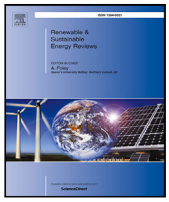
Renewable and Sustainable Energy Reviews 161 (2022) 112330

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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



Challenges and opportunities for energy system modelling to foster multi-level governance of energy transitions

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ARTICLE INFO

Keywords:
Multi-level
Governance
Energy modelling
Multi-scale
Policy-making
Energy planning

ABSTRACT

Achieving the swift energy transition necessary to meet global climate ambitions requires concerted action across governance scales, from municipal authorities to national governments. Decision-making is often closely informed by energy system modelling, making energy models a crucial tool to foster a multi-level governance system that is based on mutual understanding and coordination across scales. Here, we review 186 energy modelling studies and identify challenges and opportunities for the energy modelling community to take into account and facilitate multi-level governance systems. We show that current energy modelling practices typically focus on and aim to support a single scale, largely overlooking the multi-level nature of energy governance. Embedding multi-level governance throughout the energy modelling process entails significant obstacles but is crucial for ensuring such approaches continue to provide timely and salient decision-support.

1. Introduction

Energy systems stand at the core of global challenges from mitigating climate change to enabling energy access and reducing local pollution. Energy is also a complex interconnected issue, strongly embedded across different sectors, involving multiple actors, and with infrastructure spanning scales from local to global. This makes navigating the energy transition a unique governance challenge [1,2]. When national governments first agreed on a framework for sustainable development in Rio de Janeiro in 1992, the involvement of subnational governance institutions, in particular local government, was one of the key themes. More recently, the Paris Agreement stresses the 'importance of the engagements [sic] of all levels of government and various actors [...] in addressing climate change' [3]. The recent push towards more ambitious climate targets aimed at limiting global temperature increase to 1.5°C has led to increasing recognition of the importance of the role local governments bring to the radical and transformative societal change necessary [4,5]. This will require an effective system of multi-level governance where energy strategies and actions of governmental actors are coordinated and mutually reinforcing across scales.

Energy system models provide an internally consistent quantitative framework for thinking about the future development of the energy system. Energy models are used to design policies, develop strategies, and set long-term targets both in the private sector and by governments. At the national level, many governments make extensive use of energy models to support government policies. In the UK, for example, national-scale whole energy system models have had a striking role in setting legally binding emission targets and developing underlying energy strategies [6,7]. For subnational governance, in particular local governments, the use of energy models has been much less prevalent. However, there are efforts to underpin the increasing engagement of local authorities in energy planning with quantitative insights from energy models [8,9].

There is a growing discussion about the evolving requirements for energy system models to remain salient tools supporting decision-makers in shaping the development of energy systems. This is, for example, grounded in the increasing importance of variable renewable energies and socio-technical aspects that need to be captured adequately [10–12]. While some concerns about challenges evolving at the energy modelling-policy interface are discussed [12–14], there is limited acknowledgement of another major development: the emergence of and need for new multi-level governance arrangements. While the debate around multi-level approaches to governing is far from new, there is increasing realization that energy system models could play a crucial role in fostering coordination and more effective governance across scales [9,15]. Providing useful insights while fostering coordination across scales poses another major challenge to the energy modelling community.

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https://doi.org/10.1016/j.rser.2022.112330
Received 19 October 2021; Received in revised form 14 February 2022; Accepted 26 February 2022
Available online 1 April 2022

In this Review, we explore the current landscape, challenges, and opportunities of energy system modelling to facilitate multi-scale governance of energy transitions. In particular, this paper addresses the question to what extent current modelling practices are able to foster coordination across national and subnational scales as part of an effective and efficient multi-level governance system. Moreover, we elaborate on challenges and opportunities involved in this, sketching out potential future directions.

2. Multi-level governance and energy models

2.1. Multi-level governance and coordination

A multi-level approach to governing climate action and energy transitions that is to meet global climate and development ambitions hinges on the alignment and mutual reinforcement of targets, strategies, and actions of actors across governance scales [5]. The term 'governance scale' here refers to the governance arrangements centred around different tiers of government, from local or municipal governments, to state or provincial administrations, to national governments. While we focus our discussion on governments, this term acknowledges the role other actors play within these different tiers. Evidently, this alignment across scales requires coordination between actors, e.g., local and national government, as part of a multi-level governance system. An early definition of multi-level governance by Marks [16] describes it as 'a system of continuous negotiation among nested governments at several territorial tiers'. Indeed, it has been suggested this coordination should start with the creation of the governance arrangements itself, often largely shaped by national governments [17,18]. Given the complexity of the energy system and the cross-cutting nature of energy governance – ranging from urban planning to financial regulations [1] – coordination even between tiers of government is manifestly a complex, non-linear process.

Implementing coordination across scales will thus likely rely on manifold processes and depend on the countries' constitutional arrangements. In the UK, for example, while being a unitary state with sovereignty exercised only on the level of the nation state, devolved administrations and local authorities enjoy substantial powers with respect to the energy system, e.g., through economic development spending and planning and consenting powers [19,20]. The level of coordination across governance scales, however, has been questioned, with various changes proposed to improve it [18,21]. Kuzemko et al. [22] argue for more coordination so that the national government is aware of activities and learning taking place at the local scale, and to ensure coherence across energy plans. While local energy hubs – temporary institutions funded by the UK government to support energy projects across a set of local authorities – and heat network support programmes are seen as potentially providing elements of coordination, a more integrated and holistic approach is deemed necessary [22]. A concrete energy governance framework for the UK is suggested by Willis et al. [23], which builds on strong coordination across governance levels. It would give local authorities the responsibility and capabilities to prepare local plans in line with a devolved carbon budget to be set by the Climate Change Committee. A new body proposed by the framework, the national energy transformation commission, would fulfil, among others, a coordinating role between local authorities and national government. The need, or current lack of an integrated approach across governance scales has also been identified for other countries, e.g., with respect to renewable support in Indonesia [24] and energy policy in Germany [25].

With energy planning beginning to play an increasing role at local and regional level, it is vital that such efforts help shape energy system development across governance scales. This demands a shift from 'parallel energy planning' to a more integrated energy planning that is based on a continuous alignment of national energy objectives, local planning, and underlying policy measures [26]. This should ensure that both subnational energy planning, reflecting local characteristics and preferences, and national energy planning are mutually reinforcing [27]. Without such coordination efforts, there are risks of inconsistent energy objectives and actions being taken at different governance scales. For example, local governments may assume the availability of low-cost bioenergy resources for local heating, while national energy policy may wish to prioritize the use of that same limited resource for power generation with carbon capture and storage.

Coordinating planning processes requires two-way communication. Local authorities and other subnational actors rely on a clear set of expectations, requirements, and provisions from the national level to develop and implement energy plans in line with national objectives. On the other hand, ambitions, challenges, and barriers faced by subnational actors need to be communicated to be incorporated when designing national policies and plans [28]. Using the above example, it would be vital for national and local governments to engage in a dialogue on the use of biomass resources to facilitate a common understanding of related challenges, e.g., local heat decarbonization and negative emission requirements, and ensure biomass use is not integrated in conflicting ways in local and national energy planning.

2.2. The potential role of energy system modelling

Given the complexity of governance processes across different scales, creating a common understanding and achieving mutually reinforcing action across scales will require multiple and elaborate means of coordination. As tools already supporting decision-making at national and subnational levels [14], energy system models can play an important role in enabling this coordination.

Energy models are used in a variety of ways to support policy analysis. Gönenç and van Daalen [29] introduce a conceptual framework identifying different categories and objectives of models that also reveals the roles energy models can play in facilitating policy analysis that bridges national and subnational scales. One group of model types – analytical, advisory, and strategic models – is focused on providing relevant knowledge to aid the policy-making process in different ways. Models that provide salient input to governance processes while incorporating physical characteristics, policies, plans, or ambitions of multiple scales can be a valuable means of communication. They can either support decision-makers on a single governance level with knowledge about other scales or provide insights at multiple scales with analyses that help build a mutual understanding [30].

In contrast, the second group of model types focuses on those used as a medium for interaction. Mediation and discussion models have the potential to not only facilitate mediation and discussion of values and arguments between actors on a single governance level but also across different scales. Participatory models can encourage the involvement of stakeholders across scales in the policy process, for example, eliciting input from subnational authorities in national policy-making. Neither category is mutually exclusive and models can potentially serve multiple purposes. These functions underline the potential capability of energy models to act as boundary objects, bridging the different 'social worlds' of energy governance, aiding coordination across scales, and improving the link between knowledge and action by increasing salience, credibility, and legitimacy across scales [31,32].

3. Approach to consider multi-level governance in model-based studies

A large number of energy modelling reviews have been published in recent years, e.g., [10,33–38], with several capturing different aspects relevant to this work. Pfenninger et al. [10] consider a wide range of national-scale energy system models and identify four challenges and relevant efforts to address them. One of the challenges is concerned with different scales – both temporal and spatial – on which energy system models operate and how future developments, in particular the

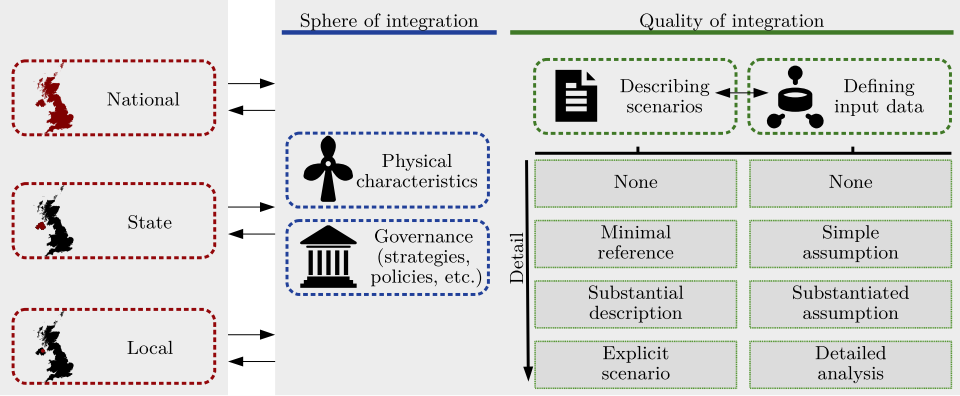

Fig. 1. Diagram depicting an overview of the analysis approach. With the target governance scale identified, the potential integration of other scales is assessed with respect to two dimensions, i.e., the sphere and quality of integration. The quality of integration consists of a quantitative and qualitative element for each of which a few guiding levels of detail are given. Icons are from [41] published under CC-BY licence.

integration of more variable renewable energy resources, require multi-scale approaches. Lopion et al. [37] also review trends and challenges in national-scale energy models including the importance of spatial and temporal resolution as well as transparency in code and data. Savvidis et al. [38] consider the relation between policy challenges and the capabilities of energy models, evaluating the ability of models to address particular policy questions but not issues concerning different governance scales. Other reviews examine models on the local scale, but do not focus on the importance of other governance scales that play a role in shaping local energy system development [33,39,40]. While some reviews highlight the importance of spatial scale and relevant multi-scale approaches, there is no review that considers the way modelling studies engage with the multi-level nature of energy governance. The aim of this work is to assess the interface of current energy modelling practices and multi-scale governance as well as to discuss the opportunities and challenges that need to be addressed for energy modelling to play a more substantive and driving role in supporting coordination across scales.

To assess this, we consider if quantitative studies and underlying models – independent of the exact role models might currently be playing within the governance process – take into account targets, strategies, or policies of actors on another governance scale. This can either be in a qualitative manner, e.g., in their scenario storylines, or in a quantitative manner, i.e., explicitly in numerical model assumptions. While acknowledging the diversity and complexity of governance systems across the world, we structure the analysis mainly around three common scales, i.e., the 'local' scale for municipal governments, 'state' scale for federated states, provinces or equivalent, and the 'national' scale for the central government of nation states. Fig. 1 depicts an overview of the analysis approach.

It is useful to differentiate two categories of models based on their target audiences. First, there are models that provide insights for actors on a single governance scale but incorporate relevant developments on other scales, and which can help to establish a one-way coordination. For example, a model that establishes energy pathways for a particular municipality while incorporating different national policy scenarios can help local authorities to align their actions with national strategies. In conjunction with other models, this can establish an iterative process of coordination between scales. Considering this definition, most energy system models will generally be capable of fulfilling this function by basing input parameters or scenario storylines on assumptions that integrate another governance scale. Thus, the main consideration here is to what extent, if at all, model-based analyses explicitly integrate assumptions with regard to another governance scale.

The second category consists of models targeting actors on two or more governance scales. These models can potentially provide consistent insights and allow for a more direct two-way coordination across governance scales. In order to be capable of providing insights pertinent to multiple scales, models need to explicitly depict relevant territories, i.e., exhibit an appropriate geographic coverage and resolution. There is therefore an important structural characteristic of such models. Here, the question is thus what such models exist and, similar to above, to what extent their applications integrate policies and strategies from multiple scales.

As this review does not aim to answer a narrow research question but attempts to advance the broader understanding of the energy modelling landscape, we do not perform a formal systematic review, yet follow a structured, semi-systematic approach [42]. The aim is not to review the vast number of academic papers and other publications that involve energy system models, but to incorporate a broad range of models with respect to geography, methodology, and sectoral focus, as well as to particularly capture potential multi-scale studies. While a substantial part of the models covered are used to directly support policy-making in various countries, all studies generally aim to provide policy-relevant insights and might contribute in one way or the other to policy debates which would benefit from insights that take into account multiple scales. The units of analysis are modelling studies in conjunction with the specific model implementation used to run underlying scenarios. That is, publications that describe the same analyses based on the same scenario runs are represented by an aggregated entry, while a study using an updated model version that incorporates new data to run a different set of scenarios would be a separate entry.

Modelling studies to be reviewed are identified in three different steps. First, a search for multi-scale, policy-relevant energy modelling analyses is conducted using all Web of Science databases. The latest search has been performed in April 2021 using the search string 'AB=((multi-scale OR multi-level OR polycentric OR ((subnational OR local OR urban OR city OR county OR municipal* OR state OR province OR prefecture) AND (national OR central OR federal OR country))) AND ("energy model*" OR "energy system model*") AND (polic* OR govern* OR decision-making OR planning))'. Second, in order to assemble a broad set of models, references of three comprehensive energy modelling reviews [10,37,39] are scanned. Third, related publications that were identified during the previous steps, e.g., through snowballing techniques, were included as well, resulting in an overall set of over 600 publications. In order to select studies for inclusion in the review, the identified studies were then filtered based on a number of inclusion criteria to arrive at set of analyses relevant to supporting decision-makers in energy planning. In particular, we only include studies if they

- include an analysis based on a quantitative model that covers at least parts of an energy system of an actual geographic area,
- balance demand and supply, even if sectors are not explicitly represented, and

Table 1
Criteria values and explanation for the qualitative multi-scale criteria.

Value	Link to other scale	Example
None	The study makes no reference to another scale.	Takase and Suzuki [43] derive energy system pathways for Japan but do not mention prefecture- or local-level aspects.
Minimal reference	There is a sole instance of an undetailed reference to another scale, usually restricted to a single sentence, or there is a more extensive, but not directly related to the scenarios, discussion in, e.g., the introduction.	Anandarajah et al. [44], while discussing energy scenarios for the UK, mention the need for local implementation of regulation in the policy discussion of scenarios.
Substantial description	There is a substantial description, this can be both vague references or detailed explanations about assumptions.	While modelling decarbonization scenarios for the Indian transport sector, Dhar and Shukla [45] describe assumptions, e.g., better urban planning and availability of finance for cities to foster public transport, in their scenario storyline.
Explicit scenario	One or more explicit scenarios are defined and feed into the analysis.	Anandarajah and McDowall [46] explore decarbonization scenarios for the UK, two of which are specifically introduced to capture Scottish energy policy.

Table 2
Criteria values and explanation for the quantitative multi-scale criteria.

Value	Link to other scale	Example
None	No parameter value is explained to be derived from another scale.	See Table 1.
Simple assumption	One or more simple assumptions are made.	Ludig et al. [47] develop power sector scenarios for a region in Germany and refer to the German nuclear policy at the time when making a simple assumption about a phase out of nuclear energy until 2030.
Substantiated assumption	One or more straightforward assumptions based on data from the other scale are used.	Lu et al. [48] integrate state-specific emission requirements of the Clean Power Plan in their energy scenarios for Indiana (US).
Detailed analysis	A comprehensive analysis of data is performed to feed into one or more parameters.	Cole et al. [49] provide an extensive analysis and description of state-level policies and how they feed into the national-scale power sector model.

- have a spatial extent relevant to subnational or national governments, i.e., at the minimum a substantial part of a municipality.

For example, models of individual buildings or facilities, or studies only estimating the technical potential of renewable energy sources are excluded.

The final set of studies is analysed manually in an open-ended fashion but also with respect to a set of simple criteria with specific levels in order to derive a quantitative overview. As depicted in Fig. 1, we evaluate studies with respect to the extent they integrate other governance scales in a qualitative manner, e.g., in their scenario storylines, and in a quantitative manner, i.e., explicitly in numerical model assumptions. For each of the two, we differentiate between links to other scales in general, i.e., based on developments, characteristics, properties, or governance aspects, and governance links in particular, i.e., targets, strategies, policies, actions of actors on the other scale, resulting in four criteria in total. The criteria values and underlying explanations for the assessment of the qualitative and quantitative criteria are given in Tables 1 and 2, respectively.

4. Current modelling practices

A broad set of 186 modelling studies across different geographies and scales is reviewed in detail (see supplementary material for details). Fig. 2 gives an overview of geographic and scale distribution of all studies. In total, 41 local, 19 state and 126 national-level models covering 40 different countries are assessed. The scope of models ranges from whole energy system (118 models), to power system (27 models), to others focusing on one or more parts of the energy system, e.g., the heat or transport sector.

In general, the review shows that current modelling studies integrate multiple governance scales to a very limited extent. Fig. 3 gives an overview of the quantitative analysis of all studies. The majority of studies either do not describe aspects from other scales other than the target governance scale, or do so only to a minimal extent. Only 9 out of the 186 studies incorporate scenarios that are specifically focused on characteristics or developments on other scales. Even fewer studies integrate governance aspects, e.g., strategies and policies of other governmental authorities. From a quantitative perspective, only around half of the studies explicitly link model data with other scales and less than one in four explicitly integrate assumptions around strategies, policies, or actions of actors on other governance scales.

We now consider review findings separately for studies aimed mainly at subnational, i.e., local and state, or national stakeholders, respectively. We then look in more detail at a subset of those models that exhibit a spatial extent and resolution that capture more than one governance scale and, thus, could potentially provide insights to decision-makers across scales. Studies are assumed to be targeting a particular governance scale if they capture the geographic entities explicitly and show and discuss respective results.

4.1. Subnational models

Given the usually substantial decision-making power reserved to national governments, their actions often have a decisive impact on local

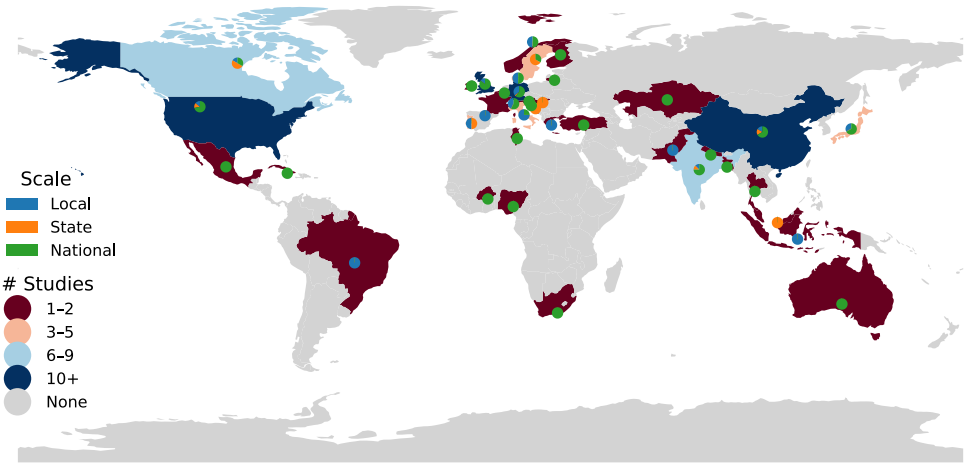

Fig. 2. Overview of the distribution of reviewed studies across scales and geographies. Countries' colouring is based on the number of studies in the particular country, while the respective pie charts show the split across different scales.

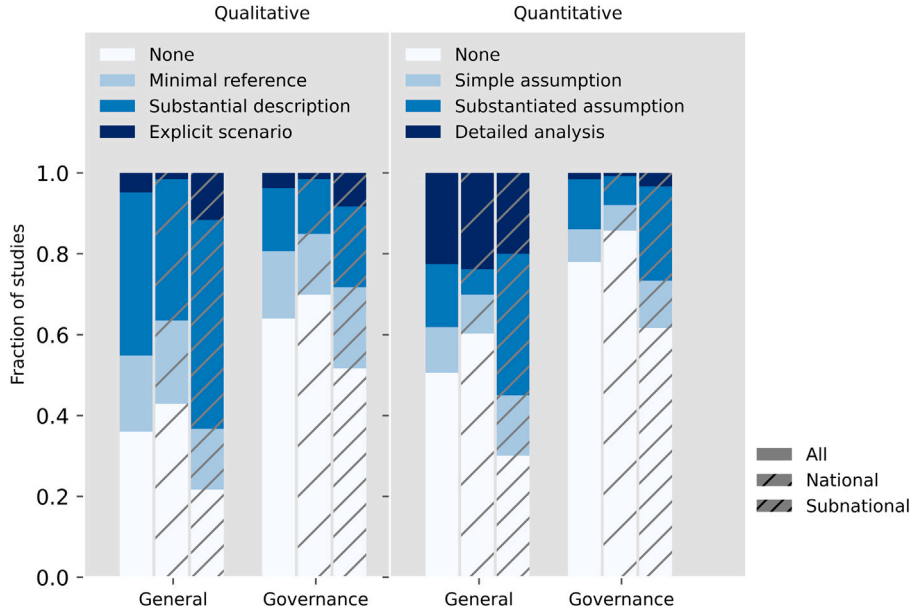

Fig. 3. Overview of the quantitative evaluation of all reviewed studies giving the fraction of studies that exhibit certain values with respect to the four multi-scale criteria.

and state-level energy systems, as well as on subnational stakeholders' ability to act. For example, cost and carbon intensity of grid electricity – often a crucial element of subnational decarbonization strategies – will likely be largely dependent on power sector regulation and policies set by the central government. There are also other national-level measures that will likely strongly influence subnational energy systems, even in analyses of 'autonomous' subnational systems, such as national support through subsidies, or investment in research and development of new technologies.

Subnational energy scenarios implicitly adopt assumptions around national-level policies, yet our review found that the policies themselves are rarely considered explicitly. For example, the carbon intensity of grid electricity is often exogenously represented in local energy system models, without explicit discussion of the national policies influencing this outcome. A similar pattern is found for technology and electricity costs. A more explicit focus on these aspects in the context of, potentially varying, national efforts could better help subnational stakeholders align strategies and adapt to policy shifts at the national scale.

We first consider models focused on local scales, e.g., at the scale of specific cities, and then those focused on larger subnational regions, e.g., states and provinces. Local energy system studies rarely make assumptions around national-level strategies and policies explicit. This is especially apparent when considering system elements that strongly depend on national action, for example, electricity from the national transmission grid. Studies seldom specify relevant characteristics, e.g., cost and carbon intensity [50], or do so but without referring to the national policies that would shape such a development [51]. Studies that do describe a link between input data and national decision-making refer, for example, to policies or strategies influencing imports into the local area, e.g., electricity [52], regulations for buildings [53] or vehicles [54], or emission targets or costs [55]. The lack of discussions that comprehensively ground assumptions in national policies conceals the influence of state and national government and hinders decision-support that takes into account the underlying governance system.

This weak link to the national level is similarly evident from a qualitative perspective. Local scenario descriptions or storylines mostly ignore state or national governance, independent of the type of model used and sectors covered, or include them only to a limited extent.

Some of the reviewed studies make isolated statements about, for example, the relevance of national policies in general [56] or particular policies that are part of the scenario [57]. Only a small subset of studies describes scenarios in detail from a state or national-scale perspective. For example, Lind and Espegren [58], while exploring three decarbonization scenarios for Oslo, describe Norway's national policy landscape, including a list of policy measures that is incorporated in the model inputs. Only one study explores scenarios that are explicitly focused on capturing different national policy developments. Yazdanie et al. [59] analyse the influence of two scenarios related to the Swiss national energy strategy on cost-optimal energy pathways for the city of Basel. The study highlights the influence of national strategies on local energy planning in Basel and how such multi-scale analyses can foster a better understanding of such links among local decision-makers.

State-level modelling studies exhibit a similar pattern to that found in local studies. While there is a widespread acknowledgement of the influence of national strategies, these are not generally examined with explicit, comprehensive national policy scenarios. Some state-level modelling studies describe isolated assumptions about national developments [48], while 4 out of 19 studies capture specific national [60,61], local [62], and both local and national scenarios [63]. Yet, these scenarios mostly focus on a certain aspect, for example, the implementation of a particular national policy, and do not integrate the national or local level in a comprehensive manner.

Both state and local energy studies address developments on other scales – particularly the national scale – more frequently than national studies. This can also clearly be seen in Fig. 3, and likely reflects the importance of national decision-making for local and regional energy scenarios.

4.2. National models

While energy policy is mainly shaped at the level of nation states, subnational stakeholders play a considerable role in enabling swift energy transitions. Federated state governments sometimes exercise substantial decision-making power over certain aspects of the energy system themselves, while fostering implementation and enforcing regulations often relies on local authorities, who are increasingly developing their own targets and plans. State and local-level policies, targets, or strategies inherently form part of the governance that underpins model-based national energy scenarios. Yet, as shown in Fig. 3, most national studies reviewed for this work did not explicitly integrate subnational governance in their scenarios. In comparison with subnational modelling studies, there is a much smaller fraction of studies that describe subnational aspects of the scenarios being explored. While studies of subnational energy systems tend to acknowledge at least to some extent the national level to situate themselves in their geographical context, studies at the national level are much more likely to overlook or disregard municipal or state actions or plans. This might be due to a lack of influence attributed to subnational actors or the challenging task of taking account of the diversity of local or state initiatives and ambitions.

The general relevance of subnational governance for national-scale energy analyses is evident in the widespread but vague references to state and local decision-making. Numerous studies discuss [64], or at least mention [44], the importance of subnational engagement in the transition, although this is not directly reflected in the scenario description itself. If local governance of energy systems feeds into the scenario design, this is usually done in a very generic manner, such as making reference to efforts in urban or rural areas in general [45], or referencing specific examples, such as transport infrastructure projects in particular municipalities [65]. Kumbaroğlu et al. [66] introduce an explicitly locally driven scenario for their energy pathway analysis for Turkey. Yet, this scenario only captures a single policy in a single municipality, i.e., the uptake of electric buses driven by plans of local authorities in Istanbul. The review did not uncover a single study that presents a comprehensive analysis of actual local efforts, strategies, or targets across a country that feeds into the scenario development. Concerning the state level, national studies more frequently make direct links to concrete policies of particular states. Studies often provide some explicit examples of policies, implying they were considered in the analysis or claim a broader analysis took place but without clarity on how they impact on the results [67].

4.3. Models with the potential to target multiple scales

One model characteristic that has not yet been discussed but which is intrinsically linked with multi-level governance is spatial resolution. While the majority of studies in this work do not rely on a model with a spatial extent and resolution that captures more than one governance scale, 32 of the 186 studies do. This allows assumptions from multiple scales to feed directly either qualitatively or quantitatively into the scenario design, without the need for aggregation. These models could create insights that are pertinent to stakeholders across scales and capture interactions across scales endogenously. For example, models could explore how a national emission budget could be translated into local climate targets across the country based on local characteristics. It allows stakeholders to explore trade-offs and to build a common understanding of energy pathways across governance scales. Despite this capacity to explicitly integrate multiple governance scales, most of the 32 studies only address a single scale and do not utilize the spatially disaggregated model structure to incorporate a detailed analysis of policies and strategies of the other scale.

20 national-level studies reviewed for this work have a state or district-scale resolution. The potential challenge of establishing such models, with respect to computational tractability and required effort to, e.g., assemble data, relate partly to the number of states and thus varies across countries. The models consider countries with a federal structure, e.g., Canada [67], or Germany [68], but also cover unitary states like the UK [46] or China [69]. Reviewed studies based on models with state-level resolution generally do not involve a more detailed integration of state-level governance than other national-scale models attempting this. The underlying studies do not explore detailed state-wise scenarios and mainly discuss insights relevant to the national scale.

Given the usually large number of local government districts within a state or country, developing and running models with a resolution that bridges these scales can be challenging. There are increasingly high-resolution models looking at specific aspects of the energy system, e.g., deriving energy demand [70,71], but only a limited number that capture more comprehensive planning approaches surveyed here. A few studies in this review bridge to the local scale but are limited in their scope, e.g., looking only at the power sector [72] or district heating [73], only consider a single local area in relation to the national energy system [15], or aggregate local areas, e.g., based on a cluster analysis [74]. Börjesson et al. [75] implement a detailed whole energy system model capturing all local areas in one of Sweden's counties. Despite exhibiting model resolutions that would potentially enable a direct representation of local policies, studies do not incorporate a detailed analysis of those as a basis for the scenario design.

4.4. Gaps and a way forward

There is a lack of energy modelling activities that attempt to integrate multiple governance scales. The vast majority of reviewed studies shy away from a meaningful analysis of strategies, policies, or targets of actors other than the ones on the target scale of the study. In particular country-scale energy modelling, which could play a crucial role in linking up national energy policy with strategies at state and local level, hardly takes into account subnational, in particular local, governance. Thus, current modelling practices have generally no or a very limited potential to facilitate coordination across scales. More

efforts bridging local, state, and national scale are necessary to facilitate a better understanding of policies across scales and enable coordinated action.

This requires energy modelling processes to take into account other governance scales in a much more comprehensive manner and to establish scenarios based on detailed analyses of targets and strategies of other governance scales. This does not necessarily require a multi-scale model with a resolution spanning two or more scales, but could be based on an exogenous analysis that feeds into a single scale model, e.g., at the national scale, or multiple models developed at different scales. Multi-scale models offer the potential for the explicit representation of multiple scales, through meaningful aggregation approaches or high-resolution models. While this offers the potential for integrated analysis that ensures analytic consistency across scales, it comes at the cost of increased model complexity. For any approach to be pertinent to local stakeholders this needs also to capture local characteristics and requirements that might shape different local pathways across a country.

5. Challenges

Developing and applying energy system models as part of collaborative processes that support multi-scale governance and coordination across scales poses a set of overarching challenges to the energy modelling community. These challenges are not necessarily solely a result of emerging multi-level governance arrangements but are often also related to other energy system developments that demand a change in modelling approaches. While acknowledging the range of issues that relate to multi-level governance, e.g., data availability and quality, we highlight three key challenges on the path towards energy modelling that facilitates coordination across governance scales.

5.1. Involving stakeholders across scales

Involving decision-makers in meaningful ways is crucial for energy modelling activities to provide purposeful support to decision-making [32,76]. In particular at the local scale, the diversity of energy system characteristics and priorities across municipalities makes engagement crucial. This is not restricted to effective communication of modelling results and insights, but requires involvement throughout the modelling process, from the decision for a particular modelling approach to answer policy-relevant questions, to the scenario creation. Engaging stakeholders in this process can provide a vital understanding and knowledge of the energy system and future pathways itself, but is also crucial in order to provide modelling insights that are salient to the policy-making process as well as regarded as legitimate by the actors involved [32].

Involving stakeholders throughout the process is also crucial for modelling efforts that seek to facilitate coordination across governance scales. This can be particularly challenging as it requires to engage stakeholders from more than one governance scale. If modelling activities target multiple governance scales and aim to facilitate a process of direct discussions across scales, a collaborative approach that involves actors from different scales is crucial to ensure the process and insights are salient and perceived as legitimate by actors across scales. Even if the target audience is a particular scale, enriching the process with input from other scales could achieve better substantiated modelling and a process that is regarded as legitimate by other scales which might be directly impacted by decisions taken based on the modelling.

While involving decision-makers across scales in modelling processes can be very enriching, it is also a significant challenge. Involving subnational authorities would require processes that are able to include a large number of actors or rely on a legitimate representation of those. There is also a large difference in the capabilities and resources of different actors in engaging in such processes. While central governments often have significant experience and resources – sometimes running their own complex energy models –, local authorities often have limited resources available for energy planning and energy modelling in particular [9,77].

5.2. Salience across scales

Evidence is most likely to be used in policy when it is considered salient by relevant decision-makers [32]. Salience, or relevance to policy problems, is directly influenced by the scale at which evidence is produced. For example, evidence produced for a national government may appear to be less relevant to city officials that know their own city's context differs from the national average. For energy modelling to provide the means to foster coordination across scales, particular energy models or system of models need to be salient in their support to decision-makers on multiple scales. Local, state, and national authorities can have starkly different decision-making contexts with respect to, e.g., aim, remit, and time frame of decisions. Taking this into account can be decisive in choosing a modelling approach or study design that is able to provide relevant insights.

For local decision-makers this context is, for example, extensively shaped by detailed local knowledge and requirements with respect to the spatial dimension of future energy system development [78]. Energy planning and energy projects have to take into account specific local circumstances and wider local planning objectives. This means that energy models that aim to support decision-making at the local scale must meet a set of requirements with respect to spatial representation and local-scale interactions between sectors. In particular, there is an increasing need for integrated modelling and assessments that capture interactions between the different sectors of local energy systems as well as local pollution, climate, land use, or transport systems, in order to provide salient input to decision-making processes at the local scale [33,79]. This is in stark contrast to regional or national scale where such local detail and interactions are difficult to capture and a different set of requirements and policy questions are at hand.

5.3. Transparency

The importance of transparency in energy system modelling has increasingly been highlighted in recent years [13,76], but we find it is particularly important for analyses that bridge governance scales. Energy models considering future energy systems are inherently subject to uncertainty [80]. Assumptions concerning model structure and input data are often based on the modellers' subjective judgement and models are not possible to validate [81]. This has led to the point that energy modelling has been described as being both art and science [81]. Yet, despite the high stakes and uncertainty in energy modelling, most models remain black boxes with neither software code nor data accessible to other interested parties [82]. This hinders independent scrutiny, decreases trust in model results, and raises critique of the findings of such model-based enquiries [13]. Transparency here entails not only the availability of code, data, and analyses – preferably under open licences – but also relates to them being made understandable to stakeholders through an intelligible structure, documentation, and direct engagement [76]. This is crucial to increase public trust in modelling efforts that seek to engage in highly contested societal topics as well as strengthening the science-policy interface. It is particularly the case for modelling efforts that seek to bridge scales. For such models to play an impactful role, they need to enjoy credibility across the social boundaries of local, regional, and national stakeholders with often opposing views that can hardly be achieved without a basic level of transparency [32].

Establishing a deep-rooted transparency in the development and application of energy system models is not a straightforward task. It requires energy modellers' commitment, and time but also appropriate funding streams [14]. Being transparent and comprehensible is particularly challenging when addressing not only national but subnational authorities, which tend to be less-resourced, with less capacity to engage in potentially complex energy modelling processes [9,83].

6. Opportunities

Despite the challenges for energy modelling to adapt to and support multi-level governance arrangements, there are also a set of developments the modelling community can take advantage of.

6.1. Growing demand for and understanding of energy system analyses at subnational scales

While local energy planning has a long history in certain countries, e.g., Sweden, where local energy planning has been legally mandated in the 1970s [84], it is only just becoming more widespread in other parts of the world. The growing interest in shaping energy systems at the subnational level also entails a growing exposure to quantitative tools that can support planning and guide action. While subnational, in particular urban energy modelling has long been an active research field in academia [33], these efforts have largely not been linked closely with decision-making processes of relevant actors. A growing demand for quantitative analyses at the local and state level provides the opportunity for the energy modelling community to engage, refine modelling approaches to suit the needs of decision-makers and, from the outset, integrate this modelling process with national-scale governance and energy system models. This also brings the opportunity to improve national-scale models itself by underpinning analyses with subnational detail and insights.

In the UK, for example, a formalized approach to local energy planning was developed and trialled recently to help local authorities establish viable strategies. The process relies on detailed modelling that allows to capture local characteristics but is also linked to an existing, widely used national energy system model [8].

6.2. Open-source modelling frameworks and open data initiatives

In recent years, a strong push towards open and transparent practices in energy modelling is providing vital building blocks for modelling endeavours that aim to bridge governance scales. There is an increasing number of open-source energy modelling frameworks, e.g., OSeMOSYS [85] and Calliope [86], open data platforms, e.g, the Open Power System Data project [87], as well as analysis and visualization toolboxes, e.g., Pyam [88]. More and more institutions release data under open licences and a growing number of energy modellers publishes the code and data underlying energy analyses. Moreover, the digitization of the energy system potentially opens up new data sources, for example, from smart meters, that could provide high-resolution data input for energy modelling if appropriate data sharing mechanisms are implemented [89].

These developments provide an opportunity to make the mammoth task of delivering multi-scale modelling efforts feasible. The use of open-source energy modelling frameworks diminishes the work needed to set up a quantitative model while allowing to adapt the framework to fit specific needs of the project. Models with openly licensed code and data, e.g., describing national energy scenarios, can be linked to own model-based analyses on a different scale, e.g., for local energy planning. Open and readily accessible data is crucial to meet the large data requirements for multi-scale, high-resolution energy models and is also precondition for making models itself transparent and freely accessible.

6.3. Advancing computational capabilities

From its onset after the oil crises in the 1970s, computational capabilities have been central in enabling energy modelling activities [89]. In recent years, energy modellers have increasingly access to ever expanding computing power, in particular through high-performance computing clusters. Open-source modelling frameworks, for example, Calliope [86] and Temoa [90] are increasingly designed for application on computing clusters. The use of advanced computing resources can drastically reduce model running times and enable higher resolution models and extensive study of the sensitivities of model runs [91]. This provides the energy modelling community with the opportunity to implement new, computationally expensive modelling approaches that seek to bridge governance scales.

7. Conclusions

The importance of effective multi-level governance to achieve ambitious climate targets is increasingly being highlighted. Yet, in this Review, we show that current energy modelling practices, while playing a crucial role in supporting decision-makers across different scales, largely overlook the multi-level nature of energy governance. For energy models to take on a decisive role in fostering coordination and mutual understanding across governance scales, the energy modelling community needs to further bridge disciplinary boundaries and address challenges towards modelling processes that integrate multiple governance scales. Such multi-scale approaches are not unprecedented and the community can also look to other fields, e.g., water management, where multi-level governance has for long played a more prominent role.

CRediT authorship contribution statement

Leonhard Hofbauer: Conceptualization, Methodology, Formal analysis, Data curation, Writing – original draft, Writing – review & editing. **Will McDowall:** Conceptualization, Methodology, Data curation, Writing – review & editing, Funding acquisition. **Steve Pye:** Conceptualization, Methodology, Data curation, Writing – review & editing, Funding acquisition.

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.

Funding

L.H.'s work was support by the Engineering and Physical Sciences Research Council, UK under grant EP/R513143/1.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.rser.2022.112330.

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