Endogenous integration of qualitative factors into quantitative energy transition modelling

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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'.

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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, their energy sectors 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 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 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 *(6)*. 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 *(6)*. These include stakeholder interviews, focus groups, ethnographic studies, policy analysis, and participatory research *(7)*. While effective, these qualitative methods are often under-used or treated as secondary to quantitative models. 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 *(1,8,9)*; 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. Their quantitative nature often imposes an over-simplified representation of reality, omitting nuances associated with complex systems, boundaries, and actors involved in decision making processes *(10)*. 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 it has resulted in the marginalisation of interdisciplinary and diverse perspectives *(11)*. 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.

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 *(12)*. 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 *(13)*. 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 *(14)*. 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 *(15)*.

Traditional energy modelling involves limited examination of modelling contexts, inputs, and results beyond techno-economic parameters *(16)*. It tends to omit non-technical drivers and constraints of transition *(10)*, 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 *(17–19)*.

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 *(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 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 *(14)* – 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 *(11)*.

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 *(12,41,47)*), 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 *(11)*.

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 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 Huckebrink 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 *(7)*, and multidisciplinary scenarios *(10)*. 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 *(19)* 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 introduced in this paper 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 categories: 1) reviews and scoping studies, and 2) case studies and analytical papers. The third phase involved an abstract analysis to identify those papers which use of any energy modelling tools within case study application as part of the methodology of the paper. Ultimately, a total of 12 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 Figure 1): (1) 'Pre-Modelling': data collection and research scoping, (2) 'Storytelling and Narratives': scenario creation, contextualisation and results analysis, (3) 'The Model' itself: current 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.

Studies within the literature which use '*bridging'* have linked qualitative considerations into modelling by conducting both qualitative and 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 by conducting separate quantitative and qualitative assessments and bringing together key themes and insights to achieve an overall regional energy security image. They found that a quantitative approach in isolation was unable to extensively capture social, environmental, and political features.

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 utilise qualitative surveys to acquire insights into household energy preferences, which are integrated as scenario parameter inputs and constraints for the model. Similarly, Geels et al *(3)* propose the methodological tool of socio-technical scenarios as a storyline method to capture social acceptance and political feasibility in computational models. They develop a case study assessing future UK electricity generation and advocate for eight iterative steps to identify 'transition bottlenecks' where tensions between qualitative narrative storylines and quantitative model generated scenarios can be identified and overcome. The research focused only on supply-side storylines and inputs, with the demand side remaining at an aggregate level with no socio-technical focus assigned to energy consumption or daily energy use practices. In a similar vein, Fortes et al *(39)* examine the case of Portugal and employ national stakeholder workshops to create qualitative energy scenarios which are then translated into model inputs. Additional workshops are completed after the modelling is completed to compare stakeholder perceptions with model outputs. The researchers found substantial differences in stakeholder assumptions and opinions on the potential 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.

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)*. Bolwig et al *(41)* looks to the case of the social acceptance of varying energy transition pathways in the Nordic-Baltic region through the addition of cost benefits and penalties as model parameters, alongside qualitative scenario creation and result assessment. They integrated social acceptance into the model through adding cost benefits and penalties to 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)* combined a literature review with interviews to identify ways in which low carbon energy transition modelling can acknowledge and integrate differing distributional impacts across communities. Stakeholder interviews were employed to gain insights into possible distributional impacts and the relevance of capturing such factors in modelling procedures and policy creation. The findings gained from the literature review and interviews were used to develop the Energy Systems Model (ESME) model to more successfully capture distributional differences through developing an interconnected tool to associate energy costs to different dwelling characteristics. The tool does this by associated a socio-economic profile to dwelling types, determines the cost to household energy services and adjusting the costs associated with households. Qualitative insights in the form of stakeholder opinions were therefore 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. The developed model only considered direct distributional impacts on the energy system, not encompassing wider economic impacts which other macroeconomic energy models are able to consider.

Table 1: An overview of existing literature integrating social considerations and/or qualitative methodologies. Level of integration typologised in line with the categories identified in Trutnevyte et al *(48)*.

Author	Year	Case Study	Model	Level of Integration	Reference
Trutnevyte et al	2014	United Kingdom	Demand, FESA, D-EXPANSE, BLUE-MLP, HESA, HAPSO	Iterative	*(37)*
Deetman et al	2015	Global	TIMER	Iterative	*(38)*
Fortes et al	2015	Portugal	TIMES_PT	Iterative	*(39)*
Chapman & Pambudi	2018	Japan	MARKAL/ TIMES	Iterative	*(40)*
Pye et al	2018	United Kingdom	ESME	Iterative	*(5)*
Bolwig et al	2020	Nordic-Baltic region	Balmorel	Merging	*(41)*
Fell et al	2020	United Kingdom	ESME	Merging	*(42)*
Geels et al	2020	United Kingdom	IMAGE, WITCH, Inertile	Iterative	*(3)*
Hof et al	2020	United Kingdom & Germany	IMAGE & WITCH	Iterative	*(43)*
Zhang et al	2021	China	AHP, GRA, TOPSIS	Bridging	*(44)*
Syranidou et al	2022	Germany	MODEX	Iterative	*(45)*
Urban et al	2024	Sweden	BeWhere	Iterative	*(46)*

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 are often limited to specific themes and to exogenous modalities. The categorisation of existing modelling studies has 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 is 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 in 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 figure 1.

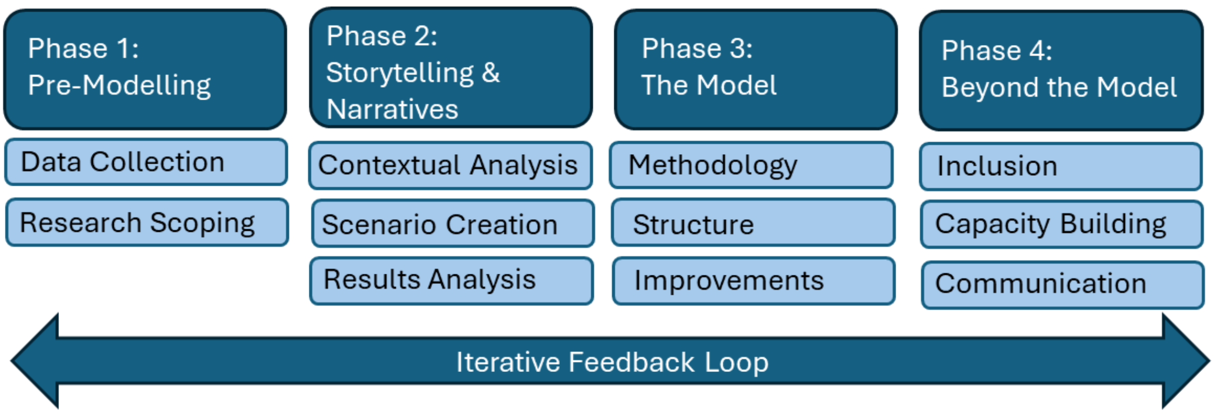

Figure 1. A conceptual diagram of the four key methodological phases identified in this paper as part of the modelling research process: Pre-Modelling, Storytelling & Narratives, The Model, and Beyond the Model. There is a constant feedback loop across all the identified stages of the research project.

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 *(14)*. 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 *(10,37,48)* where the research is continually verified and altered following stakeholder feedback.

Additionally, it is critical to recognise the diversity of experience *(19,33,40,41,47)* in energy and make sure this is reflected through careful data collection *(19,49,51)*. 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 *(3,19,40)***,** 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 *(7)*. 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 *(6)*. 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 *(17)*. 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 *(10,51)*. 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 *(10,39,42,46,52)*, 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 *(19,37,39,51,52)* 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 *(7)*. 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 *(7,10,37)* 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 *(10)*.

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 caterogisations 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 *(19,23,33,40,47)*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 *(19,42)* 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 *(19,22,24,33)* 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.

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

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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)*.

6. Conclusions and Research Recommendations

6.1. Limitations

The framework outlined in this paper begins to provide a more holistic approach to energy modelling studies, however there are limitations. The examples outlined in this study address explicit integration of qualitative considerations within the model itself, such as energy needs for street lighting, without directly addressing implicit GESI, resilience of climate adaptation measures. There is limited research which explores the implicit and indirect impacts of energy policy development on vulnerable and marginalised groups in LMICs. Therefore, to better understand and integrate, implicit qualitative and energy needs within the energy model structure itself a better understanding of such interconnections from policy changes is needed. This research subsequently recommends the development of a research agenda to understand such impacts better, looking beyond the direct and obvious implications of energy access, development and decision making on different communities within LMICs. Therefore, whilst the insights and the framework outlined within this article are generalisable, a significant amount of further work and research is required to better understand the implicit, indirect and peripheral implication and impacts of energy policy decisions on key actors, sectors and communities, including those already most marginalised and vulnerable.

6.2. Conclusion

To successfully integrate qualitative factors within energy modelling practices, and to overcome the previously identified limitations, this article recommends applying the framework developed to future modelling studies. The integration of qualitative and social considerations and methodologies within quantitative energy modelling research is complex and challenging and subsequently has seen limited exploration within the broader energy planning sphere into converging the two methodological approaches. Subsequently, this research has provided an attempt to conceptualise a move beyond an '*bridging'* or '*iterative'* approach to the integration of qualitative methodologies to achieve a '*merging'* level when quantitative energy modelling frameworks are updated to allow for the integration of such considerations within the model itself. Whilst also acknowledging that such methodological integrations exist in addition to and beyond purely the model in and of itself, encompassing every stage of the research project from the 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 questions, considerations and integration of social and qualitative approaches will differ across the case studies and energy systems being studied, the research questions being examined, the purpose of the research study being undertaken, and the wants and needs of the people impacted by such energy planning decisions.

Therefore, this article 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 *(47,56,62,68,69)*. To achieve a mixed methods approach, this research recommends the integration of qualitative methodologies and considerations into all stages of the modelling research process, categorised into (1) pre-modelling, (2) storytelling and narratives, (3) the model structure, and (4) post-modelling. Additionally, this research recommends the overcoming of historic barriers to energy modelling within LMICs by employing extensive co-design and co-production procedures, pursuing additional funding acquisition through foreign aid, and produce GESI, resilience and climate adaptation starter data kits to overcome financial and resource constraints within LMICs. Therefore, further research which aims to fully integrate social and qualitative considerations into modelling, requires collaboration between social scientists, modellers and stakeholders across the entire research process, in a co-produced and co-designed process.

Author contributions:

Neve Fields: Conceptualisation, Methodology, Writing – Original draft preparation, visualisation, Writing – Reviewing and editing. **Alycia Leonard:** Writing – Reviewing and Editing. **Martin Mutembei:** Project Administration, Writing – Reviewing and editing. **Anne Nganga:** Project Administration, Writing – Reviewing and Editing. **Leigh Martindale**: Writing – Reviewing and editing. **Marissa Bergman**: Writing – Reviewing and editing. **Mwansa Kaoma:** Writing – Reviewing and Editing. **Mark Howells**: Supervision. **Ed Brown**: Supervision.

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

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