [56] |
| | | - Input data for energy communities: electricity demand profile, a PV generation profile, and the battery parameters, community set-up, prosumer and household data, and willingness-to-pay | FRESH:COM [57] |
| | Simulation/ optimisation process | - Model considers local energy communities with properties, e.g. incentives for participant to joining the energy community, households connected to the grid, willingness-to-pay of community members | FRESH:COM [57] |
| Public acceptance and opposition | Storyline, scenario, and input parameter | - Differentiation between "technical" and "technical-social" potentials to balance techno-economic feasibility with social and political goals | Calliope [58], [59] |
| | Simulation/ optimisation process | - Alternative system configurations beyond single cost minimising designs, better balancing techno-economic feasibility with societal impacts and political goals | Callliope [58], [60] |
| | Discussion of model output | - Discussion of the results in context of local opposition and potential broader social barriers; "indirect economic effects", e.g. local economic development, job creation | Calliope [58], [61], [60] |
| Behaviour and lifestyle, and public acceptance and opposition | Storyline, scenario, and input parameter | Storylines and quantification/translation into scenarios:<br>- Accounting for society´s attitudes and lifestyle changes, e.g. willingness of the society to invest in renewable energies or promote them, changes in demand<br>- Incorporating trends in climate politics and the economy | GENeSYS-MOD [62] [63] |
| | Discussion of model output | - Qualitative discussion of (social) barriers for the transition based on literature<br>- Description of results with reference to the importance of societal commitment and behaviour change | GENeSYS-MOD [64], [65], [62] |

*Calliope*

We find that publications of Calliope address 'behaviour and lifestyle' in input parameters [56] and 'public acceptance and opposition' in input parameters and the output discussion [58]–[61]. For example, Lombardi et al. [56] apply the Calliope framework and represent behaviour changes in the input parameters. Specifically, they use household sizes, habits and meal behaviour, %-out-of-home meal, and consumption assumptions to account for people's behaviour and preferences in order to understand the effects of the electrification of Italian cooking devices and inherent changes in behaviour on the energy system. Lombardi et al. [58] and Tröndle et al. [59] also use the input parameters to address public acceptance and resistance. They distinguish between "technical" and "technical-social" potentials for renewable electricity. The latter incorporates social and ecological constraints, for example by not allowing electricity to be produced in nature conversation areas, or by prohibiting open field solar system on arable land, to ensure a socially more accepted deployment of renewables in Italy and Europe, respectively. Furthermore, Lombardi et al. [58] generate “alternative system configurations that can be used to balance techno-economic feasibility with social and political goals” (see also [60]). Tröndle et al. [59] model the possibility of electricity autarky on different levels in Europe, and found that autarky on regional and municipal levels in Europe would require dense local generation, which could meet with local opposition. They point out that there is an uncertainty about the influence of socio-political restrictions. Especially, public and political acceptance are dependent on local preferences, which vary greatly in different parts of Europe and over time, and are hard to assess in general (ibid). Lombardi et al. [58], Pfenninger et al. [61], and Tröndle [60] address public acceptance in the output discussion and put their results in context of local opposition and potential broader social barriers. For example, Pfenninger et al. [61] discuss the effect of local economic development and job creation of the results on concentrated solar power and nuclear power in South Africa.

*GENeSYS-MOD*

In the studies of GENeSYS-MOD, the social factors ‘behaviour and lifestyle’ as well as ‘public acceptance and opposition’ are included in the storylines, scenarios, and as input parameters [62], [63], and in the discussion of the model output [62], [64], [65]. Auer et al. [62] and Bartholdsen et al. [63] develop storylines and quantified scenarios to include social and political implications on decarbonisation pathways in Europe and Germany to account for underlying uncertainties, respectively. For example, Auer et al. [62] takesociety´s attitudes towards renewable energy and lifestyle changes into account, by including assumptions on the societal willingness to invest in renewable energy or promote them, and changing demands in the input parameters. To translate the storylines, Auer et al. [62] conduct an in-depth analysis of the storylines implications on the energy transition and rank the underlying features and drivers of the storylines into a scale by a structured comparative analysis. Whereas Auer et al. [62] are the storytellers themselves, Bartholdsen et al. [63] conduct stakeholder workshops to develop scenario assumptions. They incorporate assumptions on global trends in climate politics and the economy in their storylines and performed a qualitative foresight analysis to adjust the input parameters for the model cautions (e.g. different demands or cost assumptions) to develop scenarios (ibid).

Different authors ([62], [63], [64], and [65]) also use the discussion of the model output to reflect their findings against social and political realities. Auer et al. [62] point out that societal commitments and changes in lifestyle and demand patterns are important for the transformation process to be successful and, they emphasised that behavioural change needs time. Against the backdrop of their model results, Lawrenz et al. [64] and Burandt et al. [65] discuss social barriers for the energy transition in India and China based on literature. They include descriptions of the role of actors and society, the importance of behaviour and consumption development, inequality, and job market developments. Here, they also refer to the fact that in GENeSYS-MOD a social-optimal planner with perfect foresight is used to optimise economic welfare, which implies that neither local actors nor specific barriers for the adoption of technologies are taken into account [64], [65].

*FRESH:COM*

The application of FRESH:COM addresses 'behaviour and lifestyle' in the input parameters and within the optimisation process by considering individual actors' preferences in different local energy community configurations [57]. They include different properties of energy communities in the model, e.g. incentives for participant to join the energy community, households connecting to the grid, and willingness-to-pay in the model [57]. For example, higher willingness-to-pay of an individual community member reflects the greater preference to buy local PV generation. The optimisation includes the objective function to maximise social welfare of the community. They also use input data related to prosumers: electricity demand profiles, PV generation profiles, battery parameters, as well as the community set-up, prosumer and household data, and willingness-to-pay.

### 4.1.2 Simulation ESMs

We analysed three ESMs — DREEM, DESTinEE, and EnergyPLAN (see **Table A 2**) — of the six simulation ESMs in the projects, because only those three include social aspects in model applications. Similar to the optimisation ESMs, the models mainly represent social factors in terms of 'behaviour and lifestyle', as well as 'public acceptance and opposition' in all three modelling steps, as show in **Table 2**.

*DREEM*

Stavrakas and Flamos [66] include the factor 'behaviour and lifestyle' in the scenarios and input parameter as well as in the simulation process of the DREEM model. They evaluate the impact of household demand patterns and consumer behaviour for the needed flexibility in the power sector. The model has a modular design that includes assumptions on demand-response technologies, electricity demand, household appliances, and household and consumer behaviour (e.g. demand-flexibility, use of appliances) in the simulation process. Demand patterns are used to reflect the complexity of calculating accurate and sophisticated demand profiles and the importance of including the human dimension [66]. To save computational time and reduce complexity, the modellers implement many simplified assumptions, such as with regard to occupants 'behaviour, and they use "a minimal set of easily obtainable parameters and statistics, such as surveys and census data" (ibid).

Furthermore, Stavrakas and Flamos [66] highlight the potential to link DREEM and the ABM ATOM (see Section 4.3 for more information on ATOM) to take advantage of the strengths of DREEM to be integrated with other models and explore adoption scenarios of relevant technological infrastructures for a decentralised energy system. Moreover, they provide an outlook stating that DREEM coupled with a monetary framework model can shed light on the importance of behavioural implications [66].

Pre-print for Energy, Volume 239, Part A, 2022, 121706, ISSN 0360-5442, https://doi.org/10.1016/j.energy.2021.121706.

**Table 2**
Representation of social factors in simulation ESMs analysed.

| Social aspect | Potential of Integration | Description of the integration into models | Model and publications |
|---|---|---|---|
| Behaviour and lifestyle | Storyline, scenario, and input parameter | - Input data: identification of key socioeconomic drivers for annual demand (development of population growth and household sizes; the impact of cultural difficulties in regard to reduction of demand) | DESTinEE [67] |
| | | - Input parameters: demand patters, household consumption, and behaviour; using stochastic methods and historical and statistical data<br>- Scenarios include different consumption behaviour of households (e.g., heating, self-consumption) | DREEM [66] |
| | | - Input parameters: assumptions on various elements of the energy system infrastructure are based on population projections and structure<br>- Data used to construct scenarios: socioeconomic indicators, and statistics of the energy system and transport sector (consumption and associated costs and economic benefits)<br>- Different scenarios for the decarbonisation of the energy system including the transport sector in 2030 with reflections on policies that are not reflecting consumer behaviour or vehicle ownership patterns | EnergyPLAN [68], [69], [70] |
| | Optimisation/ simulation process | - Demand for energy services (e.g. distance people travel) projected to 2050 using macroeconomic relationships with population, income, energy prices, and sector-specific details<br>- Model generates national load profiles for each sector by using stochastic variations mimic the natural variability of human behaviour and the sector profiles | DESTinEE [67] |
| | | - Model incorporates modules addressing demand-response technologies, electricity demand, and household appliances including thoughts on household, consumer behaviour | DREEM [66] |
| Public acceptance and opposition | Discussion of model output | - Qualitative assessment of barriers for PV and story deployment including behaviour barriers: general attitude, psychological resistance, and political will<br>- Discussion of the results with regard to impact on economy and recommendations, socioeconomic impact (job creation, economic income)<br>- Multi-criteria analysis based on sustainability factors<br>- Socioeconomic impact on local communities | EnergyPLAN [68], [69], [70], [71] [72] |

*DESSTinEE*

We find that the DESSTinEE [67] modelling study accounts for ‘behaviour and lifestyle’ through input parameters and in the simulation process. Boßmann and Staffell [67] investigate the future electricity load curves taking into account the variability of human behaviour in Germany and Great Britain. The analysis includes the identification of socio-economic drivers of demand, such as population and income growth, for the case studies. They also take into account the development of population growth and household sizes, cultural difficulties regarding past reduction of demand in homes as well as the macroeconomic relationship of population, income, energy prices, and sector-specific details for the country´s demand for energy services, e.g. distance people travel. To synthesise the hourly demand profiles, they add “stochastic variation to each profile to mimic the natural variability of human behaviour, and the sector profiles are summed to the national load profile” (ibid).

Pre-print for Energy, Volume 239, Part A, 2022, 121706, ISSN 0360-5442, https://doi.org/10.1016/j.energy.2021.121706.

*EnergyPLAN*

We discover that applications of EnergyPLAN include 'public acceptance and opposition' in the output discussion [68], [69], [70], [71], [72] and 'behaviour and lifestyle' in input parameters [68], [69], [70]. Cantarero [68] applies EnergyPLAN to simulate the implementation of a mass public transport system in the capital of Nicaragua. For this purpose, Cantarero uses socio-economic indicators as input parameters, such as consumer behaviour, and empirical data from the energy and transport system for the scenario creation. The output discussion includes implications on the job creation potential and vehicle ownership, as well as transport choices of the population, which affect the society and outcome on the implementation of mass public transport systems (ibid).

Furthermore, several studies address the effects of the energy transition on job creation in specific case studies in the output discussion. Child, Nordling et al. [69] use EnergyPLAN for a case study on sustainable scenarios of the energy system of Aland Islands by 2030. For this, they use different socio-economic input parameters, including population projections, installed heating systems and modes of transportation. Based on the results, they calculate the potential for job creation, by using job-years estimates from the International Renewable Energy Agency (IRENA). Dorotić et al. 2019 [70] also calculate the potential for job creation based on the results of their analysis on the integration of renewable energy in the transport and energy sector in island communities. To account for different residential household consumption and behaviour, they divide the household sector in five subsectors (heating, cooling, domestic hot water (DHW) demand, cooking and other household appliances). For this purpose, they create an average reference household based on a simple bottom-up method using statistical data (ibid). Furthermore, Sun e al. [71] use the direct job creation as one of five criteria (total cost, total capacity, excess electricity, and $CO_2$ emissions) for a multi-criteria analyses to evaluate the sustainability of analysed scenarios for the electricity system in China. The authors quantify the job creation based on the results of the modelling exercise, using an employment factor approach (ibid).

In the study by Child, Haukkala et al. [72] on the role of PV and energy storages in an energy system based on 100% renwable energy in Finland by 2030, they combine their quantitative results of EnergyPLAN with an ex-post qualitative discussion of barriers for adoption of solar PV and define solutions and drivers for PV. Four categories comprise the barrier aspects: technological, economic, institutional and political, and behavioural. They account for the role of prosumers and the response of consumers towards prices, and state in their output discussion that empowerment and engagement of stakeholders as well as prosumer concepts can drive the PV deployment.

## 4.2 Integrated assessment models

We examine two IAMs models that are involved in openENTRANCE and SENTINEL: the optimisation MESSAGEix_GLOBIOM framework and simulation IMAGE framework (see **Table A 3**). Modellers address 'behaviour and lifestyle' in storylines, scenarios, and input parameters and the output

Pre-print for Energy, Volume 239, Part A, 2022, 121706, ISSN 0360-5442, https://doi.org/10.1016/j.energy.2021.121706.

discussion. **Table 3** gives an overview of the identified representation of social aspects in IMAGE and MESSAGEix_GLOBIOM.

**Table 3**
Representation of social factors in IAMs analysed.

| Social aspect | Potential of Integration | Description of the integration into models | Model and publications |
|---|---|---|---|
| Behaviour and lifestyle | Storyline, scenario, and input parameter | - Scenarios to analyse the implications of lifestyle changes including the lifestyle measures adjusted via the parametrisation<br>- Changing the parametrisation, context-dependent variables, and increasing the level of detail in the housing and transportation sector to include lifestyle measures by curtailment measure<br>- Socio-technical transition storylines using the theory MLP and subsequent quantification into scenarios and changing input parameter to quantify the MLP-storylines – e.g. cost assumptions and demand changes | IMAGE [28], [73], [74] |
| | | - SSP narratives (simulate the extent of the impact of people´s effort on climate change mitigation under different policy scenarios) | MESSAGEix_ GLOBOIM [75], [76], [77] |
| | Discussion of model output | - Implications of lifestyle changes on transition pathways by describing results and qualitative discussion on barriers and policies for lifestyle change measures taking into account literature | IMAGE [73] |
| | | - Analyses of results with regard to the assumptions of the storylines | IMAGE [28], [74] |

*MESSAGEix_GLOBIOM*

Publications applying MESSAGEix-GLOBIOM address the social factor 'behaviour and lifestyle' by employing the widely used concept of shared socioeconomic pathways (SSP)[5] to depict trends in the evolution of society and ecosystems. Zhou et al. [75] and Zhou et al. [77] used SSP to analyse investment needs and future costs in different areas of the world on a national level and aggregated regions, respectively. In their output discussion, Zhou et al. [75] point out that future research could explore co-benefits of low carbon investments and the relation to sustainable development goals, such as water availability. Furthermore, Sun et al. [76] use population assumptions based on SSP2 to inform different decarbonisation policy scenarios to analyse the „extent of the impact of people´s effort on climate change mitigation" applying different IAMs including MESSAGEix_GLOBIOM and IMAGE. Both Sun et al. [76] and Zhou et al. [75] emphasise that the exogenous input parameter settings and the model structure do not capture the uncertainty about the speed of the socio-technical transition, which affects the mitigation potential.

[5] The shared socioeconomic pathways framework encompasses „pathways of future radiative forcing and their associated climate changes with alternative pathways of socioeconomic development" [47]. The scenarios are used as narratives for future socioeconomic developments and analyse emissions under different climate policies. There are five SSP scenarios with socioeconomic assumptions of mitigation and adaption. The SSP2 scenario stands for „Middle of the road". See O'Neill et al. [47] for further information on the SSP framework.

*IMAGE*

Authors using the IAM IMAGE include ‘behaviour and lifestyle’ developments in storylines and inputs parameters [28], [73], [74] as well as in the output discussion [73] using insights from socio-technical transition studies. Van Sluisveld et al. [73] develop a framework of ‘lifestyle change interventions’ to study behavioural changes in IMAGE, and they analyse the implications of different interventions on the mitigation pathways. For this purpose, they change context-dependent variables in the household and transportation sector (called parametrisation of contextual factors), which enables them to increase the degree to which transport behaviour changes (e.g. vehicle use) and heating demand changes (e.g. more efficient use of appliances) are incorporated in the model. They analyse and assess “the possible implications of lifestyle changes” and barriers in mitigation scenarios, as well as policy measure to encourage lifestyle changes (ibid).

Hof et al. [74] and van Sluisveld et al. [28] develop storylines based on socio-technical theory and translate the storylines into quantitative scenarios. To align IAM modelling and socio-technical transition theories, van Sluisveld et al. [28] “identif[ied] transition narratives as an analytical bridge between socio-technical transition studies and integrated assessment modelling”. The socio-technical narratives focus on the role of actors in meeting the European Unions’ decarbonisation goals. For this purpose, they distinguish between two transition narratives: one driven by incumbent actors and a second driven by new actors with a negative attitude towards large-scale technologies, accounting for behavioural and cultural changes of the society. Hof et al. [74] use a similar approach: they linked the three models, IMAGE, Enertile[6] (optimisation ESM), and WITCH[7] (simulation IAM) to investigate two contrasting transition narratives on the role of actors in meeting greenhouse gas reduction targets. The narratives are based on an analysis of actors’ preferences, behavioural and cultural changes and social networks, and technological and social niche-innovations, and they inform the narrative-driven scenario development.

Van Sluisveld et al. [28] state that the translation of qualitative insights into quantitative scenarios remains “the weakest link with no definitive solution”: They distinguish between a straightforward translation for social features that are measurable (e.g. energy efficiency improvements) and a more “stylised” translation, of more vague aspects, such as social rules. All factors are specific to the model and Hof et al. [74] point out that the assumptions are “tailor-made to the model” as models have different structures. The latter is based a lot on the "arbitrary" interpretations of the researchers as the parameters are harder to interpret into the models ‘formulation [73]. Hof et al. [74] quantify actor preferences by making assumptions regarding costs and demand changes, e.g., improved learning rates or different

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[6] Enertile is a detailed bottom-up electricity system optimisation model with detailed technical representations of the underlying processes in the power sector [74].

[7] WITCH is a global dynamic model that combines an inter-temporal optimal growth model (able to capture the long term economic growth dynamics) with a detailed representation of the energy sector [74].

ownership rates of vehicles. Furthermore, van Sluisveld et al. [28] translate their qualitative assessment of niche momentum and actors behaviour into cost assumptions and adjustments of technological detail (straightforward) and assumptions of reduced household growth due to changing social norms (stylised). For this, both Hof et al. [74] and van Sluisveld et al. [28] apply an iterative process between scientist involved in MLP case studies and modellers.

## 4.3 Agent-based models

We examine the two ABMs of the two research projects: BSAM and ATOM (see **Table A 4**). ATOM extends the initial BSAM framework by focusing on consumers (BSAM focuses on power generators). Not surprisingly, we find that ATOM and BSAM are well able to examine agent decision-making under different conditions and account for 'behaviour and lifestyle', 'actor heterogeneity', 'public participation and ownership', and 'public acceptance and opposition' in all three modelling steps (see **Table 4)**.

**Table 4**
Representation of social factors in ABMs analysed.

| Social aspect | Potential of Integration | Description of the integration into models | Model and publications |
|---|---|---|---|
| Behaviour and lifestyle, actor heterogeneity, and public participation and ownership | Storyline, scenario, and input parameter | - Input: geographical and socioeconomic context of Greece including prosumers 'income, consumers' willingness to invest in residential PV, consumer attention, household´s demand, resistance of consumers to invest | ATOM [29], [78] |
| | Optimisation/ simulation process | - Model accounts for behavioural uncertainty of consumers by deriving forward-looking simulations for different behavioural profiles (i.e., different set of agent-related parameters), from willing to invest to risk averse consumers<br>- Social parameters included to simulate decision of agents: agents 'initial beliefs, social learning, agents 'resistance, agents 'probability to invest, agents 'inertia to invest | ATOM [29], [78] |
| Public acceptance and opposition, and public participation and ownership | Storyline, scenario, and input parameter | - Scenarios: scenarios modelled with BSAM and MEMO (CGE)based on quantification of implementations risks identified by stakeholders (fuzzy cognitive map); BSAM used especially for the prosumer influence (also energy communities) | BSAM [79] |
| | Discussion of model output | - Analyse output from BSAM and CGE to assess the micro-economic consequences, e.g. economic consequences of the prosuming-based part of the transition, (BSAM) of macro-socioeconomic consequences, e.g. social risks, employment, (MEMO) | BSAM [79] |

*ATOM*

We find that the studies of ATOM address different social aspects in input parameters and the simulation process. The authors use ATOM to simulate the technology adoption of PV and they quantify behavioural uncertainty of consumers regarding the decision-making criteria and agents' preferences [29]. The model considers a variety of "intertwined factors" (social, market-related, and technological) and "correlates the adoption decision with its value for [the consumers]" [29]. The social parameters included in ATOM are agents' initial beliefs, resistance, probability to invest and inertia to invest, as well as social learning [78]. ATOM consists of three so-called modules to assess agents' behaviour and preferences [66], [78]: The first module defines the key set of the parameters and the calibration process for the quantification of behavioural uncertainty of the agents based on historical data and observations by specifying the appropriate ranges of the values. The second module is a sensitivity analysis to quantify uncertainties related to “characteristics and the decision-making criteria of the agents”. The third module encompasses the scenario analysis of different policy schemes to study and simulate the behaviour under consideration of the socioeconomic and geographic context. Furthermore, Michas et al. [78] apply ATOM in a participatory transdisciplinary way with the models STEEM (statistical approximation-based model emulator) and AIM (adaptive policymaking model). They explore the development of PV and dynamic adaptive policy pathways in Greece, which also allows them to consider interactions between the agents and policy context.

*BSAM*

In BSAM, the authors include ‘public acceptance and opposition’ and ‘public participation and ownership’ in scenarios and in the discussion of the model output [79]. In contrast to ATOM, BSAM is a power sector model that focuses on the expected behaviour of power generators, and simulates power bidding and investment decisions [79]. Nikas et al. [79] use BSAM and MEMO, a CGE model, to analyse barriers to and consequences of a solar-based energy transition in Greece. BSAM assesses the micro-economic consequences and economic consequences of prosuming, and MEMO explores the macro-socioeconomic consequences and social risks, for example on employment. To capture uncertainty of the transition, they engage stakeholders in a participatory scenario definition process to assess risks and dynamics. They use the method fuzzy cognitive mapping to quantify the risks and dynamics (ibid).

## 4.4 Computable general equilibrium models

We find that all three CGE models of openENTRANCE and SENTINEL − REMES, EXIOMOD 2.0, and WEGDYN (see **Table A 5**) − consider the social aspects ‘behaviour and lifestyle’ and ‘heterogeneity of actors’ in the input parameters and the simulation process. **Table 5** presents the findings of the integration of social factors in CGE models.

**Table 5**
Representation of social factors in CGE models analysed.

| Social aspect | Potential of Integration | Description of the integration into models | Model and publications |
|---|---|---|---|
| Behaviour and lifestyle | Storyline, scenario, and input parameter | - Input parameter: Social Accounting Matrix SAM: includes preferences of consumers (and producers) for local, regional, and international products<br>- Input parameter: household data (income- and educational/skill-levels and differences between urban and rural areas, labour) to capture their heterogeneity<br>- Scenarios based on risk clusters identified by stakeholders including the cluster consumer/acceptance with social justice and behavioural change risks | REMES [80]<br>WEGDYN [81] |
| | Optimisation/ simulation process | - Regionally-differentiated analysis of households income groups and degree of centralisation of households and industry, and incorporates formulations that examines the relation between wages and unemployment rate for low-, medium, and highly-educated workers | REMES [80] |

| | | | |
|---|---|---|---|
| Behaviour and lifestyle, and heterogeneity of actors | Storyline, scenario, and input parameter | - Linking of a CGE, IAM, and ABM model to incorporate micro-level dynamics and behavioural aspects into the CGE model (and IAM) | EXIOMOD 2.0 [27] |

*REMES*

The model application of REMES reflects the social factor 'behaviour and lifestyle' in the input parameters and the simulation process step. Johansen et al. [80] apply REMES to explore the economic effects, particular the potential dividends, of a climate and energy tax reform in Norway. For this purpose, they consider four scenarios based on different assumptions about the income recycling scheme of the tax (transferred back to households or payroll tax reduction) and ways of labour market clearing (perfect or imperfect[8]). The Social Accounting Matrix (SAM)[9] database serves as a base for the input parameters that includes empirical data about the preferences of consumers (and producers) for local regional and international products and consumption of products that have a "repercussion in incomes, prices, and activity level" [80]. Furthermore, the modellers use household data, allowing to make assumptions about the heterogeneity of households, income- and educational/skill-level in different urban and rural areas, and labour rates. They analyse the effect on low-income households regarding underlying model assumptions and the macroeconomic scope of the model.

*EXIOMOD 2.0*

We find that Belete et al. [27] integrate 'behaviour and lifestyle' as well as 'heterogeneity of actors' as input parameters through linking EXIOMOD 2.0 with other models. They link the ABM BENCH[10], IAM GCAM[11], and EXIOMOD with the aim to provide the opportunity to include direct feedbacks between individual behavioural changes and general changes in market shares, and to analyse if policies have any effect on household consumptions. For example, EXIOMOD 2.0 outputs (e.g. household income, energy consumption data) are used as input data for BENCH in order to generate more insights into micro-level dynamics and impacts of individual decisions.

*WEGDYN*

The social factor 'behaviour and lifestyle' is considered in the scenario development using WEGDYN [81]. Bachner et al. [81] develop transition pathways of the iron and steel, and electricity sector in Austria and assess pathway risks in a transdisciplinary, co-productive process with diverse stakeholders. For this purpose, they use different methods of stakeholder engagement: bilateral calls, semi-structured

[8] Perfect: flexible wages, no unemployment; imperfect: rigid wages, unemployment

[9] A Social Accounting Matrix (SAM) is comprehensive and economy-wide database that records data about transactions between economic agents in a specific economy for a specific period of time and is used as a standard database for economy modelling (CGE models) [85].

[10] Behavioural change in ENergy Consumption of Households (BENCH) is an agent-based energy market model to analyse the cumulative impacts on individual behavioural changes with regard to impacts of behavioural biases, energy use, and demand side policies on regional energy targets [27].

[11] Global Change Analysis Model (GCAM) is a global dynamic-recursive integrated assessment model that represents the behaviour of, and interactions between the energy, water, agriculture and land use, the economy, and the climate system and analyse climate change mitigation policies [27].

interviews, a survey, and two workshops. The stakeholders identified so-called risk clusters followed by a prioritisation that serves as basis for the scenario development. The risk clusters include aspects like consumer and acceptance and consider risks such as a “play-off between climate mitigation and social justice” and the implications of neglecting behavioural change. The risk clusters are used for the quantitative scenario analysis of economy-wide feedbacks of the transition pathways with WEGDYN, such as changes in employment. In the output discussion, Bachner et al. [81] address that ABMs and micro-scale models could be used to capture more implementation risks, as the analysis of more detailed risks was beyond the scope of the model study and would also require the involvement of other disciplines, such as political science.

# 5 Discussion

Our findings show that almost half of the investigated modelling tools integrate social aspects to different extends in their model applications. Table 6 synthesis our results of what social aspects are how integrated in what model type. We find that specifically ABMs are well able to represent social aspects, but also find that ESM, IAM and CGE modelling teams incorporate specifically aspects of behaviour and lifestyle and partially of public acceptance and opposition. On the one hand, this clearly shows that modellers make attempts to integrate social aspects of the energy transition to their primarily techno-economic modelling approach. Hence, these modelling teams actively contribute to meet the needs by modellers and stakeholders for a better integration of social aspects in energy models (see survey at the EMP-E 2020 [82], and other paper of the SI by Süsser et al.). On the other hand, this also shows that modelling teams must further advance in representing important social drivers and constraints the energy transition.

**Table 6**
Summary of representation of social aspects in the analysed models.

| Social aspect | Potential of Integration | Model type | | | |
|---|---|---|---|---|---|
| | | ESM | IAM | ABM | CGE |
| Behaviour and lifestyle | Storyline, scenario, and input parameter | x | x | x | x |
| | Optimisation/ Simulation process | x | | x | x |
| | Discussion of model output | x | x | | |
| Heterogeneity of actors | Storyline, scenario, and input parameter | | | x | x |
| | Optimisation/ Simulation process | | | x | |
| | Discussion of model output | | | | |
| Public acceptance and opposition | Storyline, scenario, and input parameter | x | | x | |
| | Optimisation/ Simulation process | | | | |
| | Discussion of model output | x | | x | |
| Public participation and ownership | Storyline, scenario, and input parameter | | | x | |
| | Optimisation/ Simulation process | | | x | |
| | Discussion of model output | | | x | |
| Transformation dynamics | Storyline, scenario, and input parameter | | | | |
| | Optimisation/ Simulation process | | | | |
| | Discussion of model output | | | | |

We observe that most model applications address socio-economic aspects that are easily quantifiable, e.g. ex-post analysis of employment number or adjustment of input parameters to account for social acceptance and opposition. Whereas actor heterogeneity is only addressed by ABMs due to difficulty to represent different actor groups and their interactions in the other model types, transformation dynamics are not represented at all as this involves, among other things, the modelling of complex systems, which goes beyond the horizon of the models analysed [23]. Nevertheless, we agree with Pfenninger et al. [22] that modellers should avoid to model only what is easily quantifiable, and instead look for new approaches to better quantify social aspects and dynamics. However, it is apparent that it remains a key challenge how qualitative narratives can be quantified into input assumptions and scenarios due to methodological uncertainties and missing profound, empirical data. Here modelling teams will be ahead that take up these challenges and build socially more robust models.

Our analysis shows that energy modellers integrate social aspects rather ad-hoc and "on top" of the existing model. This is particularly done in qualitative storylines, but also through adjustments in scenarios and input parameters. This might be not surprising as this form of integration follows a "softer" bridging or iterating approach, and thus, not demands a restructuring of the simulation or optimisation process. In fact, incorporating social aspects would add complexity to models and a super-integration of social sciences in energy models may be unlikely [19] and not desirable. However, if the modelling exercises and the drawn implications of the model results ignore social aspects, this could lead to model results that are far off reality and could therefore jeopardise the usefulness of models especially for decision-makers. Adding to this, we find that all of the analysed models are dominated by a techno-economic modelling approach, meaning that they aim to reduce the overall system costs. But the "least costs future" might be not the one most desirable by the society. Lombardi et al. [58] and Tröndle et al. [60] present recent approaches going beyond single cost minimised electricity system designs, better balancing techno-economic feasibility with societal impacts and political goals in energy planning within the modelling framework Calliope.

We see three different ways to advance the integration of social aspects in energy models. First, model advancements are needed that go beyond the representation of social factors as exogenous assumptions, to model energy transitions that better incorporate social dynamics and change. This requires modellers to engage deeply with the requirements of integrating social aspects and to be open to alternative ways of modelling. Modellers must be willing to break up the modelling structure and simulation and optimisation process to reflect behaviour of different actors accordingly. This includes exploring alternative formulations of equations to better reflect societal dynamics in the mathematical process, but also adding additional modules or features to the existing model. These modules can complement the existing model, e.g. by capturing demand behaviour or run an employment analysis that is used as a constraint for the calculation to find energy pathways. Furthermore, increasing regional accuracy and allowing the ability to incorporate regional specifics into models, as well as including detailed household configurations could advance the representation of the social dimension (see also Köhler et al. [23] and De Cian et al. [25]). Alternatively, new models should be development that are designed to capture social factors ideally as open-source projects to include a broad modelling community and to increase transparency about the model and its results. The processes need to be co-designed with social scientist to discuss what is required for the integration. In this way, it can be ensured that the requirements for the integration of the social aspects are met. We already find inspiration from Trutnevyte et al. [21] for an elaboration of this integration strategy and from the BLUE model of Li and Strachan [83], which accounts for heterogeneity, consistency, and co-evolution of societal and political drivers.

Second, worlds of modellers and social scientist must move closer together in the framework of interdisciplinary, if not even transdisciplinary, research projects. Our analysis shows that studies lack interdisciplinary collaborations between modellers and social scientists and integrate hardly any insights from social science (e.g. theories.) in the modelling – except Hof et al. [74] and van Sluisveld et al. [28]. As social science and energy modelling have epistemic and methodological differences [18], it appears necessary to increase the involvement of social and behavioural scientists in model developments. However, there are two sides to every coin: Modellers must be open to work with researchers from other fields, whereas social scientists must conduct research that is better tailored to the modelling work. By taking both modellers and users into duty, both could advance their understanding of the other discipline and dynamics of the energy transition, collect new empirical data, and explore ways of how social aspects should be integrated. For this, the collaboration between modellers and social scientists, as well as other stakeholders, should happen through the whole modelling process: Starting from defining the research questions, the theoretical and empirical foundation, the input parameters to discussing the societal implications of the modelling results. To expand inter- and transdisciplinary research, decision-makers and funding bodies must also recognise the research demand and provide funding for such projects. This would accelerate the development of more transparent and transdisciplinary modelling tools and approaches and data that could support decision-makers in answering the social and political questions they are faced with. A better understanding of all dimensions of the energy transitions, its developments, interactions and dynamics is imperative to support decision-makers to enable a "just transition" in the sense of the Green New Deal [1].

Third, each model and model type has different capabilities to represent social aspects and hence, there are limits to what degree such aspects can be integrated [23]. It is clear from our results that none of the models has integrated all social aspects in all modelling steps. To encounter the limitations of single models in representing social factors, the linking of different models and model types can contribute to advance the understanding of social and behavioural aspects. We found that some modelling exercises already go this way. For example, the linking of an ABM and an ESM, IAM, or CGE presents the opportunity to provide behavioural insights and account for actor heterogeneity in the latter model types (see EXIOMOD 2.0 and BSAM). Even though, we believe that ABMs provide the highest potential for a holistic integration of social aspects, e.g., due to the ability to capture behaviour dynamics and interaction of agents, ABMs can also benefit from this, as they are often restricted to micro-level dynamics in specific places and lack the macroeconomic view of for example ESMs or IAMs. Thus, linking ABMs with other model types offers a broader scope of examination. For example, De Cian et al. [25] propose further research to enhance actor and institutions representations by linking ABMs and IAMs to develop agent-based IAMS. Furthermore, we call for more studies that couple CGE models with ABMs, IAMs, or ESM, as we find that this can enhance the macroeconomic perspective of CGE models by including the assessment of social factors at the micro level. Therefore, modellers should work together to leverage the full potential of each model's capability to incorporate social aspects by linking models and different model types. The process may include also further model modifications to be able to link and incorporate the different model design styles, which opens up new possibilities due to the distinct methodological approaches of the models.

We also recognise that our research has some limitations. In our study, we focused on analysing open-source energy models from the H2020 projects SENTINEL and openENTRANCE, which allowed us to include in our analysis various models and model types. We have complemented the analysis with a literature review, also to discuss our findings and compare them with recent studies using other models. Nevertheless, we may have missed important modelling approaches in our analysis. Another limitation is the focus on the integration of social aspects in current model approaches, based on the scientific publications where the models are applied. This could exclude or neglect theoretical features and ways of applying the models as it focuses on existing linkages with social aspects. Thus, our results might underestimate the degree of integration of social factors in the analysed energy models. We also acknowledge that our generalisations may not be accurate for all models of a certain model type. Furthermore, the analysed papers vary in the degree in terms of how detailed the model description is, which can influence our results. For more recent models, there is no detailed model description or model documentation (e.g., FRESH:COM, DESTinEE), while for more established models (e.g. IMAGE) a detailed model documentation exists. We acknowledge that the inclusion of the model description could provide more insights on the input data and structure of the model while a focus on applications may provide more input on the model output discussion. Moreover, the limitations of a maximum of five publications per model can affect the results. For some models we had to select which publications we include in our analysis, while for others we "only" found one scientific publications. We are aware that these limitations could skew the results and make a comparison of the models more challenging. However, we acknowledged this in our evaluation by explicitly focusing on applications and considering key characteristics of the models (e.g. input parameter, output parameter) and carefully scrutinising the implications we draw from the results.

Thus, our results represent the minimum status quo of what and how social aspects are integrated in energy models. With this, we provide an appropriate starting point for a dialogue for model improvements and for defining future research needs in the field of linking social science and energy modelling. Moreover, for modellers, social scientists, and decision-makers it is important to know what influence social factors have on the model outcomes. Therefore, we call for further research that explores the influence of social aspects on the model results, for example by conducting case studies with different social aspects and sensitivities, to understand better their effect on the energy transition.

# 6 Conclusion

Computer-based models are a popular tool to analyse future pathways of the energy transition and is widely used by decision-makers. However, energy modelling focuses mostly on techno-economic factors and do not represent social aspects in-depth. Particularly in the light of a just transition, the role of non-technical drivers and constraints of the energy transition becomes more prominent and hence, the inclusion of social aspects and social science in energy models is pivotal and can enhance modelling exercises.

Our results show that 13 out of 23 modelling tools in the H2020 projects SENTINEL and openENTRANCE account for social aspects in the modelling publications. When it comes to 'what' social aspects are integrated, we find that the energy models mainly incorporate behaviour and lifestyle, as well as public acceptance and opposition. Only the agent-based models consider partially the heterogeneity of actors and address public participation and ownership. When it comes to the 'how' of integrating those social aspects, the results show that modellers mainly use exogenous assumptions to integrate social factors, and thus, there is much potential to improve the integration of social aspects in the optimisation and simulation processes and to strengthen their representation in output and discussion. The linking of models should be further advanced to encounter the limitations of specific models and model types. Last, modelling mostly remains a disciplinary approach and there is no involvement of social sciences in study design.

We conclude that the integration of social aspects in energy models is far from being standard and common practice, but approaches exist on how to model behavioural and social aspects of the energy transition. Thus, for a more comprehensive consideration of social aspects, we emphasise that modellers must incorporate social aspects right from the start in the modelling design as we find most gaps of integrating social aspects in the simulation or optimisation process. Alternatively, modellers must be open to break existing modelling narratives within model improvements in close collaboration with social scientists. Our findings suggest that more interdisciplinary and transdisciplinary modelling projects are essential to better link energy modelling and social science. If models can depict the social realities of the energy transition better, they can become much more important and sound support tools for the transition to a climate-neutral energy system in Europe.

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Pre-print for Energy, Volume 239, Part A, 2022, 121706, ISSN 0360-5442, https://doi.org/10.1016/j.energy.2021.121706.

# Appendix

((short model name) AND (long model name) AND (model))
**AND**
((Acceptance) OR (demand) OR (controversy) OR (opposition) OR (attitudes) OR (value) OR (behavior*) OR (behaviour*) OR (consum*) OR (household*) OR (lifestyle) OR (sufficiency) OR (decision*) OR (heterogeneity) OR (heterogeneous) OR (individual*) OR (actor*) OR (participation) OR (ownership) OR (citizen) OR ("just transition") OR (access) OR (poverty) OR (wealth) OR (equality) OR (worker) OR (social*) OR (socio*) OR (society) OR (societal) OR (personal) OR (people) OR (incumben*) OR (population) OR (cultur*) OR (income) OR (agency) OR (agent) OR (prosumer) OR (belief*) OR (habit) OR (choice) OR (motivation) OR (communit*) OR (responsibl*) OR (employment) OR (job*) OR (justice) OR (equity) OR (labor) OR (labour) OR (educat*) OR (empower) OR (trust) OR (engage*) OR (preferences) OR (resistance))
**AND**
((energy) OR (power) OR (heat) OR (transport) OR (climate) OR (electricity))

**Figure A 1:** Search string

**Table A 1**
Overview optimisation energy system models.

| Model name | Short description | Input parameter | Output parameter | Optimisation/ Simulation | Publication |
|---|---|---|---|---|---|
| **Calliope** | - Calliope is an energy systems linear optimisation framework, with a focus on flexibility, high spatial and temporal resolution, the ability to execute many runs based on the same base model, and a clear separation of framework (code) and model (data) | - Time series data, e.g. on generation potentials, demands<br>- Capacity constraints per model location<br>Connections between model locations (e.g. electricity transmission grid)<br>- Energy technology definitions such as cost and performance characteristics | - Capacities of each technology at each location<br>Operational decisions for each technology, location and time step<br>- Fixed costs, variable operational costs, levelized costs<br>- Capacity factors | - User-dependent, including financial cost, CO2, and water consumption | [56], [58], [59], [61], [60] |
| **GENeSYS-MOD** | - Global Energy System Model (GENeSYS-MOD)<br>- The model endogenously determines cost-optimal investment paths into conventional and renewable energy generation, different storage technologies, and some infrastructure investments until 2050 | - Technologies, their costs and efficiency, availability<br>- Demands and residual capacity<br>- Fossil fuel prices<br>- Political boundaries | - Total costs (discounted sum of all costs in all regions and all time periods, development of those over long time horizon)<br>- Generation and shares of technologies<br>- Trade | - Calculates the lowest-cost-solutions for the transition pathway towards largely decarbonized energy systems | [62], [63], [64], [65] |
| **FRESH:COM** | - FaiR Energy Sharing in local COMmunities (FRESH:COM)<br>- The model is a multi-objective optimisation tool for optimal local renewable technology portfolio design. | - PV generation and demand of prosumers<br>- Max. Capacity of batteries and discharging power<br>- Efficiency of batteries<br>- Willingness-to-pay of prosumers<br>- Prices: average spot market electricity price, retailer´s electricity price<br>- Marginal emissions from the grid | - Purchase of prosumers from the grid and from prosumers<br>- Sales from prosumers to the grid<br>- Charging, discharging, and state of charge of prosumers battery | - Objective: maximize social welfare of a community | [57] |

**Table A 2**
Overview simulation energy system models.

| Model name | Short description | Input parameter | Output parameter | Optimisation/ Simulation | Publication |
|---|---|---|---|---|---|
| **DESTinEE** | - Demand for Energy Services, Supply and Transmission in EuropE (DESTinEE)<br>- The model is designed to test assumptions about the technical requirements for energy transport (particularly for electricity), and the scale of the economic challenge to develop the necessary infrastructure. | - energy demands, service demands and technology parameters<br>- Assumptions about the mix of technologies and technical efficiency<br>- installed capacity of different types of power station in 2050 for each country<br>- the capacity of transmission interconnectors between regions | - Project annual energy demands at country-level forwards to 2050, Synthesise hourly profiles for electricity demand in 2010 and 2050, Simulate the least-cost generation and transmission of electricity around the continent | - Costs, welfare, carbon emissions, fuel mixes | [66] |
| **DREEM** | - Dynamic high-Resolution dEmand-sidE Management (DREEM)<br>- DREEM serves as an entry point in Demand-Side Management modelling in the building sector, by expanding the computational capabilities of existing Building Energy System models to assess the benefits and limitations of demand-flexibility, primarily for consumers, and for other power actors involved. | - Parameters for buildings: Demand-Response, activity profiles, occupancy profiles, HVAC control settings, weather-climate data | - Net building electrical demand, benefits for consumers, aggregated results for n buildings, urban energy system analysis | - Modular and therefore user dependant analysis of building energy and control systems by using the open modelling library "buildings" | [67] |
| **EnergyPLAN** | - EnergyPLAN is a simulation energy model that explores “national energy planning strategies on the basis of technical and economic analyses of the consequences of different national energy systems and investments” [84]. | - Detailed hourly distributions such as heating, cooling and electricity demand (exogenous variable in the tool.)<br>- Technology efficiency, specific $CO_2$ emissions or fuel cost | - Overall running and capital costs of a system<br>- Environmental impact in terms of $CO_2$ emissions, including other key performance parameters such as share of renewable energy sources in primary energy supply, etc. | - Method is based on energy and masses flow balancing between different sectors on an hourly basis for the whole year. | [72], [68], [69], [70], [71] |

**Table A 3**
Overview integrated assessment models.

| Model name | Short description | Input parameter | Output parameter | Optimisation/ Simulation | Publication |
|---|---|---|---|---|---|
| **IMAGE** | - Integrated Model to Assess the Global Environment (IMAGE)<br>- IMAGE is an integrated modelling framework of interacting human and natural systems. The model framework is suited to large scale (mostly global) and long-term (up to the year 2100) assessments of interactions between human development and the natural environment, and integrates a range of sectors, ecosystems and indicators. | - Policy responses (climate policy, air pollution and energy policies, land and biodiversity policies), drivers (population, economy, policies, technology, lifestyle, resources);<br>- Macro-economic scenarios and exogenous assumptions on technology development and changes, preference levels, lifestyle, population, restrictions to fuel trade, and policies | - Impacts (climate impacts, agricultural impacts, water stress, terrestrial biodiversity, aquatic biodiversity, flood risks, land degradation, ecosystem services, human development) | - The impacts of human activities on the natural systems and natural resources are assessed and how such impacts hamper the provision of ecosystem services to sustain human development | [28], [73], [74] |
| **MESSAGEix_ GLOBIOM** | - The MESSAGEix_GLOBIOM framework soft links the energy model MESSAGEix and the land use model GLOBIOM, and is an economic-environment-engineering model that is used to for energy system planning, scenario development, and energy policy analysis (IIASA IAM framework) | - Socio-economic development<br>- energy demand, use, technologies, conversion<br>- macro-economic developments<br>- Land-use, water<br>- Emission factors | - Estimates of technology-specific multisector response strategies for specific climate stabilization targets<br>- Least-cost portfolio of mitigation technologies, with the choice of the individual mitigation options across regions, fuels, and sectors driven by the relative economics of the reduction measures | - Linear programming energy-economy-environment-engineering (4E) model | [75], [76], [77] |

Pre-print for Energy, Volume 239, Part A, 2022, 121706, ISSN 0360-5442, https://doi.org/10.1016/j.energy.2021.121706.

**Table A 4**
Overview agent-based models.

| Model name | Short description | Input parameter | Output parameter | Optimisation/ Simulation | Publication |
|---|---|---|---|---|---|
| **ATOM** | - Agent-based Technology adOption Model (ATOM)<br>- ATOM is an agent-based model that, apart from simulating the expected effectiveness of technology adoption under policy schemes of interest, allows to consider and explicitly quantify uncertainties that are related to agents' preferences and decision-making criteria (i.e., behavioural uncertainty) | - Market-related parameter<br>- Specification of the key parameters under the geographic and socio-economic context (historical data)<br>- Initial beliefs, social learning, resistance toward PV investment, probability of investing | - Technology adaption scenarios | - Consists of three main modelling modules calibration, sensitivity analysis (SA), and scenario analysis | [29], [78] |
| **BSAM** | - Business Strategy Assessment Model (BSAM)<br>- BSAM is an agent-based simulation model which simulates the Day-Ahead Scheduling (DAS) of wholesale electricity markets | - Constantly changing historical data and projections containing the electricity demand, RES generation, hydro generation, electricity import prices, and fuel prices<br>- No-/slowly-changing data containing technical and economic characteristics of thermal resources, interconnection capacities with neighbouring countries, market-related data<br>- RES subsidies | - In an hourly resolution the system marginal price (SMP)<br>- The total electricity costs when subsidies are considered, the electricity mix, the generation schedule of all resources, the profit/loss of each generator, and the level of curtailment applied to RES generation | - Simulates the Day-Ahead Scheduling (DAS) problem | [79] |

**Table A 5**
Overview general computable equilibrium models.

| Model name | Short description | Input parameter | Output parameter | Optimisation/ Simulation | Publication |
|---|---|---|---|---|---|
| **REMES** | - Regional equilibrium model for Norway with focus on the energy system (REMES)<br>- REMES represents the Norwegian economy with a particular focus on the energy system. REMES is used to study the effects of macroeconomic policies on the Norwegian economy and aims to improve the understanding of regional differences, needs, and barriers towards a more sustainable energy system [68]. | - Social Accounting Matrix (SAM), describing all the monetary flows between the different agents and sectors in a given base year | - Evolution of value added in different sectors and regions, the composition value for inputs and outputs for each sector and the monetary flows between different actors and sectors in the economy | - Computing the effects of counterfactual policies, which assume the role of what-if analyses, simulating the state of the economy at the end of the considered horizon | [80] |
| **EXIOMOD 2.0** | - EXtended Input-Output MODel (EXIOMOD 2.0)<br>- EXIMOD 2.0 considers the interaction and feedbacks between supply and demand of the economy (analysis of environmental impacts, energy, or transport systems and interactions and feedbacks between supply and demand of the economy). As a multisector model, it accounts for the economic dependency between sectors [69].<br>- The model assumes cost-minimizing behaviour of producers and households´ demands are based on optimising behaviour. | - EXIOBASE is the underlying database<br>- Various modules: land use, carbon pricing, material use etc. | - separate volume and price effects | - Link between the economic activities of various agents (sectors, consumers) and the use of a large number of resources (energy, mineral, biomass, land, water) and negative externalities (greenhouse gases, wastes)<br>- | [27] |

| | | | | | |
|---|---|---|---|---|---|
| **WEGDYN** | - WEGDYN is a global multi-regional multi-sectoral model, which is able to assess the economy-wide and indirect effects of economic (e.g. sectoral) system interventions such as policies or technological changes. The model is separated into different production sectors and demand agents. | - different crude steel production technologies<br>- different electricity generation technologies<br>- macroeconomic development according to SSP | - electricity mix, weighted average costs of capital, trade, electricity supply price, gross domestic product | - Supply-side constrained, meaning that capacities (capital, labor6 and resource endowments) are fully utilized, constraining macroeconomic expansion through scarcity | [81] |