

Endogenous integration of qualitative factors into quantitative energy transition modelling for development

Neve Fields^{a,*}, Alycia Leonard^b, Martin Mutembei^c, Anne Nganga^c, Leigh Martindale^a, Marissa Bergman^d, Mwansa Kaoma^e, Mark Howells^{a,f}, Ed Brown^a

^a STEER Centre, Department of Geography & Environment, Loughborough University, Loughborough, United Kingdom

^b Department of Engineering Science, University of Oxford, Oxford, United Kingdom

^c Strathmore Energy Research Centre, Strathmore University, Nairobi, Kenya

^d University College London, Institute for Sustainable Resources, London, United Kingdom

^e The University of Zambia, School of Engineering, Lusaka, Zambia

^f Centre for Environmental Policy, Imperial College London, United Kingdom

ARTICLE INFO

Keywords:

Energy policy
Energy planning
Just energy transition
LMICs
Qualitative energy research
GESI
Resilience
Climate adaptation

ABSTRACT

Energy transition research in low- and middle-income countries often employs quantitative modelling to analyse possible future development pathways which leverage clean, renewable, and efficient energy to meet societal needs and promote development. Yet such quantitative methods are often critiqued for their reductionary nature, and failure to capture the wider contextual real-world complexities in which energy decisions are made. Integrating qualitative considerations into energy modelling offers an opportunity to reflect these complexities and strengthen techno-economic research, particularly when these considerations can be structurally integrated into models themselves. By developing a framework for endogenous qualitative integration into energy transition modelling for development – through extensive stakeholder co-production, qualitative storylines, and contextual analysis – this paper outlines feasible steps for qualitative incorporation at all phases of the modelling research process. Supported by the results of a systematic literature review, it recommends that qualitative considerations, such as social dynamics, human behaviour and institutional factors - alongside a particular focus on gender and social inclusion, resilience and climate adaptation awareness - be examined and integrated at all stages of the modelling research process, conceptualised into four phases: (1) ‘Pre-Modelling’, (2) ‘Storytelling and Narratives’, (3) ‘The Model’, and (4) ‘Beyond the Model’.

1. Introduction

The paper investigates how qualitative factors can be integrated into quantitative energy modelling research procedures. It presents an approach for improving modelling research processes to address challenges in long-term energy planning in low- and middle-income countries (LMICs) via integration of qualitative methods. Moreover, it moves beyond exogenous qualitative integration to also examine how model structures can be developed to allow for endogenous representation of qualitative factors.

Access to clean energy is crucial for reducing greenhouse gas emission, improving livelihoods, and enabling critical development efforts in sectors such as education, health, and the economy, which often disproportionately impact vulnerable and marginalised groups. Within

this context, energy transition research, as a field of energy planning, has emerged to assess how energy systems can shift from fossil fuels to clean and renewable resources while affording equitable access and benefit [1]. Energy transition planning is a particularly prevalent challenge for LMICs which are experiencing simultaneous and rapid industrial and economic development and must manage these wider societal transformations while also developing their energy sectors. Additionally, energy sectors in these countries often require transformation beyond the replacement of carbon-intensive fuel and technologies with greener ones, to meet rapid demand growth and electrification, security, reliability, and energy efficiency needs [2].

Energy transition research has surged since the 2015 Paris Climate Agreement, which requires the development of Nationally Determined Contributions (NDCs) and long-term transition strategies to achieve

* Corresponding author.

E-mail address: N.Fields@lboro.ac.uk (N. Fields).

<https://doi.org/10.1016/j.rser.2025.115917>

Received 18 February 2025; Received in revised form 1 May 2025; Accepted 30 May 2025

Available online 2 June 2025

1364-0321/© 2025 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

pledged commitments [3]. Generating these NDCs and strategies requires energy models: computational software which represent energy systems and use context-specific data to provide insights into future technology development pathways, supply and demand projections, emission factors, and system costs [4]. Within energy modelling communities, transition modelling is emerging within the science-policy-engineering interface as a method for providing evidence-led insights into uncertainties surrounding future development, investment, technology, and policy [5].

Energy models are widely used by researchers, planners and policy makers to explore possible future pathways and provide insights into the implications of different policy decisions [4]. These models provide policymakers and energy planners with evidence-based insights into possible future energy transition pathways based on pre-defined techno-economic parameters [6]. They have been employed by energy ministries globally to inform policy priorities, development, and expansion plans, as well as to secure financing for energy projects [7]. They are often also used to explore transition pathways, which is crucial for energy planning within LMICs, where demand is often expected to grow rapidly based on industrialising economies alongside expanding electrification and energy sector transformations [8]. To this end, energy optimisation models are often used to form a data modelling pathway, the results of which can be extended to estimates greenhouse gas emission emissions, electrification, energy efficiency, costs, and technology choices [9].

Energy models have historically employed broadly quantitative techno-economic approaches and are widely critiqued for not adequately representing the social, political, and behavioural factors which underlie and alter energy systems [10]. They involve limited examination of modelling contexts, inputs, and results beyond techno-economic parameters [11]. As such, it tends to omit non-technical drivers and constraints of transition [12], such as social acceptance, political will, and institutional feasibility, with little to no endogenous integration of such considerations [3]. Models which ignore these factors risk producing unrealistic results, which could impact the success of policy implementation and result in negative experiences for vulnerable populations [13–15]. These are often better captured through qualitative methodologies; that is, systematic approaches for gathering and analysing non-numerical data about human behaviour, social dynamics, and institutional factors [10]. These include stakeholder interviews, focus groups, ethnographic studies, policy analysis, and participatory research [16]. While effective, these qualitative methods are often under-used or treated as secondary to quantitative models due to their perceived lack of practical applicability. Certain modelling studies have discussed the need for wider social considerations and qualitative exploration as the next step in response to their results and the limitations of the research [1,17,18]; however, these considerations are generally left for future study.

Additionally, concerns have been raised over quantitative models' simplifying assumptions and abstract representations of real-world complex structures. By quantifying complex dynamics into a limited set of representative parameters, they often over-simplify reality, omitting nuances associated with complex systems, boundaries, and actors involved in decision making processes [12]. Previous quantitative energy modelling has therefore been criticised for the underrepresentation of social sciences and the subsequent undervaluing of the insights gained from such methodologies, particularly where this has resulted in the marginalisation of interdisciplinary and diverse perspectives [19]. Neglecting to adequately consider wider societal determinants to energy systems can make the numeric model results unrealistic. For instance, if social resistance to change is neglected in modelling, overly optimistic values (e.g., for technology adoption) may be taken as realistic parameters for future scenarios, creating modelling results which are infeasible and unrepresentative of reality yet presented as likely or realistic. To avoid such errors, capturing complex dynamics within energy modelling research and policy making processes is therefore critical.

Considering these qualitative factors is particularly important for energy modelling in LMICs, which face complex development challenges and intersectional vulnerabilities. However, the unequal treatment of LMICs in the energy modelling literature means that this has often been overlooked. While there has been a shift in energy modelling towards the examination of LMICs in recent years [4,20] (see e.g., studies in Sierra Leone [21], Bangladesh [22], South Africa [23], Nepal [24], Kenya [1], and Ethiopia [25]), global modelling studies have historically often poorly represented LMICs, for instance by aggregating countries regionally (i.e. sub-Saharan Africa (SSA) as shown in Refs. [26–29]). There are also wide disparities in the number of modelling outputs across LMICs; for instance, over 35 % of published energy modelling research in SSA looks at Nigeria and South Africa [30]. Modelling studies examining LMICs have also historically been led by researchers in high-income countries (HICs), a practice widely critiqued for a lack of contextual understanding and sensitivity to the context-specific parameters and boundaries of the energy systems studied [31]. The use of externally led energy modelling to inform planning decisions within LMICs has also reduced ministry and policy-maker agency [21]. Additionally, as most existing models have been developed for HIC contexts and societal structures and transferred to LMICs, they often falling short in adequately capturing LMIC features and contexts. Their inability to capture the socio-economic characteristics of LMICs - including rapid urbanisation, urban-rural splits, political instability, climate vulnerability, large informal sectors, and active transformation in the economy and social behaviours [8] - reduces the reliability of modelling outputs [31]. Even technical features of LMICs, such as low electrification rates, high prevalence of traditional fuels, supply restrictions, transmission and distribution losses and low efficiency rates [32] have been overlooked or inadequately represented.

Furthermore, existing modelling methods have been shown to poorly represent intersectional energy needs, and particularly those of vulnerable and marginalised communities within LMICs, showing the need for qualitative endogenous integration in this context [2]. This is problematic, as energy burdens, insecurities and injustices are unevenly distributed across groups of society [33]. By representing energy usage in aggregate, quantitative models often fail to capture differing energy wants, usages, and needs across marginalised and vulnerable groups [33]. To undertake truly intersectional energy planning - which acknowledges "that everyone has their own unique experiences of discrimination and oppression, and we must consider everything that can marginalise people - gender, race, class, physical ability" [34] - it is therefore critical to include the voices and requirements of those most marginalised, and to assess how long-term energy transitions may impact groups differently [35]. Such intersectional considerations are rarely accounted for in quantitative data and methodologies [36]; seeking to include them via qualitative integration offers an opportunity to move beyond the reductionism of aggregate energy models, responding to the non-homogeneity of populations within LMICs [19].

In energy transition modelling, particularly within LMICs, there is therefore a need to integrate behavioural, social, political, and developmental considerations [4]. To do this, emerging literature have identified a need for integration of qualitative and quantitative methodologies. Hybrid approaches have been developed as an attempt to achieve a more complete and holistic representation of the energy system [3,5,37–46], but the extent to which such methodologies can adequately capture the social, political, economic, and developmental challenges inherent to LMICs lacks adequate exploration. Furthermore, while previous research has explored integrating societal and behavioural factors in modelling (e.g., public opposition and opinions towards technology types and development [6,41,47]), explicit consideration of the complex energy needs of vulnerable groups remains limited. Such factors are particularly important for energy planning within LMICs, where inequality and poverty rates remain a significant challenge [19].

This paper therefore conceptualises how quantitative modelling research practices can integrate qualitative considerations to address

challenges to long term energy planning in LMICs. A systematic literature review is undertaken to examine how qualitative methods can be integrated into modelling procedures. The literature is categorised based on the approach to qualitative integration following Trutnevyte et al. [48]. Using the results of this review, the paper builds on previous literature by assessing how qualitative considerations can be endogenously integrated in quantitative energy model structures. This assessment is synthesized in an integration framework, and recommendations are provided for model improvement to allow for a more extensive and meaningful integration.

Despite previous literature providing frameworks for the integration of qualitative insights into quantitative modelling [33,49,50], all such work focuses exclusively on exogenous integration. Additionally, all previous applications of such qualitative integrations into modelling studies have exclusively been applied to HIC contexts. The novel contributions of this work are therefore.

- (1) To create a framework for endogenous qualitative integration into energy transition model structures themselves.
- (2) To address the unique needs of energy modelling research within LMICs as they pertain to qualitative integration.
- (3) To provide a framework for endogenous qualitative integration into all stages of the energy modelling research process within LMICs to aid development.

To present these contributions, this paper proceeds as follows. Section 2 reviews existing theoretical frameworks for integrating qualitative methods into energy modelling. Section 3 outlines the methodology employed to conduct a literature review and subsequently to determine the classification of existing modelling studies, which is set out in section 4. Section 5 contains the discussion, where a conceptual framework for qualitative integration is outlined. Finally, section 6 discusses the limitation, recommendations and conclusions from the conceptual framework explored within this paper.

2. Theoretical background of qualitative integration in quantitative modelling

The literature conceptualising the linking of quantitative models to qualitative insights from the social sciences shows agreement on *stages* of integration. Vågerö & Zeyringer [33] look at qualitative integration through the theme of energy justice, while Hucklebrink and Bertsch [49] do so through behavioural considerations. Despite the varying lenses, however, both studies arrive at similar findings, and identify three main stages of the research process where qualitative and quantitative methods can be integrated: 1) narratives and storylines as inputs, 2) model structure and technology inclusion/exclusion, and 3) output discussion. These similar findings indicate that the frameworks proposed can be generalised. Adding to these frameworks, whilst De Cian et al. [50] also highlights the importance of linking narratives and empirical evidence to modelling inputs, they identify an additional integral theme of co-production and deeper community engagement throughout the research.

A distinct strand of literature has focused solely on linking qualitative factors through storytelling [51], alternatively conceptualised as storyline-based scenario creation [37], story and simulation [16], and multidisciplinary scenarios [12]. Renner and Giampietro [51] theorise the process of quantitative storytelling into three steps: (i) identifying narratives to inform and contextualise the case study, (ii) contextualising the results for feasibility, desirability and practicality, and (iii) identifying knowledge gaps in previous and existing discussions. Cabello et al. [52] outline that quantitative storytelling is particularly useful to: (i) bridge different sources and actors' knowledge, including local and community knowledge, (ii) combine both qualitative and quantitative information regarding possible development pathways and uses of resources and (iii) cocreate narratives on the most viable and desirable

socio-technical pathways. Musango [15] describes quantitative storytelling as utilising narratives as analytical tools to reveal the breadth of views on the identified problem, uncertainties, and assumptions in relation to the case study.

Further literature emphasizes the importance of considering not only the *stage* and *type* of qualitative integration, but the *depth* of integration. Trutnevyte [48] classifies this into three types: *bridging*, *iterating*, and *merging*. In bridging research, the modelling process and qualitative research is carried out in parallel, with limited interaction beyond the 'bridging' of key common theories, themes and concepts. Bridging studies therefore have the least interaction between qualitative and quantitative methods. In an iterative approach, a qualitative story is developed, and contextualisation is performed, which is translated into parameters, scenario development, and assumptions for the model. The resulting outputs are also further contextualised and revisited within the qualitative narrative. Iterative research thus involves a higher degree of integration between the methodologies. Alternatively, merging involves extensive integration via structural modification of existing models. This allows qualitative considerations to be endogenously captured through the modelling of societal factors. By contrast, in the bridging and iterating approaches, the integration of qualitative methodologies and considerations remains exogenous to the model itself. To better understand the prevalence of endogenous vs exogenous qualitative integration, Trutnevyte's [48] theoretical framework is employed within this research to aid in the categorisation of existing modelling studies with qualitative factors.

3. Methodology

A systematic literature review [53] methodology was used to identify existing literature with qualitative integration in quantitative energy modelling. The first phase involved a document search and screening process, where potential existing studies were identified, screened for relevance, then excluded or included based on eligibility. The academic searching software Scopus was applied to undertake the literature search, where the keyword search of 'energy modelling' and 'qualitative analysis' for titles, keywords and abstracts was undertaken in January 2025. Initial results presented 1821 papers. The documents then underwent a screening process based on publication year (from January 2014–December 2024), peer-review (only peer reviewed articles were considered), and language written (English), leaving 151 papers within scope. The second phase involved a bibliometric analysis [54] of the identified studies, where authorship, year of publication, case study details, modelling software, and quantity of citations were noted. Alongside this, the papers underwent initial categorisations into two groups: 1) reviews and scoping studies, and 2) case studies and analytical papers. Primarily, this research was interested in identifying case study applications and research papers. The third phase involved an abstract analysis to identify those papers which use any energy modelling tools within case study application and contain significant qualitative integration or consideration as part of the methodology of the paper. The identified articles were screened for the two main criteria of 1) a case study application utilising an energy modelling software and 2) qualitative integration forming a significant to moderate section of the research article and employed methodology. Any articles where case study applications and/or qualitative methodological integration formed only a minor portion of the research were discarded. Ultimately, a total of 11 research papers were selected for content analysis.

This analysis used the levels of integration outlined by Trutnevyte [48] to categorise existing studies by their depth of qualitative integration (i.e., bridging, iterative, or merging).

Using the results obtained in the literature review, a framework for qualitative integration in the modelling process is developed in four phases (as shown in Fig. 1) [1]: 'Pre-Modelling': data collection and research scoping [2], 'Storytelling and Narratives': scenario creation, contextualisation and results analysis [3], 'The Model' itself: current

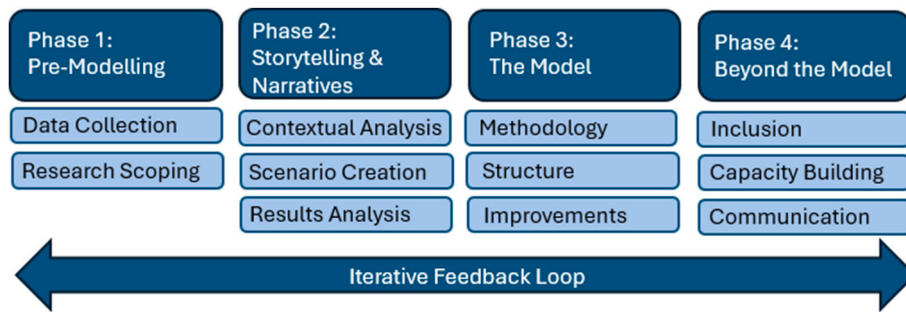


Fig. 1. A conceptual diagram of the four key methodological phases identified in this paper as part of the modelling research process: Pre-Modelling, Storytelling & Narratives, The Model, and Beyond the Model. There is a constant feedback loop across all the identified stages of the research project.

methodology, structure and future improvements, and [4] ‘Beyond the Model’: inclusion, capacity building and results communication.

4. Results

The systematic categorisation of existing energy modelling studies based on depth of qualitative integration is shown in Table 1, alongside an overview of how qualitative considerations were integrated into the studies and the methodological aims. Of the eleven identified case studies, nine assess long term energy pathway projections, with all the studies modelling to the year 2050 in line with energy targets within the

chosen countries [3,5,37,39–43]. The other three studies take alternative approaches through assessing two key years as the base year and end year [45], a back casting approach [44], and a mid-term projection with a five-year time step [46]. Additionally, the studies use a variety of modelling approaches within their studies, including simulation [45], optimisation [5,39–42,44,46], and a combination of both [3,37,43]. Several of the studies combined multiple models within their studies in attempts to address the limited real-world reflection of results from singular model applications [3,37,40,43,44].

Studies within the literature which use ‘bridging’ have linked qualitative considerations into modelling by conducting both qualitative and

Table 1

An overview of chosen literature integrating social considerations and/or qualitative methodologies. Level of integration topologised in line with the categories identified in Trutnevyte et al. [48].

Author	Case Study	Model	Modelling Approach	Level of Integration	Qualitative Integration	Aim of integration	Study Duration
Trutnevyte et al. [37]	United Kingdom	Demand, FESA, D-EXPANSE, BLUE-MLP, HESA, HAPSO	Simulation (Demand, FESA, BLUE-MLP), Optimisation (D-EXPANSE, HESA, HAPSO)	Iterative	Engagement of experts and key stakeholders to produce storylines with multiple perspectives	Lead to novel and creative ways of thinking about possible future pathways, and for accessible communication of scenario results	2008–2050
Fortes et al. [39]	Portugal	TIMES_PT	Optimisation	Iterative	Socio-economic storylines via participatory processes	Assess the interaction between social and economic factors	2010–2050
Chapman & Pambudi [40]	Japan	MARKAL/TIMES	Optimisation	Iterative	Householder and energy expert surveys, scenario design and social equity evaluation	Sustainability, societal equity preferences and user driven transition planning	1990–2050
Pye et al. [5]	United Kingdom	ESME	Optimisation	Iterative	Uncertainty qualification, result contextualisation and stakeholder engagement in analytical process	Assess uncertainty, strength of knowledge base, biases and value-ladenness and wider policy support in strategic energy planning	2010–2050
Bolwig et al. [41]	Nordic-Baltic region	Balmorel	Optimisation	Merging	Social acceptance framework and scenarios, model extension, and results analysis	Capture key factors of social acceptance of different energy transition pathways	2020–2050
Fell et al. [42]	United Kingdom	ESME	Optimisation	Merging	Stakeholder interviews and model extension	Capture distributional impacts of long-term low-carbon transition pathways	2020–2050
Geels et al. [3]	United Kingdom	IMAGE, WITCH, Enertile	Simulation (IMAGE) & Optimisation (WITCH & Enertile)	Iterative	Socio-technical scenarios	Explore social acceptance and political feasibility of low-carbon transition pathways	2010–2050
Hof et al. [43]	United Kingdom & Germany	IMAGE, WITCH & Enertile	Simulation (IMAGE) & Optimisation (WITCH & Enertile)	Iterative	Narrative based scenarios	Insights from socio-technical transition analysis on actor positioning and niche-innovations	2020–2050
Zhang et al. [44]	China	Fuzzy AHP, GRATOPSIS	Optimisation	Bridging	Root cause analysis to identify possible causes	Identification of factors to measure and improving regional energy security	2005–2017
Syranidou et al. [45]	Germany	MODEX	Simulation	Iterative	Model framework factsheets	Assessment of input data and scenario constraints to compare transmission grid models	2016 & 2030
Urban et al. [46]	Sweden	BeWhere	Optimisation	Iterative	In-depth expert interviews	Identification of opportunities, barriers, challenges, social implications, actors and policy issues of sector coupling	2019 & 2030–2050

quantitative methods in parallel and bringing together shared concepts using narratives in the scenario creation process. In these cases, the linking between methodologies remains surface-level. For example, Zhang et al. [44] look at energy security in China, through integrating qualitative considerations via root cause analysis to identify possible causes of (in)security for the energy sector. The aim of the research was to identify key factors to measure and improve regional energy security. Fuzzy AHP and GRA-TOPSIS modelling was first conducted for quantitative security assessment, followed by a separate Why-Why Diagram for qualitative security assessment. The key themes and insights were brought together, and compared, to achieve an overall regional energy security image, yet the methods remained isolated in execution and no iteration or merging occurred.

An increasing number of modelling studies have begun to move beyond surface level to 'iterative' integration, through incorporating qualitative narratives and storytelling into the wider modelling process [3,5,37,39,40,43,46]. For example, Chapman and Pambudi [40] explore the case of Japan and aim to use mixed methodologies to acquire strategic and user-driven transition scenarios which address issues of social equity and sustainability. They achieve this by conducting household and energy expert surveys to acquire a more holistic understanding of household energy systems and social equity preferences within Japan. The insights from the survey were used to build a strategic, bottom-up, and user-driven energy scenario which was conducted alongside a top-down strategic Japanese policy scenario. Both scenario results were compared via a social equity and holistic sustainability evaluation process. Similarly, Geels et al. [3] develop socio-technical qualitative scenarios to explore social acceptance and political feasibility of various low-carbon transition pathways. They develop a case study assessing future UK electricity generation and advocate for the use of storytelling techniques to identify 'transition bottlenecks', which the authors define as tensions between qualitative narratives and existing quantitative model generated scenarios, which can then be identified and overcome. Such 'transition bottlenecks' are used as a mixed method technique to guide communication of the socio-technical storylines by demonstrating how social acceptance and political feasibility of possible transition pathways can be improved by integrating stakeholders, preferences, support coalitions and policy into quantitative modelling studies.

In a similar vein, Fortes et al. [39] examine the case of Portugal and employ national stakeholder workshops in the early research stages to create socio-economic qualitative energy scenarios via participatory processes which are then translated into model inputs. Additional workshops are completed after the modelling is completed to compare stakeholder perceptions with model outputs. They aimed to use mixed methods to assess the interaction between social and economic factors and the researchers found substantial differences in stakeholder assumptions and opinions on their predicted model results with the actual quantitative scenario outputs. Divergence themes surrounded technology allocation and long-term reliance on imported resources by the model not aligning with the expectations of national stakeholders and beliefs about energy security and endogenous source reliance. They conclude, and advocate, for sure a combined approach in energy modelling studies as a method which increases the robustness of examined energy scenarios. In all of the identified 'iterative' modelling studies, whilst there is an increased interaction and feedback loop between the quantitative and qualitative methodology, such interactions remain exogenous to the energy model itself.

Whilst limited, some studies have begun to explore a 'merging' level of integration by assessing how the model structure and parameters can be altered to reflect the insights gained from qualitative methodologies employed in both 'bridging' and 'iterative' studies [41,42], thereby moving from exogenous qualitative integrations to an endogenous approach. Bolwig et al. [41] aims to develop a mix methods approach which captures key factors impacting the social acceptance of varying possible energy transition pathways for the Nordic-Baltic region. They employ exogenous qualitative methodologies via developing a social

acceptance framework to inform scenario development, and a narrative-based analysis of the quantitative modelling results. In addition to this they also integrate endogenous integrations via extending the existing model to capture the cost benefits and penalties of various technologies in line with the social acceptance narratives gained from early scenario development. Additional parameters were added to the various technologies based on their environmental, health, and distributional factors alongside their public perceptions. The authors acknowledge accuracy limitations with attributing social acceptance cost estimates to the technology choices, which could inhibit the model's success in accurately reflecting the qualitative insights gained.

Fell et al. [42] aim to integrate qualitative methodologies to capture distributional impacts of long-term low-carbon transition pathways for the UK energy sector. They exogenously integrate qualitative considerations via combining a literature review with interviews in the early research stages to identify ways in which modelling can acknowledge and integrate differing distributional impacts across various communities and household types. Stakeholder interviews were employed to understand into possible distributional impacts and the relevance of capturing such factors in modelling procedures and policy creation. The findings were used to develop the Energy Systems Model (ESME) model which endogenously captures distributional differences through an interconnected tool which applied energy costs to different dwelling characteristics. The tool associates a socio-economic profile to dwelling types, determining the cost to varying household energy services and adjusting the costs associated with household types. Qualitative insights from participatory processes were used as the basis for the model structure and methodological development, identifying priority characteristics, in this case representative consumer groups cost-benefit analysis, and high granularity. Through endogenously integrating qualitative factors into the modelling research, the authors were able to identify how policy changes and the subsequent costs associated would impact different income groups differently within the UK.

In sum, referring to Table 1, most previous research which attempts to integrate qualitative societal considerations to quantitative modelling can be categorised as 'bridging' and 'iterative'. Qualitative considerations are integrated outside the model and to aid storyline development, occasionally adjusting scenario and input parameters in response [48]. While the 'bridging' and 'iterative' approaches offer limited integration depth, these studies prove useful in taking initial steps to move beyond techno-economic quantitative modelling to strengthen the reflection of real-world complexities in model results. Nevertheless, they still fall short in achieving a fully-fledged merging of qualitative methodologies into quantitative modelling, particularly within model structure and parameters. Studies which achieve a 'merged' level of incorporation between qualitative approaches and the quantitative model provide a more thorough integration, often integrating qualitative methods at multiple stages of the modelling process.

All the identified literature has examined case studies with HICs, with limited-to-no exploration of how such methodological approaches can be applied to LMICs. There therefore remains a research gap in conceptualising how qualitative considerations can be integrated into quantitative energy modelling in LMICs. These results are next used to conceptualise such a framework, and recommendations for modelling studies to move beyond a bridging or iterative research process to reach a 'merging' [48] level of incorporation.

5. Discussion: integrating qualitative methods in energy models

This work has found that existing frameworks for qualitative integration in quantitative modelling were often limited to specific themes and to exogenous modalities. The categorisation of existing modelling studies revealed that case studies' geography remains skewed to HICs, with limited application to LMICs. Additionally, of the modelling studies which do integrate qualitative factors, the realisation of a fully 'merged' approach was scarcely achieved.

Subsequently, this discussion builds on the previous sections to conceptualise a generic framework for qualitative integration into energy models at all stages of the research process. The framework is built using best practice from the literature across multiple disciplines and sectors, acknowledging the depth of literature specific to this topic. A specific focus is put on examining how model structures themselves can be updated endogenously to reflect qualitative considerations and on LMIC contexts. The stages are defined through synthesis of literature [33,48–50], detailed in Section 2.

We conceptualise the integration of qualitative considerations in energy modelling process into four main phases, supplemented by a continuous iterative feedback loop. The first phase is ‘pre-modelling’, involving extensive stakeholder engagement in research scoping alongside bottom-up, community led data collection. The second phase is ‘Storytelling and Narrative’, outlining the need for narrative building techniques throughout the research. The third phase is ‘The model’, demonstrating how energy models can be developed to facilitate the inclusion of Gender and Social Inclusion (GESI), resilience and climate adaptation representation. The fourth phase is ‘Beyond the model’, encompassing inclusive capacity building efforts and accessible knowledge and results communication. An overview of the conceptualised modelling research process is illustrated in Fig. 1.

5.1. Pre-modelling: data collection and research scoping

The first stage is pre-modelling, conceptualised as data collection and research scoping. Each country context has varying governmental attitudes towards external technologies or involvement, with unique political and economic contexts in which modelling procedures are embedded [8]. Scoping these processes is critical for understanding the role of energy modelling processes within the research context [4]. In this sense, inclusive and holistic modelling processes in LMICs require careful context-specific approaches, acknowledging the unique features of the case study in isolation rather than taking a universal methodological approach and transferring assumptions across case studies [31].

Alongside this, a thorough mapping of all key stakeholders [50,52] involved in the energy modelling and policy making processes is key to facilitating involvement of all impacted communities and understanding how models are used and results communicated [55]. Without this understanding, models can reinforce problematic cultural tropes and build barriers to knowledge creation [56]. The modelling of LMICs without the involvement of on-the-ground stakeholders will result in a top-down approach, where the targeted populations have limited-to-no decision-making power or influence on the modelling research process and the research outcomes [57]. Understanding how modelling impacts policy, decision-making, and implementation performed by key stakeholders is critical to understanding to impacts of in/exclusion of their involvement, voices and knowledge within the modelling process [31, 55]. Further, resources should be allocated in the initial research phases to explicitly map the diverse social, political, economic, and technical interconnections between the energy sector and potential impacted communities resulting from energy policy decisions. This involves understanding the (bi)directional, indirect or direct, interconnections between communities within the LMIC, and the potential influences on, or by, the energy decisions being studied within the modelling [4,55]. For example, the impact of business markets and foreign direct investment initiatives on the priorities of the energy sector. Therefore, modelling research should systematically map the stakeholder landscape to understand the potential impact of model outputs.

It is therefore critical in the pre-modelling stage to undertake extensive and consistent co-design [4,31,43,50] of the research alongside local knowledge holders. Co-design in this context involves the explicit integration of community and stakeholder needs into all stages of the research process to ensure that the transition being studied is ethical, just, and sustainable [56]. This involves a process of iterative co-designing of all transition scenarios to be translated and analysed in

the model. This should be facilitated through an equitable partnership where in-country knowledge, involvement, and integration are prioritised alongside rigorous feasibility checks, forming an iterative process [12,37,48] where the research is continually verified and altered following stakeholder feedback.

Additionally, it is critical to recognise the diversity of experience [15, 33,40,41,47] in energy and make sure this is reflected through careful data collection [15,49,51]. Data availability remains a significant barrier to energy modelling processes in LMICs, which are often aggregate, inconsistent, and unreliable [58]. Such data often poorly reflect the on-the-ground reality and lived experiences of energy. Policy and decisions made utilising such data therefore may not allow all members of the community to benefit equally from energy service [4]. The integration of multiple community types within modelling, where disaggregated data is available, can better reflect on-the-ground realities. This could be represented through the integration of demographics [3, 15,40], such as gender, age, income, or household type, for example, to differentiate between energy consumers in modelling. Additional qualitative data on energy consumer behaviour, public opinions and energy priorities [3,41,49,50] can be collected to better reflect on the ground reality and move away from solely cost-optimisation analysis in modelling [49,59]. Such data can be spearheaded by in-county stakeholders with relevant expertise collected via surveys, questionnaires and/or focus groups [16]. Therefore, this would require the translation of qualitative information gained into quantitative and categorical parameterised modelling inputs. Adequately reflecting these contextually relevant characteristics in models requires a time-consuming disaggregation of data, but can result in more equitable community benefit from the results of the modelling research [60]. Whilst the scope of the data collection process may be limited due to the resource and funding constraints, there must be a minimum sufficient involvement of all impacted communities [61] to adequately capture qualitative considerations.

5.2. Storytelling and narratives: contextual analysis, scenario creation and results analysis

Storytelling and narrative building are the second set of methods which aid qualitative integration. These techniques can be integrated into the contextual analysis, scenario creation, and results analysis phases of the modelling research. Qualitative storylines can be generated via stakeholder workshops, interviews, surveys, questionnaires, focus groups, discussions or content analysis of existing literature [10]. Integrating storytelling into the wider modelling process facilitates cross-disciplinary collaboration across relevant actors to address nexus issues, and especially when looking at integrating resilience, and vulnerable and marginalised peoples’ energy needs into modelling [13]. Particularly, literature has stressed the importance of contextual analysis of results when integrating GESI, resilience and qualitative considerations more broadly into energy planning and energy modelling studies [4,62].

Storytelling and narrative integration can be applied within the modelling research process, from the initial contextualisation and research gap identification, scenario creation, results analysis and evaluation, to the way that the modelling results are communicated, and research findings disseminated [51]. Models accompanied by contextual narratives allow a more holistic picture to be painted when assessing the energy sector, capturing social aspects such as behaviour, institutional limitations, public opinion, actors, communities and lived experience of energy decisions [12,51]. Such research practices facilitate engagement with stakeholders at multiple levels of expertise and combining of perspectives and disciplinary backgrounds [37].

Employing storytelling in modelling research process allows quantitative analysis to be validated and strengthened by additional qualitative understandings. It also allows for the voices of key communities impacted by the research to be integrated formally into the research

process. Storytelling overcomes limitations identified previously in modelling studies by looking beyond cost optimality and understanding the wider implications of results, and structures in which energy decisions are being made.

We suggest three key stages of the research process where qualitative storytelling can be formally integrated: (i) Research Contextualisation, (ii) Scenario Creation, and (iii) Results analysis. By integrating storytelling at these stages, quantitative model structure, inputs, parameters, and scenarios can be calibrated in response to developed narratives. Qualitative storytelling forms an iterative process, as described with regards to each stage below.

- i. *Research contextualisation*: A thorough understanding of the wider political, economic, social, technical, environmental and cultural contexts of the case study is critical to examining the modelling representation and results. Participatory narrative assessment workshops [12,39,42,46,52], interviews, and stakeholder engagement are key qualitative methodologies to integrate into modelling procedures to co-create contextual knowledge, understanding of nexus issues, and understanding of uncertainties [52]. These insights can then be used to develop plausible stories and narratives.
- ii. *Scenario creation*: Qualitative scenarios [15,37,39,51,52] provide a way for stories to be examined as model inputs. This allows the modelling studies parameters to be defined by quantified inputs and constraints as identified through storytelling application [16]. Insights gained from qualitative narrative exploration can be used to create alternative scenarios to explore, and/or to add different inputs or constraints to the model beyond optimisation. This allows scenarios to reflect the prioritisation and quantification of key qualitative insights from stakeholders.
- iii. *Results Analysis*: Qualitative storytelling [12,16,37] can be used to check the plausibility of the model results [39,51,59], particularly through assessing and validating the modelling outputs as they fit within popular qualitative narratives. This involves analysing and verifying the real-world feasibility of modelling outputs within the developed qualitative narratives [12].

Continuous stakeholder engagement from key actors at all three stages can ensure maximum in-country agency, accurate representations of on-the-ground realities and robust planning [31].

5.3. The model: methodology, structure and future improvements

To move beyond a 'bridging' or 'iterative' integration of qualitative techniques within modelling, a 'merged' approach [48] requires integration of qualitative considerations into the modelling structure itself. Current energy models often allow for the integration of several qualitative considerations by translating them into quantitative model inputs, particularly through disaggregation of demand input data. Various studies have highlighted the critical need for, increasing the resolution captured within energy models in their resulting ability to more adequately capture the complex nature of modern energy systems [20, 25,63].

The main identified ways for the models to more thoroughly integrate qualitative factors is through: (i) geographical resolution, (ii) sector and sub-sector resolution, (iii) resilience, climate adaptation, and gender and social inclusion (GESI) representation, and (v) behaviours and public opinions.

- (i) *Geographical resolution*: Many energy models allow the user to define the geographical resolution of analysis [37,41]. Open-source models, such as MAED and OSeMOSYS [21,64], have flexible structures, facilitating case-by-case model development which allows for the unique characteristics of each case study to be captured, including the relevant resolution. This can

be determined as part of the research scoping and contextual analysis earlier in the research process. Initial data collection and stakeholder knowledge co-production may reveal that wider government and/or energy sector structures lend themselves to modelling at either national or sub-national levels. Modelling at various resolutions can also better capture of the nuances of differing community needs. Previous literature reviews have shown that incorporating regional specificities within a model allows more advanced representations of qualitative and societal considerations [33].

- (ii) *Sector, sub-sector, and fuel resolution*: The inclusion of different sectors, sub-sectors and fuel types [23,24] within energy models' structures can reflect the research context, providing an avenue for qualitative integration. For example, if an LMIC has highly agricultural economy, then sectoral resolution can be increased to represent the agriculture sector and have more disaggregated energy needs and sub-sectors reflected in the model (e.g., farming, livestock, forestry and fishing). To carry on this illustrative example, if research scoping, stakeholder engagement, and narrative exploration has shown the importance of irrigation for the country's agricultural development and resilience building, this can be defined as a sub-sector and captured within the model. This allows the economic development and sectoral priorities of the LMICs to be explicitly captured within the model. Similarly, energy models often aggregate fuels into general fuel categorisations such as 'traditional fuels' which includes a wide range of fuel types including charcoal, firewood, dung, and crop waste [65]. This limits the nuances and differences within the fuel types which can be reflected, particularly when modelling efficiencies and fuel switching projections. Informal sectors and household energy usages are significant areas of focus for LMICs globally, as progress towards achieving sustainable development goal 7 remains falling short with over 685 million people without access to electricity and over 2.6 billion people still relying on hazardous and inefficient traditional fuels for cooking [66]. Subsequently, national energy targets and policy priorities acknowledge and focus on efficiencies and fuel switching in informal sectors and households within LMICs. Updating model fuels will allow for such focuses to have a more detailed representation within model results.
- (iii) *Resilience, Climate Adaptation and GESI Representation*: The qualitative insights gained in the previous research stages can be used to integrate resilience, GESI, and adaptation priorities [15,23,33, 40,47] of the studied communities endogenously in the model. This is achieved via modelling parameter and constraints inputs, such as demand, through either alternative scenarios or the baseline model depending on the relevance to the study. Extensive consultation with the key stakeholders would allow such priorities and needs to be identified. Household and sectoral energy usage disaggregation [15,42] can be increased to capture relevant energy end uses for increased community resilience and climate adaption [67]. Assigning demand profiles to specific energy needs within a sector, i.e. energy for street lighting, can demonstrate how resilience and climate adaptation demands are expected to evolve across the modelling period under different scenarios. Therefore, such representation can be achieved by identifying key energy usages to increase resilience and climate adaptation measures and adding them as a segregated 'sub sectors' within the model. Similarly, disaggregation of household types [15,22,24,33] based on key characteristics relevant to the LMIC can reflect differences in experiences with energy usage and consumption across groups. Models can reflect differing baseline energy demand profiles across identified characteristics and reflect differing energy needs evolution across the modelling periods. Qualitative data on needs, wants, and priorities on GESI, resilience and climate adaptation can be translated into

quantitative inputs through either model structures via disaggregation, or modelling parameters and constraints.

- (iv) *Behaviours and Public Opinions*: Qualitative insights and data gained in previous research stages on behaviours and public opinions to transition pathways and technology options can be integrated into the models. This changes the modelling methodological approach from strict economic optimisation, through introducing qualitative socio-political opinions and behaviours [3,41,49] within the model inputs via parameters and constraints [59]. This allows the model to endogenously consider both behavioural and societal aspects of decisions pertaining to technology uptake, acceptance and use within systems.

5.4. Beyond the model: inclusion, capacity building and results communication

The fourth phase to integrate qualitative factors within modelling research is looking beyond the model and results towards inclusion, capacity building and results communication. Inclusion and co-production should continue to be an integral part of the research process beyond the model creation, to encompass the results analysis, dissemination, and communication.

To facilitate co-production, capacity building [4,31] efforts must be prioritised as part of the wider research process. Despite an increasing number of studies applying modelling to LMIC case studies, uptake of such methodologies within planning units remains low due to a lack of capacity and often overstretched resources [31]. As a result, there have been extensive calls within the energy modelling community to increase national ownership and in-country modelling capacity. Increasing institutional capacity in LMICs is crucial to produce impact driven and community led modelling research which reflects reality and represents complex contextual factors. Additionally, it is critical that any research produced within LMICs includes co-authorship and representation within literature from in-country partners and academics [4]. To achieve this, resources should be allocated to increase capacity building efforts and enhance collaborations with in-country researchers [4]. Such capacity building efforts include the development of networks of activities such as the OpTIMUS community of practice outlined in Cannone et al. [31] which focuses on maintaining, nurturing, expanding, and supporting energy modelling research practices. Alongside this, robust training and research programs, creation of a community of practice and knowledge sharing, leading to self-sustained skill development. This can build long term localised expertise in modelling methodologies, creating national hubs for knowledge sharing, facilitating further expansion of national agency [4].

Finally, consideration should be taken when choosing the appropriate means to communicate the energy modelling results. In-country experts' knowledge on the contextual landscape should be drawn upon to ensure results are presented and communicated in appropriate ways relevant to the decision-making processes [56].

5.5. Limitations

The framework outlined in this paper provides a holistic approach to energy modelling, moving beyond purely exogenous qualitative integration to examine how endogenous incorporation can be achieved, however there are limitations. Manual screening processes employed, based on self-perceived criteria, to scope relevant existing literature could have been impacted by researcher bias [68], with potentially relevant literature being omitted from the final sample. The paucity of sampled literature on this subject, whilst highlighting the lack of existing work in this space, makes a review-based approach limited, with lack of breadth in existing studies potentially limiting the applicability and relevance of the subsequent framework produced. Additionally, the framework outlined within this article is devised conceptually and has not yet been tested or applied. Future application of the framework

to energy transition modelling for an LMIC case study is necessary to examine the success of approach in adequately encompassing endogenous integration of qualitative factors into such research.

Finally, whilst this article has focused specifically on how qualitative considerations can be used to address the unique challenges and limitations of energy modelling studies for development, and within LMICs, the authors acknowledge that such approaches are also not prominent in HICs. While this article could also provide a framework for model development across a broader geographic context, further work would be needed to refine it for HICs.

6. Conclusion

The paper investigates how qualitative factors can be integrated into quantitative energy modelling research procedures. Using a structured literature review, it uncovers complexities and challenges in converging qualitative and quantitative approaches, and subsequently limited exploration within the broader energy planning sphere, particularly LMICs. Subsequently, this research endeavoured to conceptualise a way to progress beyond an 'bridging' or 'iterative' approach to the integration of qualitative methodologies to achieve a 'merging' level – that is, the design of quantitative energy modelling frameworks to allow for endogenous integration of qualitative considerations within the model itself.

To this end, it has developed a framework for endogenous qualitative integration into energy transition modelling for development. The framework identifies and outlines feasible steps for qualitative incorporation at all phases of the modelling research process. It recommends that qualitative considerations, such as social dynamics, human behaviour and institutional factors, be examined and integrated at all stages of the modelling research process, conceptualised into four phases [1]: 'Pre-Modelling' [2], 'Storytelling and Narratives' [3], 'The Model', and [4] 'Beyond the Model'. These phases encompass conceptualisation, data collection, model calibration, results analysis, recommendations and subsequent results communication.

Energy modelling studies within LMICs are not a one size fits all and subsequently the qualitative integration will differ across cases. However, generally speaking, the framework recommends that energy modelling research should be inter- and trans-disciplinary, requiring the collection, consideration and integration of bottom-up participatory and community led data and practices, alongside practicing a mixed methods approach which assesses both qualitative and quantitative aspects and methodologies at all stages of the research process [47,56,62,69,70]. Additionally, it recommends overcoming of historic barriers to energy modelling within LMICs through extensive co-design and co-production procedures and pursuing equitable international funding to overcome financial and resource constraints within LMICs. While this paper aims to start the conversation on endogenous qualitative integration, further research is needed, requiring collaboration between social scientists, modellers and stakeholders, in a co-produced and co-designed process.

CRediT authorship contribution statement

Neve Fields: Conceptualization, Methodology, Writing – original draft, Visualization, Writing – review & editing. **Alycia Leonard**: Writing – review & editing. **Martin Mutembei**: Project administration, Writing – review & editing. **Anne Nganga**: Project administration, Writing – review & editing. **Leigh Martindale**: Writing – review & editing. **Marissa Bergman**: Writing – review & editing. **Mwansa Kaoma**: Writing – review & editing. **Mark Howells**: Supervision. **Ed Brown**: Supervision.

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.

Acknowledgements

This work was supported by the UKPACT and Climate Compatible Growth (#CCG) programme of the UK's Foreign Development and Commonwealth Office (FCDO). Any views expressed in this work do not necessarily reflect the UK Government's official policies.

Data availability

No data was used for the research described in the article.

References

- Fields N, Ryves D, Yeganyan R, Cannone C, Tan N, Howells M. Evidence-based policymaking: insights and recommendations for the implementation of clean energy transition pathways for Kenya's power sector. *Energies* 2023 Dec 4;16(23):7904.
- Liao C, Erbaugh JT, Kelly AC, Agrawal A. Clean energy transitions and human well-being outcomes in lower and middle income countries: a systematic review. *Renew Sustain Energy Rev* 2021 Jul;145:111063.
- Geels FW, McMeekin A, Pfluger B. Socio-technical scenarios as a methodological tool to explore social and political feasibility in low-carbon transitions: bridging computer models and the multi-level perspective in UK electricity generation (2010–2050). *Technol Forecast Soc Change* 2020 Feb;151:119258.
- Fuchs JL, Tesfamichael M, Clube R, Tomei J. How does energy modelling influence policymaking? Insights from low- and middle-income countries. *Renew Sustain Energy Rev* 2024 Oct;203:114726.
- Pye S, Li FGN, Petersen A, Broad O, McDowall W, Price J, et al. Assessing qualitative and quantitative dimensions of uncertainty in energy modelling for policy support in the United Kingdom. *Energy Res Social Sci* 2018 Dec;46:332–44.
- Krumm A, Süsler D, Blechinger P. Modelling social aspects of the energy transition: what is the current representation of social factors in energy models? *Energy (Calg)* 2022 Jan;239:121706.
- Jaramillo M, Quirs-Torts J, Vogt-Schilb A, Money A, Howells M. Data-to-Deal (D2D): open data and modelling of long term strategies to financial resource mobilization - the case of Costa Rica. 2023.
- Bhattacharyya SC, Timilsina GR. Modelling energy demand of developing countries: are the specific features adequately captured? *Energy Policy* 2010 Apr;38(4):1979–90.
- Tan N, Vrochidis I, Luscombe H, Richardson E, Plazas Nino FA, Alexander K, et al. Data-to-Deal: developing an energy modelling analytical workflow to enhance political and financial decisions (3.0). Zenodo Repository 2024.
- Wiese F, Hilpert S, Kaldemeyer C, Pleßmann G. A qualitative evaluation approach for energy system modelling frameworks. *Energy Sustain Soc* 2018 Dec 16;8(1):13.
- Bukovszki V, Magyari Á, Braun MK, Párdi K, Reith A. Energy modelling as a trigger for energy communities: a joint socio-technical perspective. *Energies* 2020 May 5;13(9):2274.
- Ansari D, Holz F. Anticipating global energy, climate and policy in 2055: constructing qualitative and quantitative narratives. *Energy Res Social Sci* 2019 Dec;58:101250.
- Trutnevte E, Stauffacher M, Scholz RW. Supporting energy initiatives in small communities by linking visions with energy scenarios and multi-criteria assessment. *Energy Policy* 2011 Dec;39(12):7884–95.
- Hirt LF, Schell G, Sahakian M, Trutnevte E. A review of linking models and socio-technical transitions theories for energy and climate solutions. *Environ Innov Soc Transit* 2020 Jun;35:162–79.
- Musango JK. Assessing gender and energy in urban household energy transitions in South Africa: a quantitative storytelling from Groenheuwel informal settlement. *Energy Res Social Sci* 2022 Jun;88:102525.
- Prehofer S, Kosow H, Naegler T, Pregarer T, Vögele S, Weimer-Jehle W. Linking qualitative scenarios with quantitative energy models: knowledge integration in different methodological designs. *Energy Sustain Soc* 2021 Dec 12;11(1):25.
- Plazas-Niño FA, Yeganyan R, Cannone C, Howells M, Borba B, Quirós-Tortós J. Open energy system modelling for low-emission hydrogen roadmap planning: the case of Colombia. *Energy Strategy Rev* 2024 May;53:101401.
- Akpahou R, Mensah LD, Quansah DA, Kemausuor F. Energy planning and modeling tools for sustainable development: a systematic literature review. *Energy Rev* 2024 Jun;11:830–45.
- Jeuland M, Fetter TR, Li Y, Pattanayak SK, Usmani F, Bluffstone RA, et al. Is energy the golden thread? A systematic review of the impacts of modern and traditional energy use in low- and middle-income countries. *Renew Sustain Energy Rev* 2021 Jan;135:110406.
- Plazas-Niño F, Tan N, Foster V, Howells M, Quirós-Tortós J. Uncovering the applications, developments, and future research directions of the open-source energy modelling system (OSEMOSYS): a systematic literature review. *Cambridge Open Engage* (pre-print); 2024 Nov 1.
- Fields N, Collier W, Kiley F, Caulker D, Blyth W, Howells M, et al. Long-term forecasting: a MAED application for Sierra Leone's electricity demand (2023–2050). *Energies* 2024 Jun 12;17(12):2878.
- Sieed J, Komiyama R, Fujii Y. Energy demand modelling for developing economies using MAED-2 with sectoral decomposition: bangladesh case study. *J. Japan Soc Energy Res* 2020;41(5):149–54.
- Nosrati-Ghods N, De Kock S, Mosongo B, Dixon L, Kiley F, Howells M. Long-Term forecasting: a MAED application for residential water heating in South Africa (2024–2040). 2024.
- Nakarmi AM, Mishra T, Banerjee R. Integrated MAED–MARKAL-based analysis of future energy scenarios of Nepal. *Int J Sustain Energy* 2016 Nov 25;35(10):968–81.
- Gebremeskel DH, Ahlgren EO, Beyene GB. Long-term electricity supply modelling in the context of developing countries: the OSEMOSYS-LEAP soft-linking approach for Ethiopia. *Energy Strat Rev* 2023;45:101045. Available from: <https://www.sciencedirect.com/science/article/pii/S2211467X22002395>.
- Dagnachew AG, Poblete-Cazenave M, Pachauri S, Hof AF, van Ruijven B, van Vuuren DP. Integrating energy access, efficiency and renewable energy policies in Sub-Saharan Africa: a model-based analysis. *Environ Res Lett* 2020 Dec 1;15(12):125010.
- Szabó S, Bódis K, Huld T, Moner-Girona M. Sustainable energy planning: leapfrogging the energy poverty gap in Africa. *Renew Sustain Energy Rev* 2013 Dec;28:500–9.
- Sanoh A, Kocaman AS, Kocal S, Sherpa S, Modi V. The economics of clean energy resource development and grid interconnection in Africa. *Renew Energy* 2014 Feb;62:598–609.
- Taliotis C, Shivakumar A, Ramos E, Howells M, Mentis D, Sridharan V, et al. An indicative analysis of investment opportunities in the African electricity supply sector — using TEMBA (the electricity model base for Africa). *Energy Sustain Dev* 2016 Apr;31:50–66.
- Blimpo MP, Dato P, Mukhaya B, Odarno L. Climate change and economic development in Africa: a systematic review of energy transition modeling research. *Energy Policy* 2024;187:114044.
- Cannone C, Hoseinpoori P, Martindale L, Tennyson EM, Gardumi F, Somavilla Croatto L, et al. Addressing challenges in long-term strategic energy planning in LMICs: learning pathways in an energy planning ecosystem. *Energies* 2023 Oct 26;16(21):7267.
- Ghalekhondabi I, Ardjmand E, Weckman GR, Young WA. An overview of energy demand forecasting methods published in 2005–2015. *Energy Sys* 2017 May 26;8(2):411–47.
- Vägerö O, Zeyringer M. Can we optimise for justice? Reviewing the inclusion of energy justice in energy system optimisation models. *Energy Res Social Sci* 2023 Jan;95:102913.
- Gibson K, Sloane J, Perera N, Rahim S, Giroto V. Embedding inclusion in climate action: lessons from the UK PACT green recovery challenge fund portfolio [Internet]. London [cited 2025 Jan 14]. Available from: https://7376512.fs1.hu.bspotusercontent-na1.net/hubfs/7376512/grcf/GESI%20Learning%20paper/30302397_UK%20PACT%20GRCF_GESI%20Learning%20Paper_v5_FINAL%20-%20updated.pdf?utm_campaign=Country%20programme&utm_medium=email&hsmi=292937998&hsenc=p2ANqtz-4WULUMIPJslYgTKROA-76J5MGdTeu7-hYOv8TiRi8MvG-wPKGv58xq48TtuAjaR269kwSvRdEDvS OggNtvQawo48XNhjdYs2LpKAc8DyR9rhBz.Y&utm_content=292937998&utm_source=hs_email; 2024 Jan.
- Dioha MO, Montgomery M, Almada R, Dato P, Abrahams L. Beyond dollars and cents: why socio-political factors matter in energy system modeling. *Environ Res Lett* 2023 Dec 1;18(12):121002.
- Leonard A, Nguti K, Lanza MF, Hirmer S. Shedding light on vulnerability: mapping intersectional needs for inclusive energy and development planning. *SSRN Electron J* 2023.
- Trutnevte E, Barton J, O'Grady Á, Ogunkunle D, Pudjianto D, Robertson E. Linking a storyline with multiple models: a cross-scale study of the UK power system transition. *Technol Forecast Soc Change* 2014 Nov;89:26–42.
- Deetman S, Hof AF, van Vuuren DP. Deep CO2 emission reductions in a global bottom-up model approach. *Clim Policy* 2015 Mar 4;15(2):253–71.
- Fortes P, Alvarenga A, Seixas J, Rodrigues S. Long-term energy scenarios: bridging the gap between socio-economic storylines and energy modeling. *Technol Forecast Soc Change* 2015 Feb;91:161–78.
- Chapman AJ, Pambudi NA. Strategic and user-driven transition scenarios: toward a low carbon society, encompassing the issues of sustainability and societal equity in Japan. *J Clean Prod* 2018 Jan;172:1014–24.
- Bolwig S, Bolkesjø TF, Klitkou A, Lund PD, Bergaentzél C, Borch K, et al. Climate-friendly but socially rejected energy-transition pathways: the integration of techno-economic and socio-technical approaches in the nordic-baltic region. *Energy Res Social Sci* 2020 Sep;67:101559.
- Fell MJ, Pye S, Hamilton I. Capturing the distributional impacts of long-term low-carbon transitions. *Environ Innov Soc Transit* 2020 Jun;35:346–56.
- Hof AF, Carrara S, De Cian E, Pfluger B, van Sluisveld MAE, de Boer HS, et al. From global to national scenarios: bridging different models to explore power generation decarbonisation based on insights from socio-technical transition case studies. *Technol Forecast Soc Change* 2020 Feb;151:119882.
- Zhang L, Bai W, Xiao H, Ren J. Measuring and improving regional energy security: a methodological framework based on both quantitative and qualitative analysis. *Energy (Calg)* 2021 Jul;227:120534.
- Syranidou C, Koch M, Matthes B, Winger C, Linßen J, Rehtanz C, et al. Development of an open framework for a qualitative and quantitative comparison of power system and electricity grid models for Europe. *Renew Sustain Energy Rev* 2022 May;159:112055.

- [46] Urban F, Nurdiawati A, Harahap F. Sector coupling for decarbonization and sustainable energy transitions in maritime shipping in Sweden. *Energy Res Social Sci* 2024 Jan;107:103366.
- [47] Mohideen R. Technology for social well-being: strengthening urban resilience in developing countries integrating infrastructure, energy, health and social inclusion. In: 2021 IEEE conference on norbert wiener in the 21st century (21CW). IEEE; 2021. p. 1–9.
- [48] Trutnevte E, Hirt LF, Bauer N, Cherp A, Hawkes A, Edelenbosch OY, et al. Societal transformations in models for energy and climate policy: the ambitious next step. *One Earth* 2019 Dec;1(4):423–33.
- [49] Huckebrink D, Bertsch V. Integrating behavioural aspects in energy system modelling—A review. *Energies* 2021 Jul 28;14(15):4579.
- [50] De Cian E, Dasgupta S, Hof AF, van Sluisveld MAE, Köhler J, Pfluger B, et al. Actors, decision-making, and institutions in quantitative system modelling. *Technol Forecast Soc Change* 2020 Feb;151:119480.
- [51] Renner A, Giampietro M. Socio-technical discourses of European electricity decarbonization: contesting narrative credibility and legitimacy with quantitative story-telling. *Energy Res Social Sci* 2020 Jan;59:101279.
- [52] Cabello V, Romero D, Musicki A, Guimarães Pereira A, Peñate B. Co-creating narratives for WEF nexus governance: a quantitative story-telling case study in the Canary Islands. *Sustain Sci* 2021 Jul 31;16(4):1363–74.
- [53] Snyder H. Literature review as a research methodology: an overview and guidelines. *J Bus Res* 2019 Nov;104:333–9.
- [54] Donthu N, Kumar S, Mukherjee D, Pandey N, Lim WM. How to conduct a bibliometric analysis: an overview and guidelines. *J Bus Res* 2021 Sep;133:285–96.
- [55] Howells M, Quiros-Tortos J, Morrison R, Rogner H, et al. Energy system analytics and good governance -U4RIA goals of energy modelling for policy support. *Research Square Pre-Print*. 2021. p. 1–18 (version 1).
- [56] Robinson BL, Halford A, Gaura E. From theory to practice: a review of co-design methods for humanitarian energy ecosystems. *Energy Res Social Sci* 2022 Jul;89:102545.
- [57] Andersen KS, Termansen LB, Gargiulo M, Ó Gallachóir BP. Bridging the gap using energy services: demonstrating a novel framework for soft linking top-down and bottom-up models. *Energy* 2019;169:277–93. <https://www.sciencedirect.com/science/article/pii/S0360544218323648>.
- [58] Cannone C, Allington L, Cervantes Barron K, Charbonnier F, Zachau Walker M, Halloran C, et al. Designing a zero-order energy transition model: how to create a new Starter Data Kit. *MethodsX* 2023;10:102120.
- [59] Li FGN. Actors behaving badly: exploring the modelling of non-optimal behaviour in energy transitions. *Energy Strategy Rev* 2017 Mar;15:57–71.
- [60] Feenstra M, Özerol G. Energy justice as a search light for gender-energy nexus: towards a conceptual framework. *Renew Sustain Energy Rev* 2021 Mar;138:110668.
- [61] Steg L, Perlaviciute G, van der Werff E. Understanding the human dimensions of a sustainable energy transition. *Front Psychol* 2015 Jun 17:6.
- [62] Musango JK, Smit S, Ceschin F, Ambole A, Batinge B, Anditi C, et al. Mainstreaming gender to achieve security of energy services in poor urban environments. *Energy Res Social Sci* 2020 Dec;70:101715.
- [63] Rocco MV, Tonini F, Fumagalli EM, Colombo E. Electrification pathways for Tanzania: implications for the economy and the environment. *J Clean Prod* 2020 Aug;263:121278.
- [64] Howells M, Rogner H, Strachan N, Heaps C, Huntington H, Kypreos S, et al. OSeMOSYS: the open source energy modeling system. *Energy Policy* 2011 Oct;39(10):5850–70.
- [65] Bisaga I, Sindou E, Stevenson J, de Cuadra F, Sanchaz Jacob E, Leach M, et al. Integrating clean cooking into national energy access planning: tools and considerations for E-cooking planning and implementation [Internet] [cited 2024 Jul 25]. Available from: <https://mecs.org.uk/wp-content/uploads/2024/05/Knowledge-Brief-FINAL.pdf>; 2024 May.
- [66] Guta D, Baumgartner J, Jack D, Carter E, Shen G, Orgill-Meyer J, et al. A systematic review of household energy transition in low and middle income countries. *Energy Res Social Sci* 2022 Apr;86:102463.
- [67] Stockport B, Yang P, Kimani J, Leonard A, Hirmer S. Climate change adaptation, social resilience, and perceived values data from Turkana, Machakos and Narok counties, Kenya. *Data Brief* 2024 Sep;110978.
- [68] Baldwin JR, Pingault JB, Schoeler T, Sallis HM, Munafo MR. Protecting against researcher bias in secondary data analysis: challenges and potential solutions. *Eur J Epidemiol* 2022 Jan 13;37(1):1–10.
- [69] Cherp A, Vinichenko V, Jewell J, Brutschin E, Sovacool B. Integrating techno-economic, socio-technical and political perspectives on national energy transitions: a meta-theoretical framework. *Energy Res Social Sci* 2018 Mar;37:175–90.
- [70] Robinson BL, Clifford MJ, Jewitt S. TIME to change: rethinking humanitarian energy access. *Energy Res Social Sci* 2022 Apr;86:102453.