Energy Research & Social Science 92 (2022) 102775

Contents lists available at ScienceDirect

Energy Research & Social Science

journal homepage: www.elsevier.com/locate/erss

Original research article

Why energy models should integrate social and environmental factors: Assessing user needs, omission impacts, and real-word accuracy in the European Union

Diana Süsser [a], Nick Martin [b], Vassilis Stavrakas [c], Hannes Gaschnig [d], Laura Talens-Peiró [b], Alexandros Flamos [c], Cristina Madrid-López [b,*], Johan Lilliestam [a,e]

[a] Institute for Advanced Sustainability Studies, Berliner Straße 130, 14467 Potsdam, Germany
[b] SosteniPrA Research Group, Institut de Ciència i Tecnologia Ambientals, Universitat Autònoma de Barcelona (ICTA-UAB), Z Building, Campus UAB, 08193 Barcelona, Spain
[c] Technoeconomics of Energy Systems laboratory (TEESlab), Department of Industrial Management and Technology, University of Piraeus, Karaoli & Dimitriou 80, Piraeus 18534, Greece
[d] acatech - National Academy of Science and Engineering, Karolinenplatz 4, 80333 München, Germany
[e] University of Potsdam, Faculty of Economics and Social Sciences, August-Bebel-Straße 89, 14482 Potsdam, Germany

ARTICLE INFO

Keywords:
Energy modelling
Energy planning
Energy policy
Ecological crisis
Social acceptance
Environmental impacts

ABSTRACT

Energy models are used to inform and support decisions within the transition to climate neutrality. In recent years, such models have been criticised for being overly techno-centred and ignoring environmental and social factors of the energy transition. Here, we explore and illustrate the impact of ignoring such factors by comparing model results to model user needs and real-world observations. We firstly identify concrete user needs for better representation of environmental and social factors in energy modelling via interviews, a survey and a workshop. Secondly, we explore and illustrate the effects of omitting non-techno-economic factors in modelling by contrasting policy-targeted scenarios with reality in four EU case study examples. We show that by neglecting environmental and social factors, models risk generating overly optimistic and potentially misleading results, for example by suggesting transition speeds far exceeding any speeds observed, or pathways facing hard-to-overcome resource constraints. As such, modelled energy transition pathways that ignore such factors may be neither desirable nor feasible from an environmental and social perspective, and scenarios may be irrelevant in practice. Finally, we discuss a sample of recent energy modelling innovations and call for continued and increased efforts for improved approaches that better represent environmental and social factors in energy modelling and increase the relevance of energy models for informing policymaking.

1. Introduction

The European Union (EU) has set the goal of transitioning to a modern, resource-efficient, and competitive European economy, with the overarching objective of *climate neutrality* by 2050 [1]. The energy transition is crucial to this plan and is a cross-societal process, including both socio-technical and socio-ecological drivers and constraints that underlie the required system changes [2]. EU energy policy strategies under the "European Green Deal" emphasise the need to develop energy systems that provide secure, affordable and clean energy, reduce environmental impacts, and enable citizens to participate and benefit [3,4]. Nevertheless, most visions and policy goals concern the technological optimisation and economic costs or benefits of the energy transition and do not fully address multiple dimensions of truly sustainable pathways, including regional environmental impacts, material requirements of energy technologies, diverging normative views or citizen preferences. This imbalance, where energy policy is determined at the expense of factors outside the techno-economic realm, is also reflected in current energy modelling practices.

Most energy models used to inform the energy transition ignore factors other than techno-economic ones, generally seeking cost-optimal futures. They rarely consider environmental factors beyond greenhouse gas (GHG) emissions. For example, integrated assessment models (IAMs) typically only include simplified emission and land-use assumptions [5].

* Corresponding author.
E-mail address: cristina.madrid@uab.cat (C. Madrid-López).

https://doi.org/10.1016/j.erss.2022.102775
Received 27 April 2022; Received in revised form 25 July 2022; Accepted 16 August 2022
Available online 20 September 2022

Modellers often entirely ignore social aspects, or only consider them as an exogenous narrative do be discussed “on top” of techno-economic findings, as a lens through which techno-economic scenarios can be discussed [6]. Nevertheless, there is growing recognition that environmental and social factors must be included in models [7,8]. As with present energy systems, future decarbonised energy systems will face environmental constraints such as raw material or water availability [9,10]. Presently, public opposition against energy infrastructure projects is halting transition progress in Europe and across the world [11]. Ignoring such factors risks producing mathematically elegant but politically irrelevant scenario results. At the same time, modellers are bound by model and computational capacities [12] and will only include factors that are easily quantifiable or do not challenge the disciplinary barriers of their respective modelling frameworks [13].

These challenges result in a gap between the information provided by energy models and the information needed by those who use the model results. Scholars have identified gaps related to the modelling of behavioural and lifestyle changes [14], specific policy challenges [15] and modelling of political or societal paradigm shifts [16]. Neglecting these factors may result in energy policy goals or implementation strategies that conflict with environmental policy [17], or undermine social goals unknowingly [18]. As a result, oversimplified models could fail to inform policymakers about the multiple dimensions crucial for a sustainable energy transition.

Here, we investigate concrete needs for better representation of environmental and social factors in energy modelling and explore the implications of current model shortcomings. In a recent study [19], it was shown that both model users and modellers see a need for improved representation of social and environmental aspects in modelling. Here, we advance the analysis by analyzing more deeply what concrete environmental and social factors users consider most important for better representation in energy models and by examining why these factors are important and illustrating their importance. We adopt a two-fold approach: first, we empirically identify and rank specific user modelling needs for environmental and social aspects through interviews, a survey and an online workshop with different model users. Second, we investigate and illustrate the magnitude of problems arising through the omission of central social and environmental factors through real-world case studies. We show that the impact of omitted social and environmental factors could be so large as to render results unfeasible and hence irrelevant, highlighting the necessity to consider non-technoeconomic factors as integral parts of energy models.

2. Background on environmental and social factors and energy modelling

A wealth of literature exists that addresses the different environmental and social factors that can drive or hinder energy transitions. Many studies investigate environmental impacts of renewable electricity production [20,21], storage [22], electric vehicles (EVs) [23], material dependency [24], or emissions [25]. Other authors investigate social issues of energy transitions, such as behaviour and lifestyle [26–28], public acceptance [29,30] and ownership [31,32]. Some studies also integrate both perspectives, by addressing environmental justice in energy and climate policy, for example [33,34]. Below, we describe and discuss the current state of the literature regarding environmental and social factors in the energy transition and in modelling.

2.1. Environmental implications of the energy transition

The reduction of carbon dioxide (CO_2) and other GHG emissions needed for mitigating climate change dominates the debate about environmental impacts in the energy sector [35], although policy decisions and models generally only depict the direct emissions during the final stages of energy production. Indirect emissions related to other stages of production life cycles – e.g., those related to extraction of raw materials, production, transportation, and installation of components, and the ongoing maintenance and eventual decommissioning of plants – are often not accounted for and remain “hidden” [36].

The need for raw materials is another issue that has gained increasing public and political attention as the ongoing production of many sustainable energy technologies – particularly wind turbines, solar photovoltaic (PV) cells, and lithium-ion batteries – require supplies of critical raw materials (CRMs) [37]. For example, Europe is 100 % import reliant on borates, lithium, and graphite for EV batteries, silicon metal for photovoltaic panels, niobium for permanent magnets in wind turbines, and a mix of diverse rare earth elements for EV batteries and permanent magnets [38]. China remains the dominant provider of processed materials and components [37,38]. Dependency on scarce raw material often leads to geopolitical clashes, “carbon leakage” [25,40,41], externalisation of impacts [42] or environmental dumping [43]. Greater adoption of material reuse and recycling could help to alleviate such pressures [44] and, therefore, strengthening the circular economy has become a key strategy within the EU [45].

Quantifying the impacts of energy infrastructure on land, water, and biodiversity is also gaining attention, particularly within the growing literature surrounding the water-energy-food nexus [46]. For example, impacts relating to land occupation have been identified for wind and solar installations [47,48], land-use impacts and water overexploitation are often linked to bioenergy [49], and biodiversity issues can be linked to hydropower, marine and geothermal energy [50]. Although some studies have investigated land-use for solar farms [51], onshore wind turbine siting remains the most prominent example of land-use conflicts regarding renewable energy technologies [52,53]. Finally, water requirements for different energy production options is gaining attention as southern and more arid countries seek to adopt cleaner technologies and general awareness of water availability issues grows [54].

Nevertheless, despite the importance of these aspects, most of the models used to inform energy policy are limited in their consideration of environmental factors. First, most accounting methods only consider direct emissions, and the indirect emissions and other impacts embodied within energy processes. Second, CRMs are generally not considered in any detail, particularly not in the large-scale models being used to inform overarching climate policy. Third, although land availability issues continue to be an issue in energy planning processes [55–59], it is generally only modelled as a constraining factor for technical potentials and societal or political preferences for present or future land use are largely ignored.

2.2. Social drivers and barriers to the energy transition

While environmental aspects are considered constraining factors to most transition options, social aspects can both accelerate *or* impede them [11]. Although the transition to renewable energy enjoys high public approval levels within the EU [60], concrete projects often face considerable opposition [11,61]. Issues typically relate to the increasing number of renewable energy plants and associated transmission infrastructure, conflicts arising from place attachment [62], planning and siting issues [63], visual and aesthetic impacts [64], land-use conflicts [65], biodiversity loss [66–68], and noise, or health concerns [69]. Accordingly, the social acceptance of strategies and projects is gaining importance as the transition accelerates towards 2030 and 2050 targets. This includes not only acceptance of technologies, but also of new end-use services or practices and lifestyles or cultural meanings of energy [70]. The effort to increase awareness and acceptance accompanies calls for comprehensive citizen participation and ownership [71–73] and research continues about the ways that local populations make choices about consumption and investments [74], and how social acceptance is formed. However, this knowledge is yet to be widely integrated into energy models.

The energy transition has given rise to a new generation of agents who take on the role of active producers, distributors, consumers, and sellers of renewable electricity, the so-called "prosumers." Citizens may become owners, eventually consuming their own electricity, or become part of community energy projects [75], potentially bringing local benefits, such as employment and increasing project acceptance [72]. Still, the advantages and mechanisms that allow citizens to participate in transition processes are also generally excluded from energy models.

Furthermore, many researchers have studied how norms, practices and culture shape energy behaviour [76] and how consumer behaviour and lifestyle affect climate change mitigation [77]. Despite the high environmental awareness among citizens in industrialised countries, behavioural changes and sufficiency-based lifestyles are still relatively uncommon for reasons such as lack of awareness, comfort, fear of loss, or exclusion [78]. In contrast, behavioural change is often seen not as a welfare loss but as a gain in wellbeing and satisfaction [79], as beneficial lifestyle innovation [80], and the "holy grail" of sustainability [81], particularly outside mainstream economics. Nevertheless, energy sufficiency remains a marginal strategy in energy policy documents compared to energy efficiency and renewable energy sources [82]. Many models, however, assume that lifestyle changes are happening and demand-side measures have gained increasing interest to initiate consumer behaviour.

As behaviour is strongly guided by routines, public policy plays a central role in adapting behaviour, including modifying consumption and investment choices [83] and in municipal renewable energy deployment [84]. For example, some EU member states, including Germany, Spain and Denmark, implemented feed-in laws in the 1990s, thus supporting the early adoption of renewable energy technologies by individuals and municipalities [85,86].

In any case, while current energy models rarely represent these social factors, different model types do offer some capabilities [6]. For example, more nuanced bottom-up modelling approaches, like agent-based models (ABMs), can address social barriers for solar PV adoption [32] or peer-to-peer energy trading in local communities [87], while demand models can address drivers and patterns of household energy consumption [28]. However, significant modelling gaps exist, especially when dealing with transition dynamics, e.g., speed of transformations and path dependencies [7], and socio-technical systems that captures agent heterogeneity, e.g., zero-energy communities [88].

3. Methods

To highlight the relevance of including social and environmental aspects in energy modelling, we build upon a previous, related study [89], where it was shown that, in general, environmental and social aspects are relevant to modellers and users of model results. Here, working with the same data, we further investigate what environmental and social factors of the energy transition are relevant for inclusion in energy models and perform a stakeholder-based ranking of importance. We then investigate case studies where models have ignored these central environmental and social factors and illustrate their importance by comparing them to real world developments. As depicted in Fig. 1, we completed both empirical and desk research. The empirical research was implemented within the context of the EU-funded Horizon 2020 project "Sustainable Energy Transitions Laboratory (SENTINEL)." As this work coincided with the COVID-19 pandemic, we conducted all stakeholder engagement activities in an online format, as was common practice in

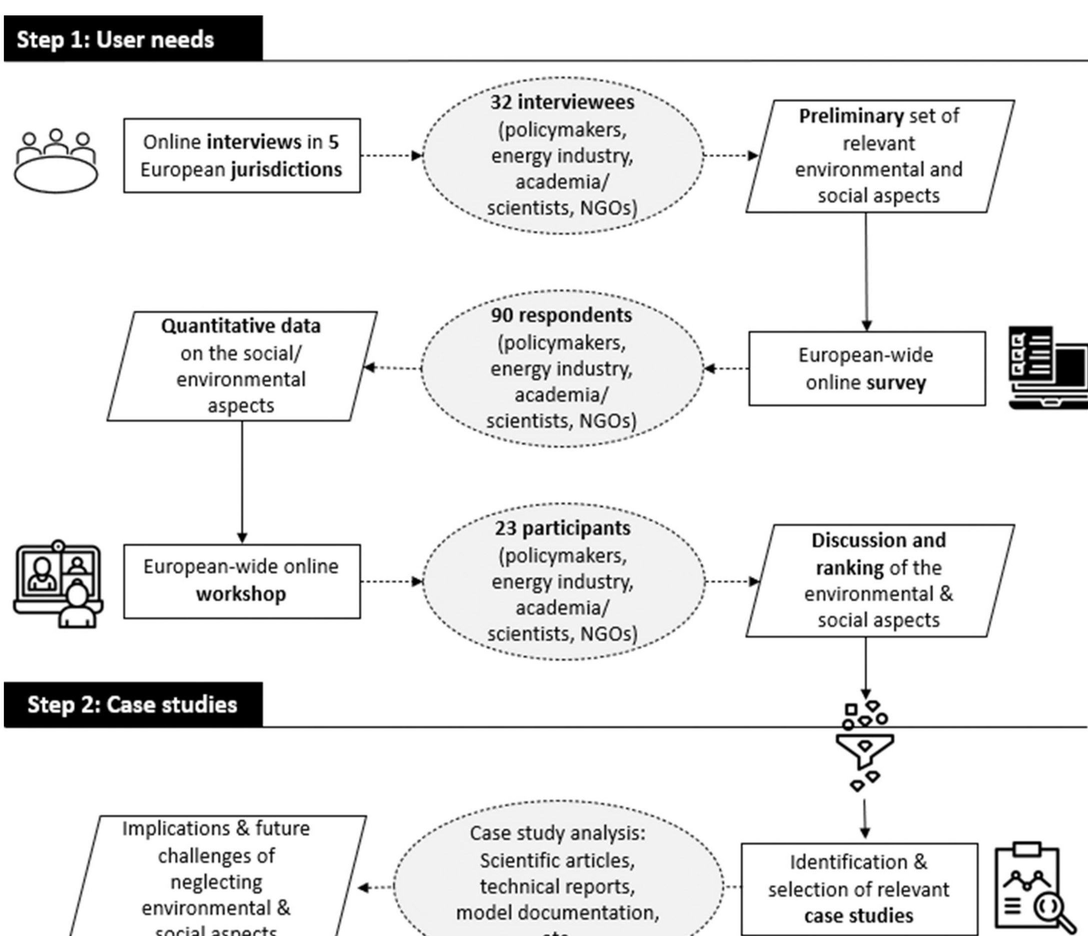

Fig. 1. Two-step approach employed within the study, consisting of empirical and desk research components.

the EU energy research community at the time [90].

3.1. User needs: identification and ranking

We conducted 32 interviews in five jurisdictions – the EU, Germany, Greece, Poland, and Sweden. This included four different stakeholder groups that participate in modelling-informed energy policymaking in Europe: scientists, non-governmental organisations (NGOs), energy industry experts and policymakers. The interviews were guided by a semi-structured guideline, were conducted in English, or in the national language of the jurisdiction, and all interviews were transcribed and anonymised after being recorded. More information is provided in the Appendix (Table A1).

Building on the interview findings, we performed a Europe-wide survey to obtain deeper insights about which social and environmental factors are important from a larger stakeholder sample. The survey was designed as a semi-quantitative online questionnaire and contained different question formats, from single and multiple choice to Likert-like scales and free-text boxes, depending on the variables to be addressed. The survey was distributed among national, European and international organisations, to representatives from politics, civil society, business/industry and research, via private and public online channels. We asked questions regarding what factors should be better represented by models and asked specific follow-up questions regarding environmental and social aspects. In all, we received a total of 90 completed questionnaires. Further information on the survey can be found in the Appendix (Table A1) and the questionnaire and anonymised aggregated data are available at Zenodo [91].

Finally, we discussed and ranked the environmental and social factors identified in a workshop with stakeholders from different EU member states. The workshop allowed us to discuss specific user needs in more detail and collect more data on the different aspects. We held one breakout session on modelling of environmental aspects and one on modelling of social aspects. For the social aspects, we integrated the ranking results from two live polls in two breakout sessions. For environmental aspects, attendants to two breakout sessions discussed and agreed a ranking. Accordingly, only integrated results are shown here. Furthermore, because only 25 stakeholders participated in the workshop, we did not distinguish between specific stakeholder groups. Further information on the workshop can be found in the Appendix (Table A1).

3.2. Case studies on omitting environmental and social factors in energy modelling

For the top-ranked user needs (Section 4.1), we identified and selected specific cases where energy system models have neglected environmental and social factors (Fig. 1). These cases illustrate the type and magnitude of problems on the relevance of model-informed policymaking that may arise when models ignore these factors. We subsequently selected four case studies in which model output and observed development are strongly misaligned because a critical social or environmental factor was ignored by the model, for different European contexts. For each case, we conducted a document analysis of modelling applications and compared these findings with real-world developments and policy targets. Our goal was not to demonstrate that models fail to predict the future, as this is not their aim; most models are used to explore possible (simplified) systems and investigate options and sensitivities. Rather, we illustrate the importance of environmental and social concerns within models so that deeper and more robust understandings of the mechanisms of transition pathways and more policy-relevant model advice can be obtained in the future.

4. Results

4.1. User needs on environmental and social aspects of the energy transition

Our findings suggest that model users want better integration of different environmental and social factors of the energy transition in models, particularly with respect to raw material demand/availability and natural impacts (environmental) and social acceptance, consumer behaviour and policy dynamics (social). Our results show that users prefer the explicit integration of social and environmental aspects over further improvements of techno-economic aspects: The workshop participants ranked “Impact on the environment and natural resources” highest, followed by policy impacts, social impacts and costs (see Appendix Fig. A1).The high-level results from the survey have been reported in [19,92]. Here, we present in more detail the environmental and social aspects model users see as particularly important, how they ranked those aspects and reasons provided for their relevance.

4.1.1. Environmental aspects

Our results identify raw material use and material circularity as central model user concerns. More than half of the survey respondents stated that they would like to see raw material demand integrated into energy models, followed by GHG emissions, air pollution, water usage and loss of biodiversity (see Fig. 2), although relevance varies strongly by user group. Energy industry and researchers tended to prioritise GHG emissions and air pollution, whereas NGOs and policymakers expressed greater concern about raw materials, water issues and biodiversity. One NGO representative underlined this by saying: *“Also, the whole environmental aspects, like the biodiversity aspect of wind energy... we can't achieve 100% renewables without having hundreds of gigawatts of offshore wind. That is going to be crucial, but you also have to do it in a sustainable way”* (EU_NGO#2).[1] Another interviewee added that *“It is a question of resource efficiency. The resources to reduce climate gases, but also that we need to use the resources we are having as efficient as possible – also if it's waste, we are using”* (Sweden_science#4).

In the interviews and at the workshop, methods to capture the full life cycle of energy technologies and infrastructures, and not only direct impacts, and the degree of externalisation of impacts that can be observed in the literature, were further central concerns. The relative importance of environmental aspects was also explored within the workshop. When asked to rank factors, participants identified four aspects of particular importance: (E1) Raw materials, (E2) Biodiversity, land use, and water use, (E3) Life-cycle perspective, and (E4) GHG emissions beyond CO_2 (Table 1). The inclusion of environmental aspects goes beyond the need to protect our ecosystems and natural resources. Indeed, the main reasons argued for the need of including environmental aspects were i) to support decision making processes, ii) to enable links to other models, policies, and strategies, and iii) to facilitate citizen empowerment and stakeholder engagement.

4.1.2. Social aspects

A high demand was also found for the better representation of social aspects in energy models. When asked to select aspects that require better integration, participants nominated three aspects most often: co-benefits of prosumerism and community energy, social drivers and barriers of innovation diffusion, and dynamics of social acceptance and individual attitudes (Fig. 3). Here again, different stakeholder groups differ in choice frequency. Social acceptance and individual attitudes were more often chosen by NGOs, whereas policymakers raised concern about the impacts of social issues on politics and policies more often than other users. Both NGOs and researchers agreed that benefits of

[1] We apply the interviewee referencing (jurisdiction_stakeholder group_interviewee number).

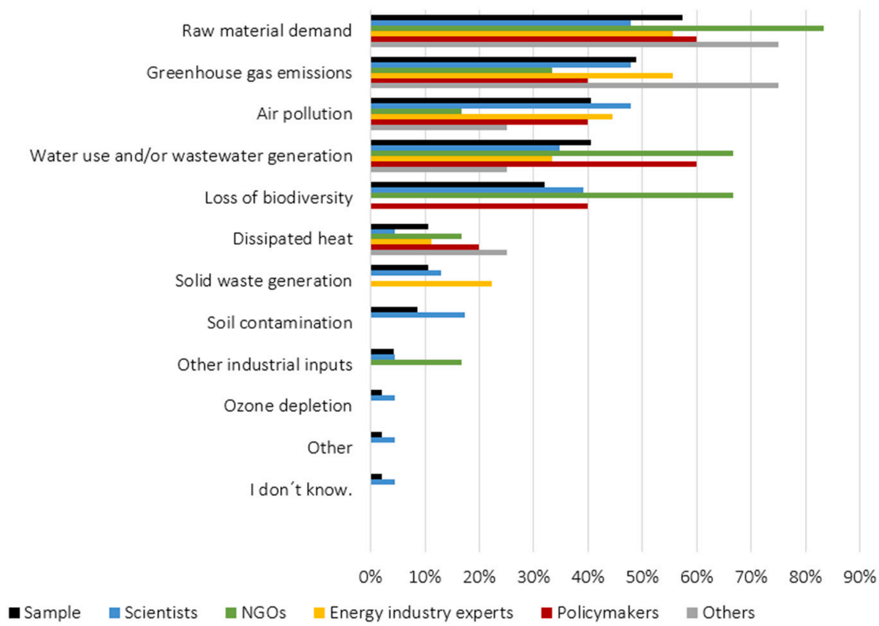

Fig. 2. Key environmental aspects identified by the user needs survey (choice frequency; up to three answers possible, voluntary question). Responses were obtained for the following question: "You stated that environmental, or resource-relevant issues should receive more attention by energy models. What environmental factors would you like to see integrated into energy models more in the future?", N = 47.

Table 1
Ranking of environmental factors to be included in energy models.

Ranking of environmental factors	
1	Raw materials
2	Biodiversity, land use, and water use
3	Life-cycle perspective
4	GHG emissions beyond CO_2

individual and community participation should receive more attention. One interviewee highlighted the interlinkage between these different factors: "*…we have connections to social acceptability, because if we go into a more decentralised approach, we can create more value for the regions, or for all European places, where you have your own creation of energy and you have your own value chains. You have local jobs, local economy, and then, local acceptance*" (EU_NGO#1).

In addition to social aspects, discussions in the stakeholder workshop also revealed the relevance of a better integration of policies in energy modelling, going beyond CO_2 prices as the only policy measure for prioritisation. During the discussion, participants expressed the need to understand the science and to compare it with ongoing policy processes, and to understand how policy changes can trigger behavioural changes. Many stakeholders also raised questions in connection to the choice of policy instruments for reaching targets. One interviewee asked: "*And in the area of policy instruments, how you can move faster with the climate action*? *What instruments do we need*?" (Sweden_scientist#4).

In the workshop, we asked stakeholders to rank different social aspects in two breakout sessions and two subsequent rounds of live polling, finding the most important aspects to be (S1) Social acceptance/opposition, (S2) Individual and community participation, (S3) Consumer behaviour and lifestyle, and (S4) Policy dynamics (Table 2). One interviewee confirmed the limitations of current energy models by stating: "*It can be in terms of social acceptance, it can be in terms of job creation, it can be in terms of socio-economic impacts that are not all factored*

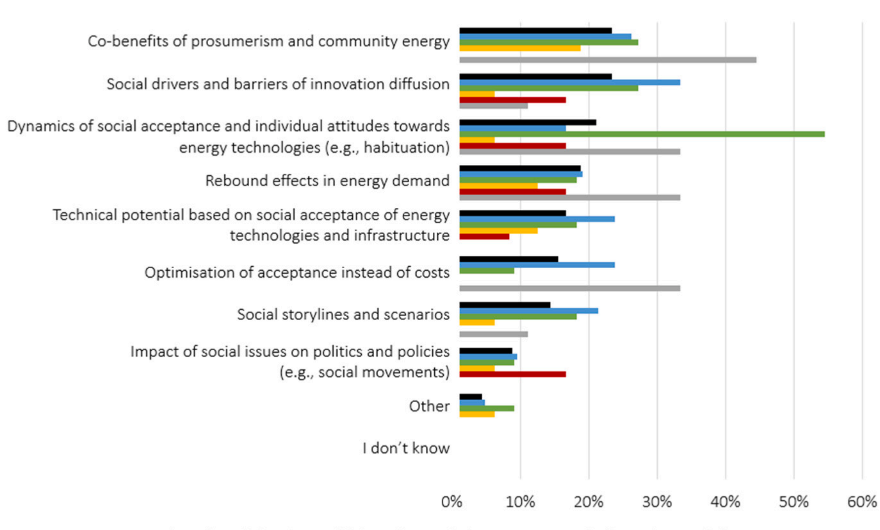

Fig. 3. Key social aspects identified by user needs survey (choice frequency; up to three answers possible, voluntary question). Responses were obtained for the following question: "You stated that social aspects should receive more attention by models. What social aspects would you like to see integrated into energy models more in the future?" (voluntary, multiple choices, up to three answers), N = 49, Explanation of terms: "Social acceptance" refers to the willingness of people to accept the installation of energy-related infrastructure, usually near them. "Optimisation of acceptance" refer to the aim of making resistance to installation as low as possible. "Social storylines and scenarios" refer to scenarios that include qualitative storylines, describing also societal developments and interactions and interdependencies between actors, technologies, and policy interventions in the context of the energy transition.

Table 2
Ranking of social factors to be included in energy models.

Ranking of environmental factors	
1	Social acceptance/opposition
2	Individual and community participation
3	Consumer behaviour and lifestyle
4	Policy dynamics

in the model that is being run" (EU_industry#2). One policymaker added that *"[t]he improved simulation of 'real-world' decision-making and behavioural aspects is always welcome and offer robust results in the quantitative analysis"* (Greece_policymaker#1). The main reasons argued for the need of including social aspects were i) to better understand people's decision-making processes and criteria, and lifestyle choices, ii) to enable citizen and community participation in the energy transition, and iii) to understand the (distributional) effects of different policy measures.

4.2. Case studies on the importance of environmental and social factors

To illustrate the potential effects of omitting the top-ranked environmental and social factors from energy modelling (Section 4.1), we undertook four case studies. We describe these case studies and the omitted user needs discussed in each in Table 3. Note that we do not explicitly illustrate point E3 (life-cycle perspective) because it is implicit in the materials issue and point E4 (GHG emissions beyond CO_2) because reducing emissions is understood to be the key motivation of the energy transition and a key variable in most energy models. For each case, we present published model scenarios – or, in some cases, the lack of suitable outputs – alongside real-world situations to highlight mismatches between model results, real-world developments and policy targets.

4.2.1. The EU electricity grid plan without people and nature

Transmission grid expansion is a key pathway for integrating fluctuating renewable supplies into power systems. Many modelling studies show that new transmission lines must be built for a least-cost electricity system in the EU. Rodríguez et al. [93] quantified the benefit of power transmission between countries to support almost 100 % renewable power, finding a cost-minimum for a grid five times as large as today's. Similarly, Tröndle et al. [29] found that the cheapest, continent-wide, fully renewable electricity supply would require twice the present transmission grid. However, they also show that if the transmission grid is used for the continental-scale balancing of net self-sufficient regional supplies, much less transmission capacity – roughly the size of today's transmission system, but with twice the cross-border capacities – would be required. Most cost-optimised renewable power scenarios critically hinge on the realisation and feasibility of grid expansion.

Beyond grid expansion, such scenarios often envisage large concentrations of generation and transmission at specific locations [29]. Therefore, local acceptance is an essential factor; if citizens in these key places do not accept the plans, the scenario becomes irrelevant as the proposed projects may be delayed or not built at all. For example, the main scenario of the German Advisory Council for the Environment projected 42 gigawatts (GW) of interconnection between Germany and Denmark, and 48 GW crossing the Skagerrak to the hydropower stations in Norway; in their "Supergrid" scenario, these interconnectors are 53 GW and 116 GW, respectively [94]. In 2020, the German-Danish interconnection capacity was 1.7 GW northward, with an ongoing expansion project to 2.5 GW [95]. The Danish mainland is just above 50 km wide at the narrowest place, suggesting that, if lines are land-based, these scenarios imply on average 1–2.5 GW of transit powerline per cross-section kilometre in Denmark. This casts great doubt on the feasibility – especially the social and political feasibility – of such a plan: Will Denmark accept such enormous capacity lines, especially if they are merely passing their country with no immediate benefit to them? Indeed, opposition from transit countries has been problematic in past projects, including the Desertec plan to import solar power from Morocco to Germany [96].

Table 3
Identified case studies for demonstrating the importance of integrating environmental and social aspects into energy modelling.

Case study	User needs
The EU electricity grid plan without people and nature	(E2) land use (S1) social acceptance / opposition
An environmental dilemma for electric vehicles in the EU?	(E1) raw materials (S3) consumer behaviour
Headwind for onshore wind power in Germany	(E2) biodiversity and land use (S1) social acceptance / opposition
Domestic investment behaviour for small-scale PV in Greece	(S2) Individual and community participation (S3) consumer behaviour (S4) policy dynamics

Most political visions and plans are model-supported. For example, the European Commission (EC) use the *EU Reference Scenario* as a central basis for their decisions [97]. Furthermore, many models, such as PRIMES, assume that the infrastructure plans within their simulations are completed as intended [97]. ENTSO-E's Ten-Year Network Development Plan (TYNPD) 2020 expects that over 300 transmission projects of some 45,000 km will be commissioned by 2040 [98], with about 50 % of projects expected to be operational by 2021–2025 (Fig. 4). However, if such plans do not materialise, models using this assumption clearly produce less meaningful results.

In reality, implementation has been slow, with only 40 % of projects on or ahead of schedule, and all others delayed or altered in various ways (Fig. 5). In 2020, 65 TYNDP transmission projects (17 %) were reported as delayed, and this only includes early projects (2021–2025) as later projects have not yet entered stages in which delays can occur [99]. This has not changed significantly over time: in 2012, a third of projects were reported as being delayed due to "*social resistance and longer than initially expected permitting procedures*" [100]. Pall et al. [101] investigated the causes of deployment delays in international power transmission projects and found that local public resistance and political interventions (strikes/blockades) are the main reason, while other research found that public opposition is the most important delay factor in national projects [102]. Underlying causes could be environmental concerns related to new grid infrastructure, as new expansions in power lines have the potential to harm local environments, and impact biodiversity during both the construction and operation phases [103].

In sum, there is a large gap between what scientific and advice-oriented models project and what is observed on the ground in transmission projects: not only are network plans much smaller than the vast-scale expansion that cost-optimising models find beneficial, but actual progress is typically much slower than models optimise/simulate. This means that system models risk generating meaningless findings, highlighting the problem of ignoring social factors in technical models.

4.2.2. An environmental dilemma for electric vehicles in the EU?

The EU aims to reduce CO_2 emissions from cars by 55 % (compared to 1990) by 2030 and proposes to ban sales of fossil-fuelled cars by 2035 [104]. Electrification of transport plays an important role in reaching net-zero emissions by 2050 [105]. A variety of energy models have explored future EV penetration rates and project EV use to increase dramatically in coming decades. For example, the International Energy Agency (IEA) Mobility Model projects 16 million electric cars in their *Stated policies scenario* in the EU by 2030 and 33 million in their *Sustainability development scenario* [106]. Statharas et al. [107] quantitatively assessed the impacts of factors that drive market penetration of electric cars in the EU, using the PRIMES-TREMOVE model, and project under the most optimistic scenario, that 18 % of the total car fleet in the EU will be electric by 2030.

Although energy models include detailed analyses of the transport

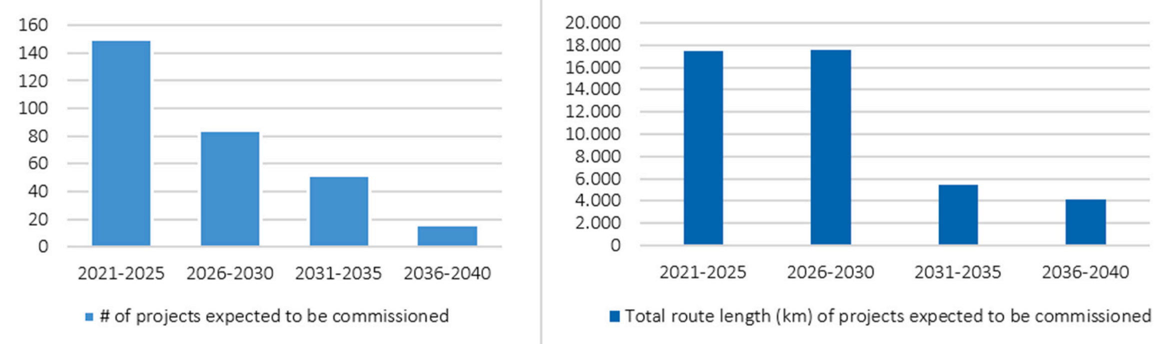

Fig. 4. Transmission project timeline in the 2020 ENTSO-E Ten-Year Network Development Plan. Data source: ENTSO-E [99].

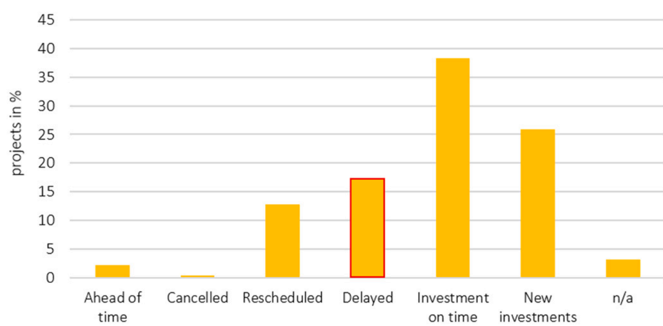

Fig. 5. Progress of all transmission investments since TYNDP 2018, n = 321 projects. "Ahead of time": expected commissioning date is earlier than anticipated in the previous TYNDP. "Rescheduled": commissioning has been postponed due to a voluntary decision. "Delayed": expected commissioning date is later due to delay (unvoluntary). "On time": no change compared to previous TYNDP. "New investments": new in the TYNDP 2020 (in comparison to 2018). Data source: ENTSO-E [99].

sector and EV numbers, very few consider raw material requirements as a potentially constraining factor in their calculations. Yet, such factors may prove critical. For example, Xu et al. [108] developed a material flow analysis showing that global EV battery demand would increase key minerals consumption by a factor of 20–30 by 2050. While progress has been made to develop methods for assessing material requirements [109] and supply risk [110] within energy models, these concepts are yet to be widely implemented, and most IAMs and energy models are yet to include CRM constraints at all.

The EU seeks to increase its EV fleet from about 3.2 million in 2020 [105] to at least 30 million by 2030 [111]. Although electric car registrations in Europe more than doubled in 2020 compared to 2019 [112], this target requires a sharp increase in sales, especially as there are large differences across Europe: Norwegian new sales now exceed 75 %, whereas many Eastern and Southern European countries remain below 5 % [113]. Adding to concerns about range and charger availability, many consumers and policymakers also question whether the technology is more environmentally friendly [114,115].

For EV battery production, the materials of most concern in current designs are lithium, cobalt and natural graphite. New, advanced battery designs are under development and may bring increasing demand of silicon, titanium and niobium [38], all of which are considered critical by the EC [116]. The EU relies almost exclusively on imported raw materials in battery manufacturing, with one-third imported from China and one-fifth from Latin America and Africa, respectively (ibid). Processed materials, particularly those used for cathodes and anodes, are also imported, especially from China (52 %) and Japan (31 %) [116]. The EU does not produce any of the finished battery assemblies it uses, importing these mainly (66 %) from China (ibid). Europe thus faces a two-fold challenge: not only are many needed materials scarce in general, but almost all of them are not produced domestically, making the European EV strategy vulnerable to supply risks.

Bobba et al. [38] made material demand projections for lithium-ion battery production for three future e-mobility pathways, showing that even the lowest deployment pathway for batteries alone requires several times the present total EU consumption of lithium, cobalt and graphite (Table 4). This suggests that serious limitations may occur unless the EU can drastically increase its supplies of the three CRMs considered. Even if the EU imports all its EV batteries [117], global resources and production remain limited, showing that there is a very real threat to the accelerated uptake of EVs, both in Europe and globally [118]. This raises the question of how feasible such projections are if they neglect material constraints, or whether sufficiency strategies for avoiding mobility, or shifting to other modes of transport, do not need to be pushed much more in the social and political debate.

4.2.3. Headwind for onshore wind power in Germany

Wind power substantially contributes to the power mix in Germany. In 2020, around 18 % of gross electricity production came from onshore and about 5 % from offshore plants [119]. In December 2021, the German onshore wind power capacity was 56 GW [120] and, as the energy transition progresses, it will likely become the most important electricity source [121]. The Renewable Energy Act 2021 aims for 71 GW capacity by 2030 [122], while the government's long-term climate scenarios foresee 80 GW [123]. These targets equal an annual average expansion of 1.7–2.7 GW/year.

Many studies are investigating the wind power expansion needs for decarbonising the German power system. For example, Fraunhofer ISE [124] analysed options for GHG neutrality by 2045 using the REMod model in which energy system simulation and cost-optimisation are coupled (hybrid optimisation). Modellers developed four scenarios characterised by multiple restrictions. The *Reference*, *Inertia* and *Sufficiency* scenarios assume a German onshore wind fleet of up to 230 GW. Meanwhile, in the *Unacceptance* scenario, where it is assumed that expansion struggles from strong public opposition, capacity only reaches up to 80 GW; instead, emissions targets being achieved via a massive expansion of solar PV (660 GW), which may also face strong opposition due to high installation rates. Either way, the more ambitious wind deployment figures roughly correspond to a tripling and quadrupling of current onshore capacity and an average expansion pace of up to 7 GW/year.

The deployment rates required for such climate-neutral system projections depart strongly from the observed development. While Germany seemed almost "on track" with growing annual expansion rates between 3.7 and 5.2 GW onshore wind power during 2014–2017, this pace has since dropped to 1.1–1.9 GW/year [125]. The decline was caused by changes in the policy support (shift from feed-in-tariff to auctions) and, especially, difficulties with installation permits, often originating from local opposition to new wind power projects

Table 4
Current total EU consumption and projected requirements for EV batteries alone for three key materials. Projected electric vehicle numbers are listed in accordance with low-, medium-, high-demand scenarios (LDS, MDS, HDS). Adapted from Bobba et al. [38].

		2020	2030			2050		
			LDS	MDS	HDS	LDS	MDS	HDS
Total EU consumption *[tonnes]*	Cobalt	30,000						
	Lithium	6000						
	Graphite	250,000						
Projected EV requirements *[tonnes]*	Cobalt		38,000	67,000	120,000	38,000	110,000	290,000
	Lithium		32,000	51,000	90,000	48,000	130,000	260,000
	Graphite		340,000	500,000	820,000	700,000	1,800,000	2,700,000
Projected EV requirements *[times total EU consumption in 2020]*	Cobalt		1.3	2.2	4.0	1.3	3.7	9.7
	Lithium		5.3	8.5	15.0	8.0	21.7	43.3
	Graphite		1.4	2.0	3.3	2.8	7.2	10.8

[126,127]. Despite broad support for the energy transition in general, one-fifth of the population rejects or strictly rejects further deployment of onshore wind power [128], with numerous anti-wind citizen initiatives emerging [129]. The causes of opposition, indicated by lawsuits and local resistance, are manifold and largely connected to environmental and social factors. Some 20 % of all onshore wind power projects are affected by litigation [63], mainly from environmental organisations, but also from citizens and citizen initiatives, often raising concerns about biodiversity [47]. This situation is similar around Europe [130,131]. A further key driver of wind power opposition is its land use, owing to the vast amounts of land required for wind farms, potentially triggering direct land-use conflicts, and public opposition due to visual and aesthetic landscape impacts [125,126]. In the long run, wind power land use could be substantial, at least 1–2 % the German land area [132,133].

In summary, large disconnects exist between what models say is necessary for carbon-neutrality and what is feasible given the opposition (Fig. 6). On the one hand, current onshore wind development does not align with prominent scenario results (except, for example, *Unacceptance* scenarios). On the other hand, current policy targets are not ambitious enough to reach the demanded wind fleet. The latter might, however, change as the government plans to update the expansion targets of onshore wind power in the Renewable Energy Act, with a substantial increase in the annual auction volume to 10 GW by 2027 [134]. If the law passes the parliament, Germany is on the path to reach more than twice the installed capacity compared to current plans by 2035 and soon even overtake the ambitious *Reference* scenario of the Fraunhofer study. However, if the government does not react to the causes of the "wind market implosion", especially the growing opposition to wind power plants routed in environmental and social factors, its expansion plans might fail and possibly contribute to further resistance.

4.2.4. *Domestic investment behaviour for small-scale PV in Greece*

In June 2009, the Greek government introduced the "Special programme for the deployment of solar photovoltaics (PV) on buildings and roofs", which simplified installation procedures for domestic solar PV installers and provided a generous feed-in-tariff of €550/MWh to attract investments [136]. Later that year, the process for the transposition of the Renewable Energy Directive into the national legislation was initiated. Different energy models were used in this process to evaluate the energy policy scenarios developed, and to perform a sensitivity analysis taking into account different evolution paths of fiscal/regulatory

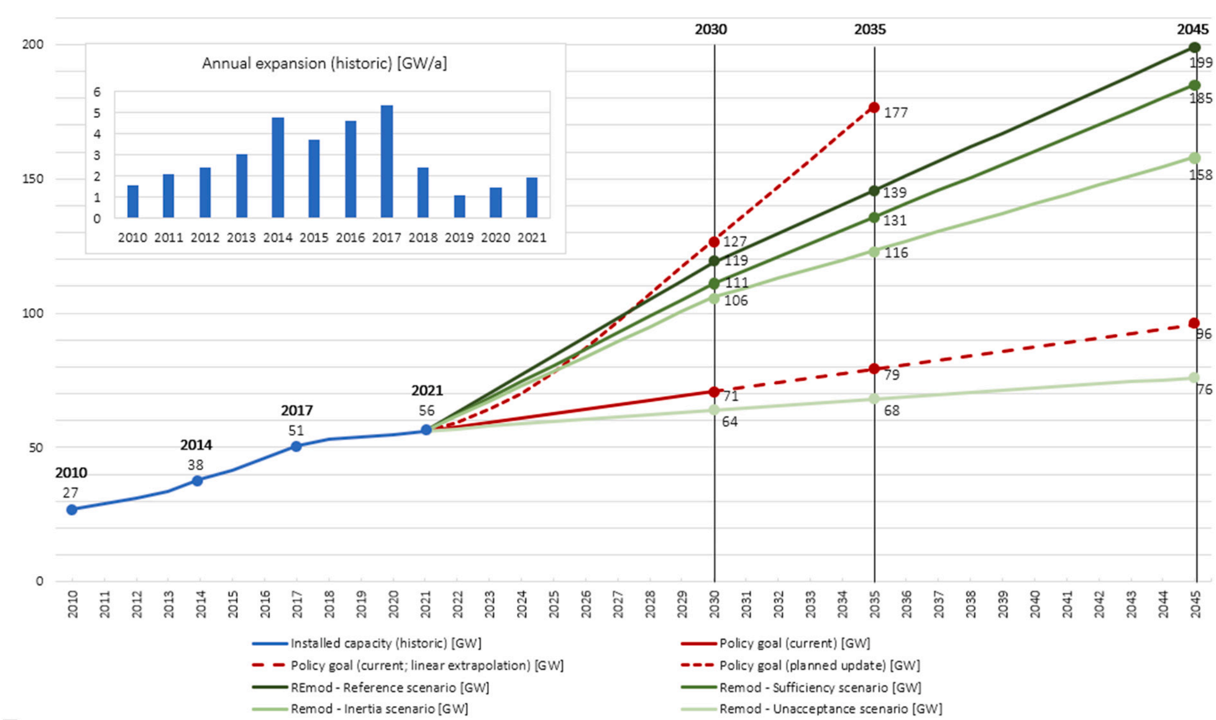

Fig. 6. Installed onshore wind capacity in Germany. Real-world developments, policy goals, and modelled needs in a 100 % renewable future. Data sources: [122,124,134,135] and linear inter- and extrapolation of missing data; rounded values.

parameters. In particular, the TIMES-MARKAL model [137] was used to calculate the specific targets for each type of technology, underneath the overall national renewable target, while the ENPEP model [138] was used for the assessment of different policy measures for achieving the targets. Both models used inputs from the models WASP [139] (used for optimum electricity generation planning) and COST (used for the stochastic simulation of the electricity generation system). Based on this modelling work, the government set the 2020 target to 2200 MW of total PV capacity [140], while model results suggested that the feed-in-tariff policy design would drive consumer investments in a linear way to the achievement of the 2020 PV target (Fig. 7).

However, the targets defined by the model and set by the government were disconnected from the adoption realities on the ground. Many consumers saw the feed-in tariff as an attractive source of additional revenue during a period of great financial distress for the country, leading to a PV boom in 2009–2013. Thus, the model-based target of 2200 MW of PV capacity by 2020 was met and exceeded in 2013 [141]. Consequently, the government, without consulting any further model-based analyses, imposed an additional tax on consumer incomes from renewable electricity generation, simultaneously with a reduction on tariffs to counterbalance negative fiscal implications [142]. This political decision shook the confidence of domestic investors in the stability and credibility of the support system [143,144], leading to a complete shutdown of the domestic PV market [32].

Here, once again, neither the political reality nor the consumer behaviour was reflected in the energy models used to inform policy-making. Accordingly, model-supported policy expectations and reality diverged: the adoption was first much higher than the energy models anticipated, and then completely collapsed following the policy change. Indeed, the policy change was such a strong shock that subsequent efforts to rekindle the residential uptake of PV expansion through a net-metering scheme [146] did not work, causing the updated 2020 PV target of 3300 MW (by end of 2019) to fail.

This case study demonstrates the problems arising from a non-adaptive model-informed policymaking process, the consequences of not being flexible and allowing for contingency measures in case of a policy failure, and of the necessity for energy models to evaluate consumer response to specific policy incentives, especially when high tariffs are provided. By only using top-down optimisation models for target setting, model-informed policymaking risks being misleading: such models assume a benevolent planner with central control over the system and investments, but investor behaviour may be very different than this centrally-planned perspective assumes. If policy measures whose success depends on investor responses are based only on top-down optimisation model results ignoring actual behaviour, there is a risk that the policy will fail, triggering either too much or too little investment.

5. Discussion

Our results show that model users request better integration of the environmental and social factors of the energy transition into energy models so that models can provide results that better represent real-world developments, thereby improving their usefulness as policy advice tools. According to users, environmental factors should go beyond GHG emissions and include the demand of raw materials, impacts on biodiversity, land use and water consumption, and other indirect and externalised impacts. Among the social factors, we identified social acceptance, individual and community participation, consumer behaviour and lifestyles, and policy preferences and dynamics as the most relevant. The identified needs largely align with the environmental and social factors that are currently discussed in the scientific literature (Section 2), underlining their relevance.

In our four case studies, we show that omitting the environmental and social factors ranked most important to model users may lead to less relevant, or even misleading, results in several ways:

1) Neglecting social factors can lead to unrealistic model assumptions and misleading findings about the *speed* of the transition: The cases of grid expansion in the EU and onshore wind power in Germany show that public opposition, related to land-use and biodiversity concerns, substantially delays the implementation of the energy transition, often by many years and for single projects over a decade. Similarly, the Greek case study on solar PV illustrates the perils of ignoring investor behaviour and solely basing target-setting on top-down optimisation models assuming a benevolent central planner, in this case resulting in overly rapid deployment.
2) Models may make unrealistic assumptions about the *potential* of renewable energy if they focus only on the technical potential, ignoring societal preferences and their impact on land availability. The example of onshore wind power in Germany shows that wind power expansion can be hindered when wind turbines are not accepted in certain areas. Whether temporary or permanent, such delays can reduce local and, consequently, countrywide wind capacity potentials.
3) Not considering the demand of land and raw materials for renewable energy assets and related infrastructure may generate scenarios that neglect central *impacts* of the energy transition and support

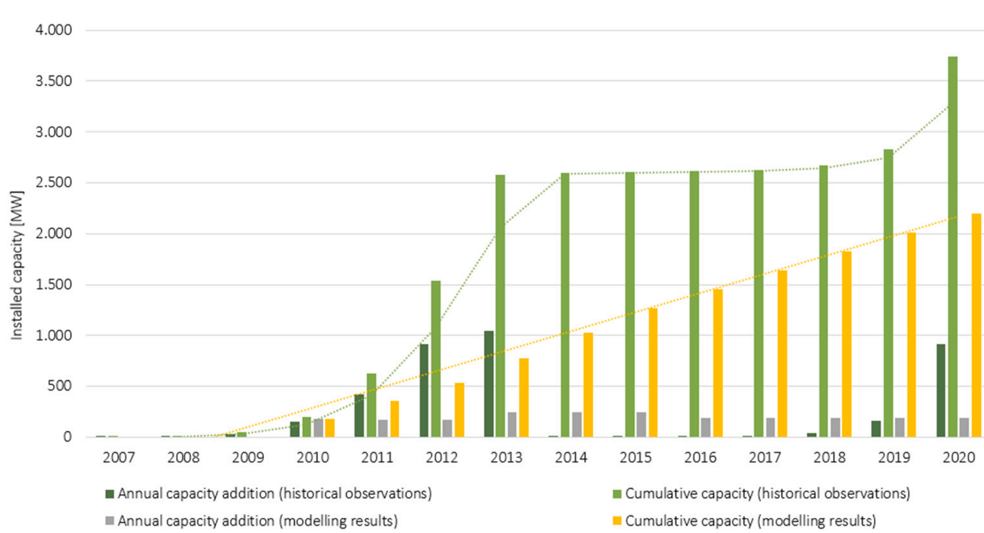

Fig. 7. Total PV capacity installed in Greece during the period 2007–2020: Modelling results vs historical observations. Data source: [140,145].

technology options that cannot materialise or that bring substantial supply risks. The case of EV batteries shows that the availability of raw materials could become both a deployment constraint and a geopolitical or economic risk factor as the transition progresses, unless a significant system change is made regarding the recycling of materials. Furthermore, land-use conflicts are an increasing problem for deployment of renewables and infrastructure.

4) Ignoring environmental concerns and societal preferences can lead to problematic or misaligned *design* of future energy and mobility systems. Our cases indirectly show that consumers have strong attitudes and opinions towards technologies such as EV and wind turbines and should therefore also have an influence on the siting of renewable energy and planning of solutions more broadly.

Collectively, this demonstrates a large need to integrate social and environmental factors as variables in energy models. Achieving this is difficult because such variables must be based on context-specific empirical observation and because transitions are dynamic processes and change, possibly fundamentally, over time. For example, environmental impacts and resource demands could be reduced during the transition via circularity initiatives or by innovations in new materials. Accordingly, technological change must also be depicted in environmental assessments, including emerging approaches such as prospective life cycle assessment (LCA). Similarly, the drivers of public opposition against wind power may be different in, for example, Germany and Greece, and will likely change between now and 2030. To depict such developments, models may need to endogenise social factors, modelling the underlying drivers such as regional density and size of existing wind farms [147] instead of considering them as exogenous variables, as independent factors of a multi-criteria analysis, or ex-post indicators. Furthermore, political realities and regulation – both of which are dynamic – greatly affect transitions, for example, by adding constraints such as wind farm distance rules or alleviating constraints such as recycling requirements to avoid material shortage. These may also “change the sign” of a factor, turning a barrier into a driver; e.g., enabling community renewables can reduce opposition and create a new potential transition driver. Several approaches for including environmental and social factors into energy models are emerging and, although none of them fully integrate all such issues, the seeds for doing so are probably being sown; we discuss existing approaches for such integration in Sections 5.1 and 5.2.

Adding these additional factors will align energy models more closely to observable realities and will thus make them more policy relevant. However, it will also make models more complex, reducing their transparency and risk increasing the “black-box“ nature of models. To avoid overloading models and, indeed, increase their usefulness as advice tools, it is essential to include stakeholders in the modelling process, both to provide data and, critically, context for that data and for the context-sensitive interpretation of model outputs.

5.1. Approaches for integrating environmental factors in energy models

Several approaches exist to better represent environmental factors in energy models. One promising approach is the integration of life-cycle perspectives and data sources into energy models, which provides greater access to high-resolution raw material information and other valuable environmental indicators. For example, Pehl et al. [148] and Luderer et al. [149] linked IAMs with LCA information using the THEMIS model [150], enabling high-resolution GHG emissions and several other environmental impacts to be included within modelling processes. This concept has recently been expanded by allowing life-cycle data to be manipulated within Python environments, enabling outputs from models to be directly automated with LCA calculations. For example, the PREMISE model [151] allows different background electricity mixes and other parameters from the IMAGE model to inform future LCA processes to account for future changes in renewable energy use or technological improvements [23]. In any case, none of these approaches allow for the further analysis of LCA outputs beyond the simple aggregation of values across system components.

Few attempts have been made to include detailed information about raw materials demand and supply within energy models. One notable example is the MEDEAS-World model [152], which includes a module that accounts for the materials and energy required for energy infrastructure manufacturing. The model quantifies the material requirements for implementing renewable energy infrastructure, including 19 CRMs, and compares these with current global availability estimates to detect potential supply issues. As such, it represents a much-needed initial foray into the inclusion of CRM aspects within a detailed IAM suite.

To facilitate greater analysis of raw material aspects and LCA outputs with and across energy system levels, scholars developed the ENBIOS module [153]. ENBIOS takes system specification data (“energy mix” and other information) from models, combines this data with raw material requirement information and calculated environmental and socio-metabolic indicator data to produce extensive outputs such as life cycle impact assessment indicators and bespoke indicators derived from life cycle and other data. ENBIOS also directly integrates raw material supply risks, circularity and local impacts at the point of extraction via a methodology that combines life-cycle inventory data, supply risk and end-of-life recycling input rate data [154], and localised environmental performance data for the countries from which materials are sourced [153,154]. As such, it brings a more systemic method to the assessment of material use and environmental impacts than previous approaches while offering a first attempt at quantifying these impacts alongside the socio-metabolic aspects that also apply to energy systems. Outputs from ENBIOS can be used to inform the selection of subsequent model scenarios or, for example, guide constraint parameters.

5.2. Approaches for integrating social factors in energy models

The need to integrate social factors into energy models has been previously addressed, and several approaches exist. These are typically focused on implementing social factors as constraints, but some have attempted to integrate them as explicit variables within energy models. For example, the Quantification of Technological DIffusion and sociAl constraiNts (QTDIAN) toolbox allows modellers both to include real-world, non-idealised policy constraints (e.g. actual national/regional setback distances for wind power), and to base scenario construction on observed policy objectives beyond GHG elimination, such as decentralisation/centralisation or transmission system preferences [157]. Seeking to enable model-based assessment of the impact of different policy measures, Best et al. [158] built a database for energy sufficiency policies, allowing the explicit integration of sufficiency indicators into energy modelling. Presently, there is a strong trend towards integration of social science and humanities in energy system analysis, and several model frameworks are being rebuilt to become more realistic and holistic.

Including public acceptance of renewable energy deployment strategies in new modelling frameworks has become a particular recent focus. One approach is to seek the fair geographical distribution of production and infrastructure assets, thus avoiding overly strong concentration of deployment in single regions [159]. Others seek to generate scenario-based options to identify which parts of a deployment trajectory are necessary, and where more flexibility is available, as a first step towards increasing stakeholder engagement and including public deliberations about the most attractive pathways for a country or region. For example, the “spatially explicit practically optimal results” (SPORES) approach explores nearly cost-optimal systems. Applying SPORES to Italy, Lombardi et al. [160] find that only photovoltaic and storage technologies are necessary components for a zero-carbon power system by 2050, whereas wind power choices are more flexible, allowing for deliberation-centred planning. Yet others include “resistance factors" for grid expansion, including these in their model to generate delay-minimal expansion pathways instead of purely cost-optimal ones [159].

Adopting an entirely different approach, McKenna et al. [59] quantified the visual impacts of onshore wind in energy system analyses, basing the analysis on "scenicness" values of onshore wind sites [161]. In four scenarios for onshore wind potential, they gradually reduced the technical potential by quartiles of the scenicness distribution, revealing that the windiest locations are generally also the most scenic ones. Hence, including this parameter in models could greatly reduce the wind power potential, while generating more relevant results and exposing conflicts between landscape protection and renewables, facilitating solution-oriented deliberation.

Finally, although energy modelling is still dominated by central planner-based optimisation modelling, alternatives are emerging, including models that describe actor behaviour instead of top-down optimal deployment [88,162]. Such models, including ABMs, can be used both to inform policy design decisions and to set appropriate targets. For example, Melliger et al. [163] explored the effects of exposing renewable electricity technologies to market competition using an ABM fed with investor behaviour data from a conjoint analysis [164]. They show that although policies to increase competition seek to reduce energy system costs, they likely both slow down deployment and increase costs because investors flock to still supported and more expensive technologies. Similarly, addressing the same case in section 4.2.4, the agent-based technology adoption model (ATOM) simulates the diffusion of small-scale PV in Greece under the net-metering scheme currently in operation [30,141], based on behavioural profiles of small-scale investors. Indeed, ATOM shows that the existing net-metering policy is unable to achieve the 2025 and 2030 PV targets due to policy shortcomings, a finding that could not be detected using system optimisation models.

5.3. Limitations and future research

Our study shows that energy models should consider environmental and social aspects of the energy transition and indicates the magnitude of the problems arising by ignoring such factors. However, we acknowledge the limitations of our study in terms of generalisability of user needs as we were not able to capture needs and differences between EU member states, or in countries beyond the EU. Just as social and environmental barriers and drivers may differ across both time and countries, user needs for model-based information will also be both dynamic and context-sensitive. Whereas we believe that the barriers we explore – material requirements, opposition, etc. – are relevant to all countries, the relative importance of each factor may differ, depending on political factors, geography and transition progress. Further studies could explore the context-specific needs and reasons for modelling requirements to support the further improvement of modelling tools tailored to specific countries and challenges.

Furthermore, we have presented illustrative, non-exclusive examples of situations where energy modelling studies have generated problematic or unfeasible policy-advice because they did not sufficiently consider environmental or social factors. However, model results do not (always) directly lead to policy decisions, but are – and should be – only one source of information among others [165]. Further research could investigate how policy and decision-making processes deal with factors that are not considered in energy models and what concrete impact this has on policy decisions.

It is also noted that the levels of granularity within current LCA databases make it difficult to localise the various impacts that occur along the overall supply chains that produce energy and infrastructure. As such, it may be unclear whether the emissions, resource requirements and impacts assigned to a process are occurring locally or in various other regions of the world. This is less of an issue for GHG emissions, where impacts are assumed to occur globally, regardless of their origin. However, a shortcoming exists when assessing more localised impacts–e.g., air and water pollution or land use. There are a few initiatives working on the regionalization of Life Cycle Data and methods [166]. This movement is merely taking off, but we do advocate for its relevance and potential contributions in the assessment of environmental (and social) impacts of the energy transition.

Lastly, we call for more research on integrating or linking environmental and social aspects into and with modelling, going beyond the consideration of those factors as "add-ons". For example, future research could soft link energy models with environmental models to assess wider environmental impacts of transition pathways and energy systems.

6. Conclusions

We conclude that users want *better* models regarding the representation of environmental and social factors, and we have demonstrated that ignoring these critical aspects of the energy transition can lead to wrong or misleading evidence about the potential of renewable electricity, and the speed, impacts and technological options of the energy transition. While the modelling community is taking steps to better incorporate social and environmental factors into energy models, our results suggest that many of these key areas are not yet considered in sufficient detail and that existing approaches have not been sufficiently applied. While energy models will undoubtedly continue to be used to inform policymaking, our study is a call to energy modellers to further advance the representation of these factors in models or to advance the interlinking of different modelling tools. This includes the mainstreaming of social and environmental factors as explicit variables in models, possibly even by endogenising particularly important parameters, such as social preferences, into the models based on context-sensitive empirical data. Including these factors would vastly improve the robustness of energy system models and, ultimately, would increase the suitability and meaningfulness of models to informing policy decision regarding the complex interplay between energy requirements, societal objectives and environmental considerations as Europe and the world continue advancing towards climate neutrality.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This work has received funding from the European Union's Horizon 2020 research and innovation programme (Grant agreement 837089, SENTINEL project). We would also like to thank the stakeholders for taking the time to participate in the online interviews, the online survey, and the workshop. This paper is an original paper, building on content from the SENTINEL Deliverables 1.2, 2.1 and 2.4 by the same authors.

Appendix A

Table A1
. Stakeholder engagement activities and participants.

Method	Questions and content	Engaged model users	Further information
Interviews in five jurisdictions: the EU, Germany, Greece, Poland, Sweden	The interview guidelines included these questions to energy modellers: - In your opinion, what kind of information should an energy model deliver, now and in the future, to inform decision-making (processes) in energy policy? - In your opinion, how should the process of model development be designed to increase the chance of the later model use in policymaking? - Which conditions must be given that increase the chance that you would use the models or the results, respectively, in future policymaking/your work? Question to non-modellers included: - What are the current and future challenges or aspects of the energy transition that should be integrated into future energy models? - In your opinion, what kind of information should an energy model deliver to help make good decisions about energy policy/energy issues? - Which conditions must be given that increase the chance that you would use the models or the results, respectively, in future policymaking/your work?	32 interviewees: 11 policymakers, 4 energy industry experts, 5 NGO representatives, 12 researchers	Complete interview guideline: [167]
Online survey	The survey was designed around six sections: 1) Personal background, model use, and general demands, 2) Model content, 3) Model design, 4) Modelling process, 5) Modelling outreach, 6) Others and demographic data.	90 complete responses from 12 policymakers, 16 energy industry experts, 11 NGO representatives, 42 researchers	Complete survey: [91]
Workshop on user needs for energy modelling, European Member States	Five breakout sessions: Session 1: Social and policy aspects in energy models Session 2: Including environmental aspects in energy system models Session 3: Modelling energy demand and supply Session 4: Modelling the economic impacts of the energy transition Session 5: Designing the model platform of SENTINEL	23 non-SENTINEL participants from different European Member States: 2 policymakers, 11 energy industry experts, 6 NGO representatives, 4 researchers	Full list of participants: [168]

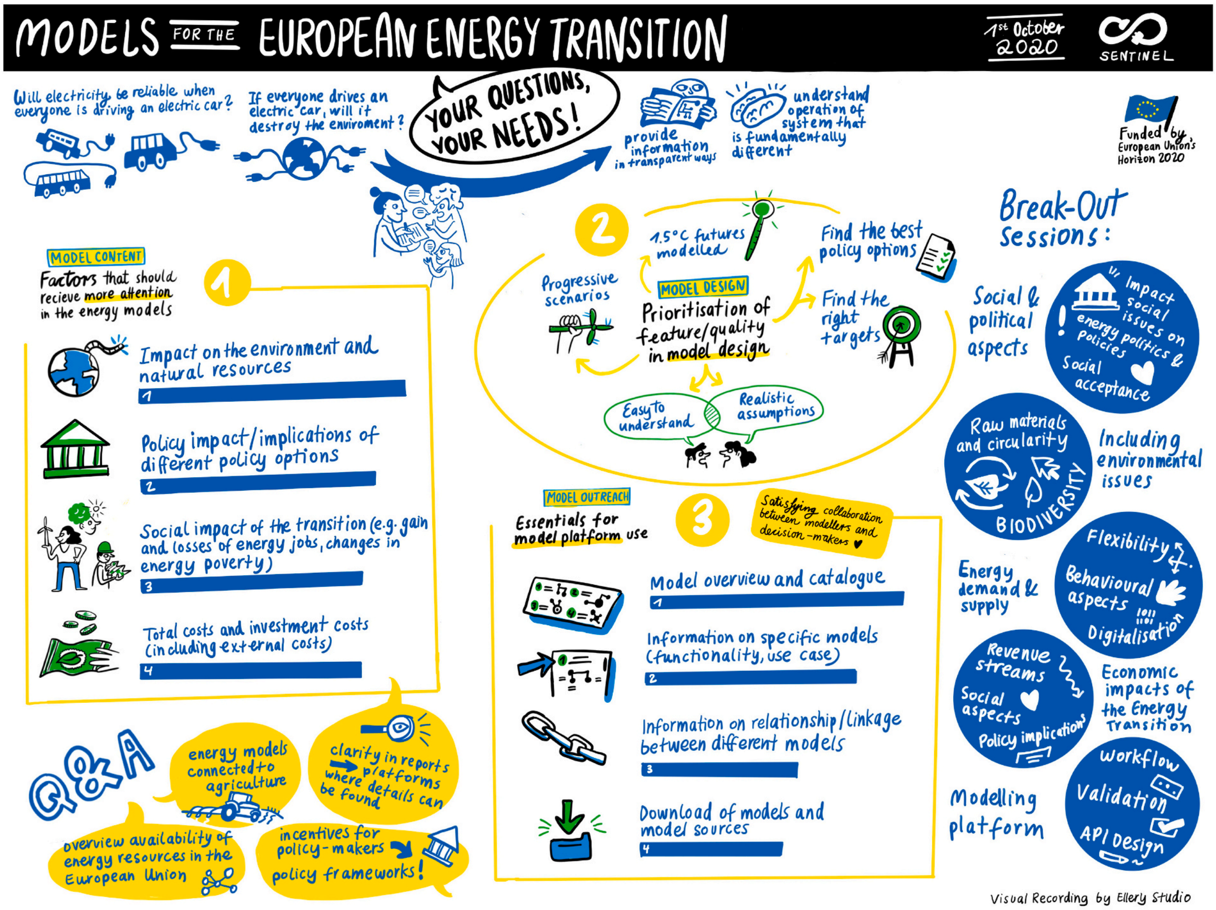

Fig. A1. Graphical recording of the workshop, including a ranking of factors that receive more attention in energy models.

References

[1] European Commission, Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions: The European Green Deal - COM/2019/640 Final, European Commission, Brussels, 2019.

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

[3] European Commission, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee, the Committee of the Regions and the European Investment Bank, A Framework Strategy for a Resilient Energy Union with a Forward-Looking, 2015.

[4] European Commission, in: Clean Energy for all Europeans COM(2016) 860 Final, 2016, pp. 1–13. https://eur-lex.europa.eu/resource.html?uri=cellar:fa6ea15b-b7b0-11e6-9e3c-01aa75ed71a1.0001.02/DOC_1&format=PDF.

[5] IAMC, Integrated Assessment Modeling Consortium Wiki, 2020.

[6] A. Krumm D. Süsser P. Blechinger , Modelling social aspects of the energy transition: current and potential representations in energy models, Energy. (n.d.).

[7] E. Trutnevyte, L.F. Hirt, N. Bauer, A. Cherp, A. Hawkes, O.Y. Edelenbosch, S. Pedde, D.P. van Vuuren, Societal transformations in models for energy and climate policy: the ambitious next step, One Earth 1 (2019) 423–433, https://doi.org/10.1016/j.oneear.2019.12.002.

[8] A. Nikas, J. Lieu, A. Sorman, A. Gambhir, E. Turhan, B.V. Baptista, H. Doukas, The desirability of transitions in demand: incorporating behavioural and societal transformations into energy modelling, Energy Res. Soc. Sci. 70 (2020), 101780, https://doi.org/10.1016/j.erss.2020.101780.

[9] V. Moreau, P.C.Dos Reis, F. Vuille, Enough metals? Resource constraints to supply a fully renewable energy system, Resources 8 (2019) 29, https://doi.org/10.3390/resources8010029.

[10] G. Calvo, A. Valero, Strategic mineral resources: availability and future estimations for the renewable energy sector, Environ. Dev. (2021), 100640, https://doi.org/10.1016/j.envdev.2021.100640.

[11] B.K. Sovacool, D.J. Hess, R. Cantoni, D. Lee, M. Claire Brisbois, H. Jakob Walnum, R. Freng Dale, B. Johnsen Rygg, M. Korsnes, A. Goswami, S. Kedia, S. Goel, Conflicted transitions: exploring the actors, tactics, and outcomes of social opposition against energy infrastructure, Glob. Environ. Chang. 73 (2022), 102473, https://doi.org/10.1016/j.gloenvcha.2022.102473.

[12] G. Savvidis, K. Siala, C. Weissbart, L. Schmidt, F. Borggrefe, S. Kumar, K. Pittel, R. Madlener, K. Hufendiek, The gap between energy policy challenges and model capabilities, Energy Policy 125 (2019) 503–520, https://doi.org/10.1016/j.enpol.2018.10.033.

[13] S. Pfenninger, A. Hawkes, J. Keirstead, Energy systems modeling for twenty-first century energy challenges, Renew. Sust. Energ. Rev. 33 (2014) 74–86, https://doi.org/10.1016/j.rser.2014.02.003.

[14] S. Chatterjee, V. Stavrakas, G. Oreggioni, D. Süsser, I. Staffell, J. Lilliestam, G. Molnar, A. Flamos, D. Ürge-Vorsatz, Existing tools, user needs and required model adjustments for energy demand modelling of a carbon-neutral Europe, Energy Res. Soc. Sci. 90 (2022), 102662, https://doi.org/10.1016/j.erss.2022.102662.

[15] G. Savvidis, K. Siala, C. Weissbart, L. Schmidt, F. Borggrefe, S. Kumar, K. Pittel, R. Madlener, K. Hufendiek, The gap between energy policy challenges and model capabilities, Energy Policy 125 (2019) 503–520, https://doi.org/10.1016/j.enpol.2018.10.033.

[16] R.H.E.M. Koppelaar, J. Keirstead, N. Shah, J. Woods, A review of policy analysis purpose and capabilities of electricity system models, Renew. Sust. Energ. Rev. 59 (2016) 1531–1544, https://doi.org/10.1016/j.rser.2016.01.090.

[17] C.A. Scott, S.A. Pierce, M.J. Pasqualetti, A.L. Jones, B.E. Montz, J.H. Hoover, Policy and institutional dimensions of the water-energy nexus, Energy Policy 39 (2011) 6622–6630, https://doi.org/10.1016/j.enpol.2011.08.013.

[18] M.M. Sokołowski, R.J. Heffron, Defining and conceptualising energy policy failure: the when, where, why, and how, Energy Policy 161 (2022), 112745, https://doi.org/10.1016/J.ENPOL.2021.112745.

[19] D. Süsser, H. Gaschnig, A. Ceglarz, V. Stavrakas, A. Flamos, J. Lilliestam, Better suited or just more complex? On the fit between user needs and modeller-driven improvements of energy system models, Energy (2021), 121909, https://doi.org/10.1016/j.energy.2021.121909.

[20] J.A. Hollingsworth, E. Ravishankar, B. O'Connor, J.X. Johnson, J.F. DeCarolis, Environmental and economic impacts of solar-powered integrated greenhouses, J. Ind. Ecol. 24 (2020) 234–247, https://doi.org/10.1111/jiec.12934.

[21] J. Li, S. Li, F. Wu, Research on carbon emission reduction benefit of wind power project based on life cycle assessment theory, Renew. Energy 155 (2020) 456–468, https://doi.org/10.1016/j.renene.2020.03.133.

[22] C.J. Barnhart, S.M. Benson, in: On the Importance of Reducing the Energetic and Material Demands of Electrical Energy Storage 6, 2013, pp. 1083–1092, https://doi.org/10.1039/C3EE24040A.

[23] A. Mendoza Beltran, B. Cox, C. Mutel, D.P. van Vuuren, D. Font Vivanco, S. Deetman, O.Y. Edelenbosch, J. Guinée, A. Tukker, D.P. Vuuren, D. Font Vivanco, S. Deetman, O.Y. Edelenbosch, J. Guinée, A. Tukker, When the background matters: using scenarios from integrated assessment models in prospective life cycle assessment, J. Ind. Ecol. 24 (2020) 64–79, https://doi.org/10.1111/jiec.12825.

[24] T. Watari, B.C. McLellan, D. Giurco, E. Dominish, E. Yamasue, K. Nansai, Total material requirement for the global energy transition to 2050: a focus on transport and electricity, Resour. Conserv. Recycl. 148 (2019) 91–103, https://doi.org/10.1016/j.resconrec.2019.05.015.

[25] S. Nabernegg, B. Bednar-Friedl, P. Muñoz, M. Titz, J. Vogel, National policies for global emission reductions: effectiveness of carbon emission reductions in international supply chains, Ecol. Econ. 158 (2019) 146–157, https://doi.org/10.1016/j.ecolecon.2018.12.006.

[26] F. Lombardi, M.V. Rocco, E. Colombo, A multi-layer energy modelling methodology to assess the impact of heat-electricity integration strategies: the case of the residential cooking sector in Italy, Energy 170 (2019) 1249–1260, https://doi.org/10.1016/j.energy.2019.01.004.

[27] T. Boßmann, I. Staffell, The shape of future electricity demand: exploring load curves in 2050s Germany and Britain, Energy 90 (2015) 1317–1333, https://doi.org/10.1016/j.energy.2015.06.082.

[28] V. Stavrakas, A. Flamos, A modular high-resolution demand-side management model to quantify benefits of demand-flexibility in the residential sector, Energy Convers. Manag. 205 (2020), 112339, https://doi.org/10.1016/j.enconman.2019.112339.

[29] T. Tröndle, J. Lilliestam, S. Marelli, S. Pfenninger, Trade-offs between geographic scale, cost, and infrastructure requirements for fully renewable electricity in Europe, Joule 4 (2020) 1929–1948, https://doi.org/10.1016/j.joule.2020.07.018.

[30] V. Stavrakas, S. Papadelis, A. Flamos, An agent-based model to simulate technology adoption quantifying behavioural uncertainty of consumers, Appl. Energy 255 (2019), 113795, https://doi.org/10.1016/j.apenergy.2019.113795.

[31] T. Perger, L. Wachter, A. Fleischhacker, H. Auer, PV sharing in local communities: peer-to-peer trading under consideration of the prosumers' willingness-to-pay, Sustain. Cities Soc. (2020), 102634, https://doi.org/10.1016/j.scs.2020.102634.

[32] A. Nikas, V. Stavrakas, A. Arsenopoulos, H. Doukas, M. Antosiewicz, J. Witajewski-Baltvilks, A. Flamos, Barriers to and consequences of a solar-based energy transition in Greece, Environ. Innov. Soc. Trans. 35 (2019) 383–399, https://doi.org/10.1016/j.eist.2018.12.004.

[33] D.J. Hess, R.G. McKane, C. Pietzryk, End of the Line: Environmental Justice, Energy Justice, and Opposition to Power Lines, 2021, https://doi.org/10.1080/09644016.2021.1952799 doi:10.1080/09644016.2021.1952799.

[34] S. Avila, Environmental justice and the expanding geography of wind power conflicts, Sustain. Sci. 133 (13) (2018) 599–616, https://doi.org/10.1007/S11625-018-0547-4, 2018.

[35] G. Iacobuta, N.K. Dubash, P. Upadhyaya, M. Deribe, N. Höhne, National climate change mitigation legislation, strategy and targets: a global update, Clim. Policy 18 (2018) 1114–1132, https://doi.org/10.1080/14693062.2018.1489772.

[36] M. Pehl, A. Arvesen, F. Humpenöder, A. Popp, E.G. Hertwich, G. Luderer, Understanding future emissions from low-carbon power systems by integration of life-cycle assessment and integrated energy modelling, Nat. Energy 2 (2017) 939–945, https://doi.org/10.1038/s41560-017-0032-9.

[37] S. Carrara, P.Alves Dias, B. Plazzotta, C. Pavel, Raw Materials Demand for Wind and Solar PV Technologies in the Transition Towards a Decarbonised Energy System, EUR 30095 EN, Publications Office of the European Union, Luxembourg, 2020, https://doi.org/10.2760/160859.

[38] S. Bobba, S. Carrara, J. Huisman, F. Mathieux, C. Pavel, Critical Raw Materials for Strategic Technologies and Sectors in the EU: A Foresight Study, Publications Office of the European Union, Luxembourg, 2020, https://doi.org/10.2873/865242.

[40] L. Liu, G. Huang, B. Baetz, K. Zhang, Environmentally-extended input-output simulation for analyzing production-based and consumption-based industrial greenhouse gas mitigation policies, Appl. Energy 232 (2018) 69–78, https://doi.org/10.1016/j.apenergy.2018.09.192.

[41] G. Saevarsdottir, H. Kvande, B.J. Welch, Aluminum production in the times of climate change: the global challenge to reduce the carbon footprint and prevent carbon leakage, JOM 72 (2020) 296–308, https://doi.org/10.1007/s11837-019-03918-6.

[42] É. Lèbre, M. Stringer, K. Svobodova, J.R. Owen, D. Kemp, C. Côte, A. Arratia-Solar, R.K. Valenta, The social and environmental complexities of extracting energy transition metals, Nat. Commun. 111 (11) (2020) 1–8, https://doi.org/10.1038/s41467-020-18661-9, 2020.

[43] J. Ma, Q. Duan, Environmental dumping and international unionized oligopolies, SSRN Electron. J. (2009), https://doi.org/10.2139/ssrn.1494877.

[44] G. Gaustad, M. Krystofik, M. Bustamante, K. Badami, Circular economy strategies for mitigating critical material supply issues, Resour. Conserv. Recycl. 135 (2018) 24–33, https://doi.org/10.1016/j.resconrec.2017.08.002.

[45] A. Mayer, W. Haas, D. Wiedenhofer, F. Krausmann, P. Nuss, G.A. Blengini, Measuring progress towards a circular economy: a monitoring framework for economy-wide material loop closing in the EU28, J. Ind. Ecol. 23 (2019) 62–76, https://doi.org/10.1111/jiec.12809.

[46] F. Diaz-Maurin, J.J. Cadillo-Benalcazar, Z. Kovacic, C. Madrid-López, T. Serrano-Tovar, M. Giampietro, R.J. Aspinall, J. Ramos-Martin, S.G.F. Bukkens, The Republic of South Africa, in: M. Giampietro, R.J. Aspinall, J. Ramos-Martin, S.G. F. Bukkens (Eds.), Resour. Account. Sustain. Nexus Between Energy, Food, Water L. Use, Routledge, Abingdon, 2014, pp. 194–213, https://doi.org/10.4324/9781315866895.

[47] C.C. Voigt, T.M. Straka, M. Fritze, Producing wind energy at the cost of biodiversity: a stakeholder view on a green-green dilemma, J. Renew. Sustain. Energy 11 (2019), 063303, https://doi.org/10.1063/1.5118784.

[48] L. Bennun, J. van Bochove, C. Ng, C. Fletcher, D. Wilson, N. Phair, G. Carbone, Mitigating biodiversity impacts associated with solar and wind energy development, in: Guidelines for Project Developers, IUCN, Gland, 2021, https://doi.org/10.2305/IUCN.CH.2021.04.en.

[49] A. Santangeli, T. Toivonen, F.M. Pouzols, M. Pogson, A. Hastings, P. Smith, A. Moilanen, Global change synergies and trade-offs between renewable energy and biodiversity, GCB Bioenergy 8 (2016) 941–951, https://doi.org/10.1111/gcbb.12299.

[50] A. Gasparatos, C.N.H. Doll, M. Esteban, A. Ahmed, T.A. Olang, Renewable energy and biodiversity: implications for transitioning to a green economy, Renew. Sust. Energ. Rev. 70 (2017) 161–184, https://doi.org/10.1016/j.rser.2016.08.030.

[51] M. Giamalaki, T. Tsoutsos, Sustainable siting of solar power installations in Mediterranean using a GIS/AHP approach, Renew. Energy 141 (2019) 64–75, https://doi.org/10.1016/j.renene.2019.03.100.

[52] S. Gross, Renewables, Land Use, and Local Opposition in the United States, Brookings, Washington, DC, 2020.

[53] G. Felber, G. Stoeglehner, Onshore wind energy use in spatial planning—a proposal for resolving conflicts with a dynamic safety distance approach, Energy. Sustain. Soc. 4 (2014) 22, https://doi.org/10.1186/s13705-014-0022-8.

[54] K. Huang, M.J. Eckelman, Appending material flows to the National Energy Modeling System (NEMS) for projecting the physical economy of the United States, J. Ind. Ecol. (2020), https://doi.org/10.1111/jiec.13053.

[55] E. Rinne, H. Holttinen, J. Kiviluoma, S. Rissanen, Effects of turbine technology and land use on wind power resource potential, Nat. Energy 3 (2018) 494–500, https://doi.org/10.1038/s41560-018-0137-9.

[56] R.Y. Shum, A comparison of land-use requirements in solar-based decarbonization scenarios, Energy Policy 109 (2017) 460–462, https://doi.org/10.1016/j.enpol.2017.07.014.

[57] I. Capellán-Pérez, C. de Castro, I. Arto, Assessing vulnerabilities and limits in the transition to renewable energies: land requirements under 100% solar energy scenarios, Renew. Sust. Energ. Rev. 77 (2017) 760–782, https://doi.org/10.1016/j.rser.2017.03.137.

[58] K. Palmer-Wilson, J. Donald, B. Robertson, B. Lyseng, V. Keller, M. Fowler, C. Wade, S. Scholtysik, P. Wild, A. Rowe, Impact of land requirements on electricity system decarbonisation pathways, Energy Policy 129 (2019) 193–205, https://doi.org/10.1016/j.enpol.2019.01.071.

[59] R. McKenna, I. Mulalic, I. Soutar, J.M. Weinand, J. Price, S. Petrović, K. Mainzer, Exploring trade-offs between landscape impact, land use and resource quality for onshore variable renewable energy: an application to Great Britain, Energy (2022), 123754, https://doi.org/10.1016/j.energy.2022.123754.

[60] European Union, Climate Change. Special Eurobarometer 513, 2021, https://doi.org/10.2834/437.

[61] J. Cohen, K. Moeltner, J. Reichl, M. Schmidthaler, An empirical analysis of local opposition to new transmission lines across the EU-27, Energy J. 37 (2016), https://doi.org/10.5547/01956574.37.3.jcoh.

[62] P. Devine-Wright, S. Batel, My neighbourhood, my country or my planet? The influence of multiple place attachments and climate change concern on social acceptance of energy infrastructure, Glob. Environ. Chang. 47 (2017) 110–120, https://doi.org/10.1016/j.gloenvcha.2017.08.003.

[63] J. Quentin, Hemmnisse beim Ausbau der Windenergie in Deutschland. Ergebnisse einer Branchenumfrage zu Klagen gegen Windenergieanlagen sowie zu Genehmigungshemmnissen durch Drehfunkfeuer und militärische Belange der Luftraumnutzung, Berlin, 2019.

[64] K. Borch, Mapping value perspectives on wind power projects: the case of the danish test Centre for large wind turbines, Energy Policy 123 (2018) 251–258, https://doi.org/10.1016/j.enpol.2018.08.056.

[65] A. Månsson, A resource curse for renewables? Conflict and cooperation in the renewable energy sector, Energy Res. Soc. Sci. 10 (2015) 1–9, https://doi.org/10.1016/j.erss.2015.06.008.

[66] C.C. Voigt, T.M. Straka, M. Fritze, Producing wind energy at the cost of biodiversity: a stakeholder view on a green-green dilemma, J. Renew. Sustain. Energy 11 (2019), 063303, https://doi.org/10.1063/1.5118784.

[67] D.P. Vasilakis, D.P. Whitfield, S. Schindler, K.S. Poirazidis, V. Kati, Reconciling endangered species conservation with wind farm development: cinereous vultures (Aegypius monachus) in South-Eastern Europe, Biol. Conserv. 196 (2016) 10–17, https://doi.org/10.1016/j.biocon.2016.01.014.

[68] V. Kati, C. Kassara, Z. Vrontisi, A. Moustakas, The biodiversity-wind energy-land use nexus in a global biodiversity hotspot, Sci. Total Environ. 768 (2021), 144471, https://doi.org/10.1016/j.scitotenv.2020.144471.

[69] L.D. Knopper, C.A. Ollson, L.C. McCallum, M.L.W. Aslund, R.G. Berger, K. Souweine, M. McDaniel, Wind turbines and human health, Front. Public Health 2 (2014) 1–20, https://doi.org/10.3389/fpubh.2014.00063.

[70] F.W. Geels, Socio-technical transitions to sustainability: a review of criticisms and elaborations of the multi-level perspective, Curr. Opin. Environ. Sustain. (2019), https://doi.org/10.1016/j.cosust.2019.06.009. In press.
[71] R. Cowell, G. Bristow, M. Munday, Acceptance, acceptability and environmental justice: the role of community benefits in wind energy development, J. Environ. Plan. Manag. 54 (2011) 539–557, https://doi.org/10.1080/09640568.2010.521047.
[72] D. Süsser, A. Kannen, 'Renewables? Yes, please!': perceptions and assessment of community transition induced by renewable-energy projects in north frisia, Sustain. Sci. 12 (2017) 563–578, https://doi.org/10.1007/s11625-017-0433-5.
[73] B.J.A. Walker, B. Wiersma, E. Bailey, Community benefits, framing and the social acceptance of offshore wind farms: an experimental study in England, Energy Res. Soc. Sci. 3 (2014) 46–54, https://doi.org/10.1016/j.erss.2014.07.003.
[74] J. Balest, E. Pisani, D. Vettorato, L. Secco, Local reflections on low-carbon energy systems: a systematic review of actors, processes, and networks of local societies, Energy Res. Soc. Sci. 42 (2018) 170–181, https://doi.org/10.1016/j.erss.2018.03.006.
[75] European Commission, in: Energy Union Package - A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy, COM (2015) 80 Final, 2015, pp. 1–21.
[76] J. Stephenson, B. Barton, G. Carrington, A. Doering, R. Ford, D. Hopkins, R. Lawson, A. McCarthy, D. Rees, M. Scott, P. Thorsnes, S. Walton, J. Williams, B. Wooliscroft, The energy cultures framework: exploring the role of norms, practices and material culture in shaping energy behaviour in New Zealand, Energy Res. Soc. Sci. 7 (2015) 117–123, https://doi.org/10.1016/j.erss.2015.03.005.
[77] F. Creutzig, J. Roy, W.F. Lamb, I.M.L. Azevedo, W. Bruine De Bruin, H. Dalkmann, O.Y. Edelenbosch, F.W. Geels, A. Grubler, C. Hepburn, E.G. Hertwich, R. Khosla, L. Mattauch, J.C. Minx, A. Ramakrishnan, N.D. Rao, J.K. Steinberger, M. Tavoni, D. Ürge-Vorsatz, E.U. Weber, Towards demand-side solutions for mitigating climate change, Nat. Clim. Chang. 8 (2018) 268–271, https://doi.org/10.1038/s41558-018-0121-1.
[78] E. Toulouse, H. Gorge, M. Le Dû, L. Semal, Stimulating energy sufficiency: barriers and opportunities, ECEEE Summer Study Proc. (2017) 59–68.
[79] S. Samadi, M.-C. Gröne, U. Schneidewind, H.-J. Luhmann, J. Venjakob, B. Best, Sufficiency in energy scenario studies: taking the potential benefits of lifestyle changes into account, Technol. Forecast. Soc. Chang. 124 (2017) 126–134, https://doi.org/10.1016/j.techfore.2016.09.013.
[80] T. Göllinger, Systemisches Innovations- und Nachhaltigkeitsmanagement, 2012.
[81] J.E. Morrissey, S. Axon, R. Aiesha, J. Hillman, A. Revez, B. Lennon, N.P. Dunphy, M. Salel, E. Boo, Identification and characterisation of energy behaviour change initiatives, in: Deliverable D4.4 of ENTRUST Project, 2016, https://doi.org/10.5281/ZENODO.3479377.
[82] C. Zell-Ziegler, J. Thema, B. Best, F. Wiese, J. Lage, A. Schmidt, E. Toulouse, S. Stagl, Enough? The role of sufficiency in European energy and climate plans, Energy Policy 157 (2021), 112483, https://doi.org/10.1016/j.enpol.2021.112483.
[83] L. Tummers, Public policy and behavior change, Public Adm. Rev. 79 (2019) 925–930, https://doi.org/10.1111/puar.13109.
[84] L.V. Lerman, W. Gerstlberger, M.Ferreira Lima, A.G. Frank, How governments, universities, and companies contribute to renewable energy development? A municipal innovation policy perspective of the triple helix, Energy Res. Soc. Sci. 71 (2021), 101854, https://doi.org/10.1016/j.erss.2020.101854.
[85] F. Mey, M. Diesendorf, Who owns an energy transition? Strategic action fields and community wind energy in Denmark, Energy Res. Soc. Sci. 35 (2018) 108–117, https://doi.org/10.1016/j.erss.2017.10.044.
[86] D. Süsser, M. Döring, B.M.W. Ratter, Harvesting energy: place and local entrepreneurship in community-based renewable energy transition, Energy Policy 101 (2017) 332–341, https://doi.org/10.1016/j.enpol.2016.10.018.
[87] T. Perger, L. Wachter, A. Fleischhacker, H. Auer, PV sharing in local communities: peer-to-peer trading under consideration of the prosumers' willingness-to-pay, Sustain. Cities Soc. (2020), 102634, https://doi.org/10.1016/j.scs.2020.102634.
[88] A. Mittal, C.C. Krejci, M.C. Dorneich, D. Fickes, An agent-based approach to modeling zero energy communities, Sol. Energy 191 (2019) 193–204, https://doi.org/10.1016/j.solener.2019.08.040.
[89] D. Süsser, H. Gaschnig, A. Ceglarz, V. Stavrakas, A. Flamos, J. Lilliestam, Better suited or just more complex? On the fit between user needs and modeller-driven improvements of energy system models, Energy 239 (2022), 121909, https://doi.org/10.1016/j.energy.2021.121909.
[90] D. Süsser, A. Ceglarz, V. Stavrakas, J. Lilliestam, COVID-19 vs. Stakeholder engagement: the impact of coronavirus containment measures on stakeholder involvement in european energy research projects, Open Res. Eur. 1 (2021) 57, https://doi.org/10.12688/openreseurope.13683.1.
[91] H. Gaschnig, D. Süsser, A. Ceglarz, V. Stavrakas, A. Flamos, J. Lilliestam, Survey Questionnaire and Results on User Needs for Energy Models for the European Energy Transition, Related to Süsser et al. (2021), Zenodo, 2021 [Data set].
[92] H. Gaschnig, D. Süsser, A. Ceglarz, G. Stavrakas, V. Giannakidis, A. Flamos, A. Sander, J. Lilliestam, User needs for an energy system modeling platform for the European energy transition. Deliverable 1.2. Sustainable Energy Transitions Laboratory (SENTINEL) project, in: Eur. Comm. Inst. Adv. Sustain. Stud. (IASS), Potsdam, 2020.
[93] R.A. Rodríguez, S. Becker, G.B. Andresen, D. Heide, M. Greiner, Transmission needs across a fully renewable european power system, Renew. Energy 63 (2014) 467–476, https://doi.org/10.1016/j.renene.2013.10.005.
[94] German Advisory Council on the Environment, Pathways Towards a 100% Renewable Electricity System, 2011.
[95] Energinet, Kassø-Frøslev: New Electricity Interconnector to Germany, 2020.
[96] J. Lilliestam, S. Ellenbeck, C. Karakosta, N. Caldés, Understanding the absence of renewable electricity imports to the European Union, Int. J. Energy Sect. Manag. 10 (2016) 291–311, https://doi.org/10.1108/IJESM-10-2014-0002.
[97] European Commission, EU Reference Scenario 2020. Energy, Transport and GHG Emissions. Trends to 2050, 2021.
[98] ENTSO-E, Ten-Year Network Development Plan 2020, 2021.
[99] ENTSO-E, TYNDP 2020 Projects Sheets, 2021.
[100] ENTSO-E, in: 10-Year Network Development Plan 2012, Report, 2012, pp. 1–219.
[101] G.K. Pall, A.J. Bridge, J. Gray, M. Skitmore, Causes of delay in power transmission projects: an empirical study, Energies 13 (2019) 17, https://doi.org/10.3390/en13010017.
[102] S. Perras, Electricity Transmission Line Planning - Success Factors for Transmission System Operators to Reduce Public Opposition, Techn. Univ., Diss, Dresden, 2015.
[103] L.D. Biasotto, A. Kindel, Power lines and impacts on biodiversity: a systematic review, Environ. Impact Assess. Rev. 71 (2018) 110–119, https://doi.org/10.1016/j.eiar.2018.04.010.
[104] European Commission, The European Green Deal, 2019, https://doi.org/10.1128/AAC.03728-14.
[105] IEA, Global EV Outlook 2021, International Energy Agency, Paris, 2021.
[106] IEA, Global EV data explorer. https://www.iea.org/articles/global-ev-data-explorer, 2021.
[107] S. Statharas, Y. Moysoglou, P. Siskos, G. Zazias, P. Capros, Factors influencing electric vehicle penetration in the E.U. By 2030: a model-based policy assessment, Energies 12 (2019) 2739, https://doi.org/10.3390/en12142739.
[108] C. Xu, Q. Dai, L. Gaines, M. Hu, A. Tukker, B. Steubing, Future material demand for automotive lithium-based batteries, Commun. Mater. 1 (2020) 99, https://doi.org/10.1038/s43246-020-00095-x.
[109] A. Boubault, S. Kang, N. Maïzi, Closing the TIMES integrated assessment model (TIAM-FR) raw materials gap with life cycle inventories, J. Ind. Ecol. 23 (2019) 587–600, https://doi.org/10.1111/jiec.12780.
[110] L. Talens-Peiró, N. Martin, G. Villalba-Méndez, C. Madrid-López, Integration of raw materials indicators of energy technologies into energy system models, Appl. Energy 307 (2022), 118150, https://doi.org/10.1016/j.apenergy.2021.118150.
[111] European Committee of the Regions, EU Must Support Every Region, City and Village to Deliver Zero Transport Emissions by 2050, 2022 (n.d.).
[112] IEA, Trends and Developments in Electric Vehicle Markets, 2021.
[113] EEA, New registrations of electric vehicles in Europe. https://www.eea.europa.eu/ims/new-registrations-of-electric-vehicles, 2021.
[114] A. Burkert, H. Fechtner, B. Schmuelling, Interdisciplinary analysis of social acceptance regarding electric vehicles with a focus on charging infrastructure and driving range in Germany, World Electr. Veh. J. 12 (2021) 25, https://doi.org/10.3390/wevj12010025.
[115] Continental, Many People Still Doubtful About Electric Cars' Environmental Friendliness, 2021.
[116] European Commission, Study on the EU's List of Critical Raw Materials (2020) - Final Report, Publications Office of the European Union, Luxembourg, 2020, https://doi.org/10.2873/11619.
[117] M. Naumanen, T. Uusitalo, E. Huttunen-Saarivirta, R. van der Have, Development strategies for heavy duty electric battery vehicles: comparison between China, EU, Japan and USA, Resour. Conserv. Recycl. 151 (2019), 104413, https://doi.org/10.1016/j.resconrec.2019.104413.
[118] L. Xu, M. Fuss, W.R. Poganietz, P. Jochem, S. Schreiber, C. Zoephel, N. Brown, An environmental assessment framework for energy system analysis (EAFESA): the method and its application to the european energy system transformation, J. Clean. Prod. 243 (2020), 118614, https://doi.org/10.1016/j.jclepro.2019.118614.
[119] Statista, Anteil Erneuerbarer Energieträger an der Bruttostromerzeugung in Deutschland in den Jahren 2020 und 2021. https://de.statista.com/statistik/daten/studie/171368/umfrage/struktur-der-bruttostromerzeugung-durch-erneuerbare-energien-in-deutschland/, 2022.
[120] Arbeitsgruppe Erneuerbare Energien - Statistik, Monatsbericht zur Entwicklung der erneuerbaren Stromerzeugung und Leistung in Deutschland. Stand: 12.06.2020, Umweltbundesamt, 2020.
[121] Fraunhofer ISI, Consentec, ifeu, Langfristszenarien für die Transformation des Energiesystems in Deutschland. Modul 0: Zentrale Ergebnisse und Schlussfolgerungen Studie im Auftrag des Bundesministeriums für Wirtschaft und Energie, 2017.
[122] Bundesregierung, in: Gesetz für den Ausbau erneuerbarer Energien (ErneuerbareEnergien-Gesetz - EEG 2021), 2021, p. 3138. Manuscript.
[123] Das Umweltbundesamt, Windenergie an Land. https://www.umweltbundesamt.de/themen/klima-energie/erneuerbare-energien/windenergie-an-land#flaeche, 2021.
[124] J. Brandes, M. Haun, D. Wrede, P. Jürgens, C. Kost, H.-M. Henning, Wege zu einem klimaneutralen Energiesystem – Update Klimaneutralität 2045, 2021.
[125] Deutsche WindGuard GmbH, Status des Windenergiezubaus an Land in Deutschland - Halbjahr 2021, 2021.
[126] J. Quentin, Ausbausituation der Windenergie an Land im Jahr 2020, Berlin, 2020.
[127] K. Witsch, Trotz Milliardeninvestments und grüner Finanzprodukte: Ausbau der Windkraft stockt, Handelsblatt, 2021.
[128] O. Renn, I. Wolf, D. Setton, Soziales Nachhaltigkeitsbarometer der Energiewende, 2020, https://doi.org/10.7802/2120.
[129] A. Gardt, T. Broekel, P. Gareis, Blowing against the winds of change? The relationship between anti-wind initiatives and wind turbines in Germany, in: Pap.

Evol. Econ. Geogr. (PEEG), Utr. Univ. Dep. Hum. Geogr. Spat. Planning, Gr. Econ. Geogr, 2021, p. 2119.
[130] V. Kati, C. Kassara, Z. Vrontisi, A. Moustakas, The biodiversity-wind energy-land use nexus in a global biodiversity hotspot, Sci. Total Environ. 768 (2021), 144471, https://doi.org/10.1016/j.scitotenv.2020.144471.
[131] D.P. Vasilakis, D.P. Whitfield, S. Schindler, K.S. Poirazidis, V. Kati, Reconciling endangered species conservation with wind farm development: cinereous vultures (Aegypius monachus) in South-Eastern Europe, Biol. Conserv. 196 (2016) 10–17, https://doi.org/10.1016/j.biocon.2016.01.014.
[132] Bund-Länder-Kooperationsausschuss, Bericht des Bund-Länder-Kooperationsausschusses zum Stand des Ausbaus der erneuerbaren Energien sowie zu Flächen, Planungen und Genehmigungen für die Windenergienutzung an Land, 2021.
[133] T. Tröndle, Supply-side options to reduce land requirements of fully renewable electricity in Europe, PLoS One 15 (2020) 1–19, https://doi.org/10.1371/journal.pone.0236958.
[134] Federal Ministry for the Economy and Climate Action (BMWK), Kerninhalte der Referentenentwürfe des BMWK zur Novelle des Novelle des Wind-auf-See-Gesetzes und zum EEG-Entlastungsgesetz. https://www.bmwi.de/Redaktion/DE/Downloads/E/Kerninhalte_EEG_WindSeeG.pdf?__blob=publicationFile&v=4, 2022.
[135] B.W. (BWE), Windenergie in Deutschland - Zahlen und Fakten. https://www.wind-energie.de/themen/zahlen-und-fakten/deutschland/, 2021.
[136] P. Anagnostopoulos, N.A. Spyridaki, A. Flamos, A "new-deal" for the development of photovoltaic investments in Greece? A parametric techno-economic assessment, Energies 10 (2017) 1173, https://doi.org/10.3390/en10081173.
[137] R. Loulou, M. Labriet, ETSAP-TIAM: the TIMES integrated assessment model part I: model structure, Comput. Manag. Sci. 5 (2008) 7–40, https://doi.org/10.1007/s10287-007-0046-z.
[138] Environmental E.S.A. A. Center for Energy, in: Energy and Power Evaluation Program (ENPEP-BALANCE): Brief Model Overview - Version 2.25, 2008, pp. 1–7.
[139] J. Santisirisomboon, B. Limmeechokchai, S. Chungpaibulpatana, Impacts of biomass power generation and CO taxation on electricity generation expansion planning and environmental emissions, Energy Policy 29 (2001) 975–985, https://doi.org/10.1016/S0301-4215(01)00028-3.
[140] Ministry of Environment and Energy, 1st National Renewable Energy Action Plan (NREAP), 2010.
[141] S. Michas, V. Stavrakas, S. Papadelis, A. Flamos, A transdisciplinary modeling framework for the participatory design of dynamic adaptive policy pathways, Energy Policy 139 (2020), https://doi.org/10.1016/j.enpol.2020.111350.
[142] I. Koumparou, G.C. Christoforidis, V. Efthymiou, G.K. Papagiannis, G. E. Georghiou, Configuring residential PV net-metering policies – a focus on the Mediterranean region, Renew. Energy 113 (2017) 795–812, https://doi.org/10.1016/j.renene.2017.06.051.
[143] S. Papadelis, V. Stavrakas, A. Flamos, What do capacity deployment rates tell us about the efficiency of electricity generation from renewable energy sources support measures in Greece? Energies 9 (2016) https://doi.org/10.3390/en9010038.
[144] A. Flamos, A sectoral micro-economic approach to scenario selection and development: the case of the Greek power sector, Energies 9 (2016) 1–12, https://doi.org/10.3390/en9020077.
[145] S. Psomas, in: Status and Outlook of the Greek PV Market, Hell. Assoc. Photovolt. Co, 2018, pp. 1–14.
[146] S. Tselepis, The PV market developments in Greece, net-metering study cases, in: Conf. 31st EUPVSEC, Hamburg, 2015.
[147] D. Setton, Soziales Nachhaltigkeitsbarometer der Energiewende 2018, 2019, https://doi.org/10.2312/iass.2019.002.
[148] M. Pehl, A. Arvesen, F. Humpenöder, A. Popp, E.G. Hertwich, G. Luderer, Understanding future emissions from low-carbon power systems by integration of life-cycle assessment and integrated energy modelling, Nat. Energy 2 (2017) 939–945, https://doi.org/10.1038/s41560-017-0032-9.
[149] G. Luderer, M. Pehl, A. Arvesen, T. Gibon, B.L. Bodirsky, H.S. de Boer, O. Fricko, M. Hejazi, F. Humpenöder, G. Iyer, S. Mima, I. Mouratiadou, R.C. Pietzcker, A. Popp, M. van den Berg, D. van Vuuren, E.G. Hertwich, Environmental co-benefits and adverse side-effects of alternative power sector decarbonization strategies, Nat. Commun. 10 (2019) 1–13, https://doi.org/10.1038/s41467-019-13067-8.
[150] T. Gibon, R. Wood, A. Arvesen, J.D. Bergesen, S. Suh, E.G. Hertwich, A methodology for integrated, multiregional life cycle assessment scenarios under large-scale technological change, Environ. Sci. Technol. 49 (2015) 11218–11226, https://doi.org/10.1021/acs.est.5b01558.
[151] C. Mutel, B. Cox, Wurst (n.d.), https://github.com/polca/wurst.
[152] I. Capellán-Pérez, I. de Blas, J. Nieto, C. de Castro, L.J. Miguel, Ó. Carpintero, M. Mediavilla, L.F. Lobejón, N. Ferreras-Alonso, P. Rodrigo, F. Frechoso, D. Álvarez-Antelo, MEDEAS: a new modeling framework integrating global biophysical and socioeconomic constraints, Energy Environ. Sci. 13 (2020) 986–1017, https://doi.org/10.1039/c9ee02627d.
[153] N. Martin, L. Talens-Peiró, G. Villalba-Méndez, R. Nebot-Medina, C. Madrid-López, The Energy Transition Beyond Climate Neutrality: Deeper Evaluations of Impacts and Constraints in Future Systems, 2022. Manuscript.
[154] European Commission, Study on the EU's list of Critical Raw Materials (2020). Factsheets on Non-Critical Raw Materials, Brussels, Belgium, 2020, https://doi.org/10.2873/867993.
[157] D. Süsser, H.Al Rakouki, J. Lilliestam, The QTDIAN modelling toolbox–quantification of social drivers and constraints of the diffusion of energy technologies, in: Deliverable 2.3. Sustainable Energy Transitions Laboratory (SENTINEL) Project, 2021, https://doi.org/10.48481/iass.2021.015.
[158] B. Best, J. Thema, C. Zell-Ziegler, F. Wiese, J. Barth, S. Breidenbach, L. Nascimento, H. Wilke, Building a database for energy sufficiency policies, F1000Research 11 (2022) 229, https://doi.org/10.12688/f1000research.108822.1.
[159] M. Degel, M. Christ, L. Becker, J. Grünert, Sozial-ökologische und technisch-ökonomische Modellierung von Entwicklungspfaden der Energiewende, Berlin, 2016.
[160] F. Lombardi, B. Pickering, E. Colombo, S. Pfenninger, Policy decision support for renewables deployment through spatially explicit practically optimal alternatives, Joule 4 (2020) 2185–2207, https://doi.org/10.1016/j.joule.2020.08.002.
[161] R. McKenna, J.M. Weinand, I. Mulalic, S. Petrović, K. Mainzer, T. Preis, H.S. Moat, Scenicness assessment of onshore wind sites with geotagged photographs and impacts on approval and cost-efficiency, Nat. Energy 6 (2021) 663–672, https://doi.org/10.1038/s41560-021-00842-5.
[162] T. Zhang, W.J. Nuttall, Evaluating government's policies on promoting smart metering diffusion in retail electricity markets via agent-based simulation, J. Prod. Innov. Manag. 28 (2011) 169–186, https://doi.org/10.1111/j.1540-5885.2011.00790.x.
[163] M. Melliger, E. Chappin, Phasing out support schemes for renewables in neighbouring countries: an agent-based model with investment preferences, Appl. Energy 305 (2022), 117959, https://doi.org/10.1016/j.apenergy.2021.117959.
[164] M. Melliger, J. Lilliestam, Effects of coordinating support policy changes on renewable power investor choices in Europe, Energy Policy 148 (2021), 111993, https://doi.org/10.1016/j.enpol.2020.111993.
[165] D. Süsser, A. Ceglarz, H. Gaschnig, V. Stavrakas, A. Flamos, G. Giannakidis, J. Lilliestam, Model-based policymaking or policy-based modelling? How energy models and energy policy interact, Energy Res. Soc. Sci. 75 (2021), 101984, https://doi.org/10.1016/j.erss.2021.101984.
[166] C. Mutel, X. Liao, L. Patouillard, J. Bare, P. Fantke, R. Frischknecht, M. Hauschild, O. Jolliet, D. Maia de Souza, A. Laurent, S. Pfister, F. Verones, Overview and recommendations for regionalized life cycle impact assessment, Int. J. Life Cycle Assess. 24 (2019) 856–865, https://doi.org/10.1007/s11367-018-1539-4.
[167] D. Süsser, A. Ceglarz, H. Gaschnig, V. Stavrakas, G. Giannakidis, A. Flamos, A. Sander, J. Lilliestam, The use of energy modelling results for policymaking in the EU. Deliverable 1.1, in: Sustainable Energy Transitions Laboratory (SENTINEL) Project, European Commission, 2020.
[168] D. Süsser, H. Gaschnig, A. Ceglarz, V. Stavrakas, G. Giannakidis, A. Flamos, A. Sander, J. Lilliestam, Models for the European Energy Transition: Your Questions, Your Needs!, Workshop Synthesis Report, 2020.