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How does energy modelling influence policymaking? Insights from low- and middle-income countries

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ABSTRACT

Energy system models are widely used to explore, analyse and plan energy futures and sustainable transitions. These models, typically developed in high-income countries, have more recently been applied in low- and middle-income countries (LMICs). As a result, the role that models play in informing decisions in such contexts lacks adequate exploration. Drawing on 35 qualitative interviews with energy system modellers and policymakers, this research examines the experiences of developing and using energy system models that support decision-making in LMICs. The findings suggest that many conventional modelling approaches do not account for the political economy influences and developmental challenges specific to LMICs, with implications for modelling processes and outcomes. The interviews highlighted the need to understand the roles played by diverse stakeholders in shaping modelling processes, as well as the communication, interpretation and use of energy models. This indicates that, particularly in modelling projects which bring in external modellers, a good understanding of the country context is essential to design appropriate model scenarios and for their interpretation in policymaking. Finally, more in-country capacity is needed to foster local ownership of modelling projects.

1. Introduction

Energy system models are mathematical, computer-based models that represent energy systems at different scales. They are used to simulate and explore future pathways for energy systems, demand and supply trajectories, and implications for markets, policy, emissions, and energy security [1–4]. As simplified depictions of reality, they support decision-making processes by informing policymakers about different energy futures and helping them to evaluate timelines and policy options regarding investments and technology [1,5,6]. 'Modelling frameworks' are generic tools that can be filled with context-specific data, while the term 'models' is used to refer to the context-specific implementation in modelling projects using relevant data [7].

Following the oil crisis of the 1970s, as well as increasing climate awareness and technological developments in the 1980s and 1990s, many energy modelling frameworks have been developed in, and applied to, high-income countries (HICs) [8–11], as well as countries in Latin America [12–14]. Since the 2015 Paris Agreement, signatories have been required to develop national climate commitments, including Nationally Determined Contributions (NDCs) and long-term strategies. As a result, energy models are increasingly being applied in low-and-middle-income countries (LMICs) [15,16]. For example, energy models have been developed for Ghana [17], Pakistan [18], Indonesia [19] and Ethiopia [20]. While an underrepresentation of African countries is still evident in the application of some modelling tools [21,22], energy transition modelling activities on the continent are generally increasing [16]. However, many models, having been developed in HICs and transferred to LMICs, are biased towards HIC contexts. As such, they may not account for the unique characteristics of LMICs, such as different costs of capital, regulatory structures, levels of access to and demand for electricity, usage of traditional biomass, political instability, informal economies, and climate vulnerability [10,11,20,23–27].

Abbreviations: HICs, High income countries; LMICs, Low-and middle-income countries; SSA, Sub-Saharan Africa; CCG, Climate Compatible Growth; EM, Energy modellers; PM, Policymakers; IO, International organisation; MESSAGE, The Model for Energy Supply Strategy Alternatives and their General Environmental Impact; TIMES, The Integrated MARKAL-EFOM System; LEAP, Long-range Energy Alternatives Planning system.

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Furthermore, many models focus on reducing emissions in the energy sector, which may not be a priority for LMICs with lower baseline emissions and lower levels of electricity access and consumption [5,27].

In HICs, energy modelling frameworks such as the Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE) [28], The Integrated MARKAL-EFOM System (TIMES) [29], and the Low Emissions Analysis Platform (LEAP) [30] have become an integral part of policymaking processes [31–34]. Some studies have examined and evaluated the connection between energy modelling and policymaking in these contexts [1,35–37]. The ways in which policy processes draw on models are versatile and differ between jurisdictions [1]. While energy modelling is recognised as a useful input into decision making, it is regularly criticised for falling short of capturing qualitative, socio-economic, and policy features which shape energy systems [38,39]. Hence, modelling must not be the only input into policymaking, but is rather to be seen as informing decision-making alongside other evidence. Many energy modelling projects are also criticised for a lack of inclusion of non-academic stakeholders, indicating limited *'process democratisation'* (p1) [38].

In LMICs, the connection between energy modelling and policymaking remains largely unexplored. Existing studies on energy modelling in LMICs focus on more general issues, such as data availability and quality, as well as lower capacities for energy modelling [5,40]. Many LMICs lack capacity to draw on energy modelling for decision-making due to, for example, limited human and financial resources [6]. A longstanding concern in policymaking has been a lack of institutional capacity to use and engage with energy modelling [23,41–43]. It is often the case that modellers from HICs lead or support modelling projects in LMICs, given their comparatively longer experience. For example, Musonye et al. (2020) found that most energy modelling projects in Sub-Saharan Africa (SSA) were led by European institutions [44]. Likewise, Blimpo et al. (2024) point out that the majority of energy modelling research on Africa was conducted by non-Africa-based authors [16]. This external leadership has been criticised for lacking context-specific knowledge and sensitivity and for neglecting the different socio-economic dynamics of countries [5,23,45]. For example, global integrated assessment models, such as the ones drawn on by the Intergovernmental Panel on Climate Change, tend to poorly represent African countries, for instance by pooling together Africa and the Middle East as a region [5,46]. As a result, calls for national leadership on modelling projects and the strengthening of in-country modelling capacity are growing. For SSA, Mulugetta et al. [40] find that capacities for energy system planning differ widely across countries, with some nations being able to base their energy transition decisions on model outputs, while others have only limited capacity to draw on the insights from modelling. This imbalance is reflected in research on energy transition modelling, where Blimpo et al. [16] find that a large share (35 %) of energy transition modelling research in SSA is focused on the two largest economies South Africa and Nigeria, with the rest of research being distributed in smaller shares among several other countries. Mulugetta et al. [40] call for better and more evidence-based decision making in *every* African country – an essential requirement given that many nations are making fundamental decisions regarding their future energy systems. Generally, the increase and institutionalization of modelling capacity in LMICs are seen as important for integrating modelling in decision-making and accelerating energy transitions [16,23,40,41]. While these studies emphasise the importance and the potential of energy modelling for LMICs, the current role of modelling in policymaking and the political influences on modelling have not yet received sufficient attention.

Given the growing use of energy system models in LMICs, the sparsely researched dynamics between energy modelling and policymaking in LMICs warrants further investigation and, in particular: the influence of political economy on modelling processes; engagement between modellers, policymakers and other relevant stakeholders; and the ways in which modelling tools are applied to policy questions. This research therefore sought to investigate the following questions: 1) How is modelling currently being undertaken in LMICs? 2) What factors, such as stakeholder interests and engagement, shape modelling processes? And, vice versa, 3) How do modelling results shape policymaking in LMICs?

To answer the research questions, this study draws on 28 semi-structured interviews with energy modellers, supplemented by seven interviews with policymakers, working on energy planning in LMICs. The interviews explored participants' experiences of developing and applying energy models in LMICs and, in so doing, contribute to a better understanding of how energy modelling is currently used in policymaking in LMICs, including potential challenges and how these may be addressed. The research was conducted as part of the Climate Compatible Growth (CCG) programme. Funded by the UK Foreign, Commonwealth and Development Office, CCG aims to support investment in sustainable energy and transport systems to meet development priorities in LMICs. A core focus of CCG is energy modelling, and the views of CCG researchers have influenced the design and objectives of this research.

The rest of this study is structured as follows. Section 2 describes the materials and methods used to address the research questions, including semi-structured interviews with modellers and policymakers. Section 3 discusses findings from the interviews, such as key influences on modelling processes, different ways of stakeholder engagement, and the role of modelling in policymaking. Finally, Section 4 presents the main conclusions and outlines some areas for further research.

2. Materials and methods

Throughout this study, actors who use and work with energy system models on local, national and regional scales, make decisions on the input and assumptions of the model, and perform the modelling exercise, are referred to as *energy system modellers* [47]. *Externals* are defined as non-national actors, while *nationals* are in-country actors. Meanwhile, *policymakers* are actors involved in the design and implementation of energy-related policies with the opportunity to draw on modelling results to inform decision-making processes. However, sometimes, the two roles cannot be easily distinguished [47], for example when modellers work in the government and make or support planning-related decisions. Furthermore, the term *LMICs* is used while recognising that it is a blanket term describing a huge diversity of country contexts [48]. However, the term is used considering that, in the global context, energy models were firstly applied predominantly in HICs and their more recent use in many LMICs demands the acknowledgment of different starting points and circumstances [27]. While acknowledging this, the research simultaneously aims to carve out and illuminate the diversity of contexts regarding capacities, perceptions, interests, and influences among LMICs.

2.1. Research design

This research adopted an exploratory, qualitative approach, using semi-structured interviews, to shed light on the role of energy modelling in policymaking in LMICs. Qualitative research is commonly used to address exploratory questions to understand diverse perspectives and contexts [49] and to generate insights and knowledge on a topic, especially within contexts where no or little previous research has been conducted [50,51]. This was appropriate for this research due to the limited exploration of the relationship between energy modelling and policymaking in LMICs. The chosen method of data generation was semi-structured interviews, which enabled exploration of the viewpoints of modellers and policymakers regarding the design, implementation, communication and use of energy modelling and outcomes [50,51].

Two interview topic guides were developed, one for energy modellers and one for policymakers. They were similar in structure but contained different questions, reflecting the professional roles and responsibilities of the two groups. In addition to introductory and closing questions, the guides were organised along three main thematic areas found in modelling processes - from model setup to running the model to communication of results. Both interview guides are available in the supplementary material. Ethics approval was obtained from the departmental research ethics committee in October 2022.

Table 1
Overview ofN participant codes per region and organisation.

<!–Col Count:4–>Geography	Code	Participating modeller (EM) or policymaker (PM)	Organisation
East Africa	EAfr	EAfr-EM1	Academia
		EAfr-EM2	National energy company
		EAfr-PM1	National energy company
		EAfr-PM2	Ministry of Energy
Southern Africa	SAfr	SAfr-EM1	Governmental institute
		SAfr-EM2	Consultancy
		SAfr-EM3	Independent consultant
		SAfr-EM4	Consultancy
		SAfr-PM1	Ministry of Energy
West Africa	WAfr	WAfr-EM1	Academia
		WAfr-EM2	Academia
		WAfr-EM3	International development organisation
		WAfr-PM1	International development organisation
Latin America	LAm	LAm-EM1	Non-profit research organisation
		LAm-EM2	Ministry of Economy and Finance
		LAm-EM3	Academia
		LAm-EM4	Academia
		LAm-EM5	Consultancy (former intergovernmental organisation)
		LAm-EM6	Academia
South Asia	SAsia	SAsia-EM1	Non-profit research organisation
		SAsia-EM2	Civil society organisation
South-East Asia	SEAsia	SEAsia-PM1	Academic (policy advisor)
		SEAsia-PM2	Government ministry
International Organisations	IO	IO-EM1	Academia
		IO-EM2	Academia
		IO-EM3	Academia
		IO-EM4	Academia
		IO-EM5	Civil society organisation (former Academia)
		IO-EM6	Intergovernmental organisation
		IO-EM7	Academia
		IO-EM8	Civil society organisation
		IO-EM9	Intergovernmental organisation
		IO-EM10	Multilateral development bank
		IO-EM11	International research centre
		IO-PM1	Intergovernmental organisation

2.2. Sampling and data collection

A purposive sampling strategy was initially adopted wherein participants were chosen on the basis of their professional expertise [52]. The identification of participants drew upon the authorship team's professional networks, with the CCG network being an essential starting point. Five CCG modellers were also interviewed. Additional interviewees were identified using snowball sampling as each interviewee was asked to recommend further potential participants based on their own professional network [53].

In total, 35 interviews with 28 energy modellers and seven policymakers were conducted between October 2022 and January 2023. Verbal or written consent was given by all participants, and interviews lasted on average one hour. Most interviews were conducted online using MS Teams, with five done in person. The professional affiliations of participants ranged from universities, ministries, utilities, institutes, and intergovernmental institutions to consultants. The majority (13) of interviews were conducted with participants based in an African country, with their work focused predominantly on the country they resided in. They were followed by participants working for international, energy- or development-focused organisations (12) who were based all around the world, and had worked with different LMICs over the years. Ten interviews were conducted with participants focused on countries in Latin America (6) and Asia (4). Table 1 gives an overview of the regions included in this research, the participants, their codes, and the type of organisations that they are affiliated with.

2.3. Analysis

With the permission of participants, all interviews were recorded and transcribed. After generating initial memos, which recorded first reflections on the data and emergent themes, a thematic analysis was undertaken. This is a nonlinear, iterative analytical process which enables the identification of patterns and themes in the data [54]. The software NVivo was used to aid data organisation and analysis [55,56], and to group the data into overarching thematic areas and sub-areas in a process called coding, using both inductive and deductive approaches [55,56]. Initial themes were discussed amongst the research team, and the coding structure was revised and refined during the analysis to aid analytical rigour.

2.4. Limitations

A limitation of this research is the uneven split in participants between modellers and policymakers, which is partly due to the research focus on modellers. Furthermore, it was challenging to engage with policymakers as the sampling strategy drew on the professional networks of researchers and provided comparatively more connections to modellers. The response rate of invited policymakers (~44 %) was also slightly lower than modellers (~69 %), which led to a greater emphasis on modellers' viewpoints. We found that some policymakers who participated in the research were more time constrained and therefore some responses were less detailed than those of the modellers'. Moreover, some regions are represented more strongly in the sample: many participants were based in Africa, which can also be traced back to the CCG network, which shaped the sampling strategy. Additionally, the sample might be affected by selection bias, as people who agreed to take part in this research may have higher interest in the interface between modelling and policymaking than others, and thus be more familiar with the topic.

3. Recognising diverse contexts - energy system modelling and policymaking in LMICs

Energy systems in LMICs differ from those in HICs in several important ways; for example, levels of access to electricity, use of traditional biomass, and informal economies [10,20,24,25]. Additionally, each country has a unique political economy in which modelling processes are embedded. Different attitudes of governments towards external influences, such as technologies or innovation, play an important role in defining whether and how energy modelling is taken up in research, policy and planning. Several factors are influential in the wider context, such as a country's capacities for modelling, as well as different systems of governance. Hence, a key theme to emerge in this study was that modelling projects in LMICs demand context-specific approaches, which acknowledge the unique circumstances and diversity of each country, instead of making blanket assumptions. An understanding of the political economies and the environmental, social and cultural contexts of LMICs is necessary to comprehend the ways in which modelling results are used in decision-making. Participants highlighted the importance of knowing the characteristics of a country's energy system, including the context-specific costs of finance for technologies, and the impact of historic reliance on specific energy sources on policymaking, which may result in a lock-in to certain technologies. Modellers may only be aware of such circumstances if they understand country contexts and collaborate with local experts. These findings are reflected in literature, for example, Barbrook-Johnson et al. [57] highlight the importance for modelling communities in HICs to partner with in-country experts in LMICs to build modelling approaches for effective energy planning. Moreover, participants highlighted a need to increase local capacities, rather than continuing the status quo that often relies on externally driven modelling efforts. This again aligns with calls for increasing energy planning and modelling capacity in the literature [5,23,40,44], which emphasise that capacity building must be '*designed from, and rooted in, the local context*' (p.671) [46], especially in development contexts. Due to a lack of self-determination and lacking opportunity for leadership and design by those that need the capacity, Sokona [46] highlights that decades of capacity building efforts in energy planning in Africa have largely failed.

Reflecting on these diverse starting points and contexts, the interviews revealed that energy modelling is used to achieve different objectives across countries. For example, in SSA, objectives typically included electrification planning and electricity system expansion, as well as modelling the impacts of variable renewable energies on grid stability. Conversely, modelling efforts in Latin America, where access to electricity is nearly universal, were driven by the need to understand the impacts of energy system decarbonisation and emissions of different energy pathways. Other objectives raised in the interviews included the climate resilience of hydropower-driven energy systems, export dynamics around natural gas, land use change and deforestation, crop production change and emissions, energy efficiency in steel and cement, and biomass energy strategies.

The interviews also revealed several distinct approaches for undertaking modelling projects, which involved various configurations of government, research institutions, and other actors. For instance, sometimes modelling projects were exclusively conducted at universities or other research institutions without government involvement. Meanwhile, other approaches were led by, or centred on, governmental entities: participants described, for instance, collaborations between national or local government bodies, often the Ministry of Energy or the Ministry of Environment, and an external international organisation that provided funding for the modelling project. Yet another approach was for a governmental body, such as the energy ministry or utility, to undertake the modelling or collaborate with in-country institutions, such as universities or think tanks, to obtain modelling support. The distinction between those approaches is relevant for the discussion that follows.

The following section sets out the results and discussion and is structured around themes that emerged from the analysis, summarised in Table 2 and discussed in detail in the subsequent sections.

3.1. Diverse perspectives on energy modelling held by policymakers

A significant influence highlighted by participants that defines if, and in what ways, modelling is taken up and used in policymaking in a country, were the perspectives of policymakers on energy modelling. Various attitudes were presented ranging from positive, with increasing interest in modelling, to more neutral and even sceptical perceptions. The diversity of perspectives may pertain to the relative newness of energy modelling in many LMICs which means it may be unfamiliar to policymakers. As modelling gains traction, the interviews suggest that countries are at significantly different starting points regarding their capacities and institutional networks for energy modelling. Some modelling experience and capacity was described to exist in some countries, while in others it was minimal or non-existent. According to a

Table 2
Summary of key themes.

Section	Theme	Summary
3.1	*Diverse perspectives on energy modelling held by policymakers*	• Policymakers hold wide-ranging perspectives regarding the usefulness of modelling activities. Attitudes can vary between countries and within governments (e.g. between ministries). • Attitudes range from positive or neutral, to sceptical. This variation may relate to: the recency of uptake of modelling activities within the country, *who* is conducting the modelling, the level of competing priorities, transparency of modelling approaches, and further political economy factors. • Possible solutions to increase policymaker appetite for modelling include: enhancing local capacity, improving transparency, and trust-building efforts.
3.2	*Wide-ranging influences on modelling projects*	• Various objectives and assumptions influence modelling activities, and how their results are received by policy actors. • Policymakers can insist on certain data being utilised to fit political interests; contest results; or utilise modelling results to retrospectively justify a decision already made. • Societal and wider circumstances influence modelling. For example, certain energy sources face societal resistance, even if the modelling results suggest their suitability. Hence, results can become contested.
3.3	*The importance of context-specific data*	• Model assumptions cannot be reliably transferred from one country context to another. Obtaining accurate, context-specific data is highly important; inaccurate or outdated assumptions can reduce trust and reliability. • Certain countries and regions (e.g. Africa) have limited data, and external assumptions may be unsuitable.
3.4	*Stakeholder engagement in modelling*	• The findings suggest variation in how, and to what extent, diverse stakeholders are involved in the modelling process. • Inclusive approaches can be seen in Latin America as participatory approaches are often embedded from the outset. • In some regions, academia and policymakers have a high level of collaboration, whereas other countries have limited relationships between such stakeholders.
3.5	*Balancing stakeholder priorities and independence*	• The varied level of stakeholder engagement in modelling entails complexities as to balancing competing priorities and independence. • Modelling conducted by independent stakeholders (e.g. thinktanks) provide alternative scenarios without political influence. Conversely, involving policymakers can increase the relevance of modelling results. Hence, there can be a thin line between independence and influence from government stakeholders.
3.6	*The role of modelling in policymaking*	• Modelling results can have a varying degree of application in policymaking across countries, and it can sometimes be difficult to ascertain how influential modelling activities are for policymaking. • In Latin America, the findings suggest modelling is an important activity for energy planning. In other regions and countries, the uptake of modelling results in policymaking is less clear.

participant, a '*critical mass for energy modellers in developing countries*' (IO-EM8), had not yet been established. Hence, a theme to emerge from the interviews related to a lack of in-country modelling capacity: participants repeatedly criticised the status-quo, which is dominated by external actors from HICs that fund and lead modelling projects, with insufficient emphasis on building local modelling capacities. Different attitudes held by policymakers, reflecting these different capacities and experiences, were highlighted in the interviews. These perceptions are likely linked to wider political economy factors, such as structures of governance and socio-economic dynamics of a country.

It is important to highlight that this section is skewed towards statements about policymakers made by modellers due the uneven split in participants between modellers and policymakers. Future research efforts should focus on conducting research with policymakers to understand their perspectives in greater depth.

Many interviewees reported increasing interest from policymakers in energy system modelling. A variety of reasons behind this development was given, although a common rationale was increased pressure for climate action. This linked to a need to create Paris-Agreement-aligned NDCs (LAm-EM3, LAm-EM5), and to secure climate finance from international bodies, which demand modelling-driven energy plans as a condition to release funding (IO-EM5). One participant acknowledged the increasing need for energy modelling '*to inform our domestic energy policy, but also to inform [the country's] position in the climate negotiations*' (SAsia-EM1), pointing towards the relevance of modelling in international climate debates. This reflects existing observations, such as by Niet et al. [58] who highlight growing interest in sustainable development, as well as the complexity of integrating variable renewables, as drivers for energy modelling. Another reason identified was an interest in quantitative data for energy planning (EAfr-PM1, WAfr-EM3). Modelling was believed to make energy planning easier and more effective (WAfr-EM3). Finally, another motivation for modelling is the growing desire to bring energy planning to a level of subnational granularity, which has been raised by Hofbauer et al. [59].

Participants also described country cases where policymakers were less engaged with modelling activities, for example due to competing priorities. In the context of one government, issues such as social conflicts around the implementation of the census were mentioned as the reason for less engagement with modelling (LAm-EM2). This shows that demand for modelling may rise and fall over time depending on governmental priorities, which can also change with the political orientation of different governments. This dynamic was suggested to cause instability for modelling teams (LAm-EM3). One participant mentioned scepticism by policymakers towards modelling studies, often underpinned by a lack of trust due to limited transparency, particularly when modelling is undertaken by external actors. Indeed, this can result in a preference for local modellers to join or lead projects:

> '*[The government] do not trust the modelling because the modelling was made by the foreign expert. (…) They would like to have domestic modeller to join the simulation with the foreign expert, or they can't understand what they do. That's why when all staff can tell the boss that we have done, this result can explain - and then that would be better*' (SEAsia-PM1)

This sentiment is also reflected in the work of Mutiso [5] who argues that modelling endeavours and their outcomes will be seen as more credible among African policy makers if they are led by Africans. It is worth highlighting that the perceived trustworthiness of externals in modelling projects may differ between countries, and may link to broader perceptions of externally-led or funded collaborations. Furthermore, a crucial factor regarding trustworthiness was shown to be the level of transparency in and understanding of modelling processes. The interviews revealed a lack of understanding of modelling processes as another potential reason for low levels of trust – especially considering the newness of modelling activities in many LMICs. For example, EAfr-EM1 attributed mistrust by policymakers to a limited awareness of the capabilities of modelling tools, which they argued was symptomatic of poor relationships between the government and the university sector. In another country, WAfr-EM2 described how policymakers were often confused by different entities presenting differing modelling results on the same topic. However, divergent outcomes may be expected if studies are based on different assumptions or data sources (Wafr-EM2). Globally, non-modellers may struggle to understand the assumptions behind and functioning of models because of their complexity and opacity [1, 60]. There may be different degrees of transparency depending on the model type (e.g. optimisation or simulation) as the tasks of modellers in the process and the degrees of insight into the endogenous calculation process differ between these types [61]. Besides this, policymaker IO-PM1 argued it was the modellers' responsibility to be transparent about the data and assumptions made in their models, but that these were often not communicated clearly enough:

> "*Unfortunately, (…) [the modelling community] is not transparent. No one discusses the assumption that they're [making], (…) just (…) the results.*" (IO-PM1)

Opacity, due to the model structure or a lack of transparent communication, makes it hard to establish knowledge management structures in modelling teams and hinders the establishment of institutional networks to build national capacity [4]. This can lead to wasted efforts especially in countries where modelling is a more recent practice [4].

Some participants offered insights into how they sought to increase policymakers' understanding of, and thus interest in, energy modelling. It was argued that a key enabler for a positive attitude towards modelling was a collaborative relationship between governments and knowledge institutions that conduct modelling. For example, in one Latin American country, the planning ministry worked with a university-based modelling team to develop key indicators for their long-term energy planning (LAm-EM4). In this collaboration, the stakeholders discussed and updated targets together on a yearly basis. To address initial doubts and misconceptions about modelling, LAm-EM4 collaborated with the policymakers by answering their questions and explaining the process in depth. This way, policymakers changed their views from seeing energy modelling as *'just a waste of time'* to finding that it could generate '*some interesting results*' (LAm-EM4). The open, collaborative approach between policymakers and academia proved vital to enable cooperation in modelling. Another approach that supported trust-building was to '*capture[s] local realities so that the policymakers will have more confidence (…) to use these models*' (WAfr-EM2). This implies that modelling exercises should be highly context-specific to increase relevance and trustworthiness. This should be done in addition to making sure that communication with policymakers is nurtured and sustained over time, while building their understanding of the advantages and disadvantages of modelling. The process of integrating models into decision-making demands deep collaboration between policymakers and modellers and may be referred to as *socialising models* [57]. Barbrook-Johnson et al. [57] find that a crucial aspect in this regard is stable and large-scale funding, which is needed for modelling teams to build long-term capacity and to be able to respond to policymakers' needs.

3.2. Wide-ranging influences on modelling projects

Concerning the modelling process itself, the interviews revealed a diverse range of country-specific interests and influences that shape modelling assumptions and objectives. Notably, governmental actors played a significant role, with modellers receiving instructions concerning data or objectives, and encountering competing priorities among various ministries and governments. Furthermore, societal influences played an important role in shaping modelling efforts.

The interests of governmental actors shaped modelling processes in various ways. A key theme revolved around data and assumptions. For instance, in one country, governmental stakeholders insisted on using only '*official*' sources, rejecting modelling results based on data from academic journals or other sources (Lam-EM6). Another government interacted closely with modellers at the power utility and provided predefined targets and constraints, such as specific energy access targets or economic growth projections (EAfr-PM2). Policymakers were observed to steer projects in certain directions to provide support for specific policy agendas (SAsia-EM1). A modeller described being tasked with modelling a scenario driven by electoral promises, despite it being viewed infeasible by the modeller (IO-EM2). This illustrates how modelling can be employed to support the formulation and justification of political pledges; indeed, a participant described energy modelling '*as a tool by the politicians to try and legitimise the politically palatable.*' (SAfr-EM2). Some participants also highlighted challenges in modelling scenarios that deviated from national policies and targets, with governments being reluctant to change policies and instead using modelling to justify decisions that had already been made (IO-EM9, IO-EM5). In another case, the modeller '*present[ed] the results and they [stakeholders] were like, "we have to chip that a little bit here because that's not doable. It's not politically viable"*' (LAm-EM4). This type of post-design justification is not a new issue, having been described in 1987 by Wilbanks [41], nor is it unique to LMICs [1].

A further theme to emerge related to the conflicts of interests that arise between different ministries or individual politicians. For instance, a modeller observed contrasting perspectives between the Ministry of Economy and the Ministry of Environment on the exploration and export of natural gas (LAm-EM1). Another modeller highlighted disagreements between the Ministry of Environment and the Ministry of Energy regarding the planning of a coal power plant, claiming that modelling played a role in ultimately supporting the establishment of a gas power plant instead of a coal plant (IO-EM11). However, institutional silos and limited inter-departmental communication was mentioned to hinder the integration of different sectoral perspectives, despite energy-related issues being inherently interconnected with other sectors (LAm-EM1). Difficulties in data sharing across ministries were also evident, as some were reluctant to share data with others, or were only willing to cooperate under specific conditions, such as formal project engagement (IO-EM5). On an individual level, personal conflicts among politicians could significantly impact goal setting if '*everything just changes because someone doesn't like someone*' (SAfr-PM1). Personal political interests meant that policymakers sought to prioritise their preferred energy projects or power plant operations, even if they contradicted a model's recommendations. In some cases, if policymakers could not see a personal or political advantage, they had no interest in modelling at all (IO-EM8). This relates to the previous point on scepticism stemming from a lack of knowledge of the advantages and potential of modelling – combined with opposition if policymakers think that the results will work against their desired goals.

In addition to governmental actors, societal and wider circumstances play a significant role in shaping the modelling process. This is evident, for example, in societal resistance to specific energy sources. For instance, WAfr-EM3 gave the example of a community in a West African country rejecting a hydro project despite residing in an area with substantial hydropower potential, as they had witnessed the successful implementation of solar power in other communities and thus preferred its adoption. Similarly, in a Latin American country, there was resistance to expanding the use of biomass, possibly due to scepticism stemming from insufficient research on the implications and externalities associated with this unfamiliar energy source (LAm-EM6). Other countries exhibited a strong focus on specific energy sources due to factors such as historical reliance or abundance. For example, hydropower was described to have a special standing in Ethiopia as a well-established source of energy, resulting in lower interest in developing alternative sources despite evidence of the benefits of solar and wind (IO-EM11). Furthermore, an armed conflict in East Africa had implications on modelling projects. The conflict complicated data collection efforts and hindered discussions on decentralising the energy system (IO-EM4, EAfr-EM1). While such dynamics are exogenous, it is crucial for modellers to be aware of them in order to design modelling approaches with realistic assumptions, thereby enhancing their relevance to a country's unique circumstances.

3.3. The importance of context-specific data

Participants consistently emphasised the importance of country-specific knowledge for modellers, with one crucial aspect centring around data: here, context-specific knowledge played a vital role in determining which data should be used. An important risk identified was the potential use of inaccurate or outdated data (LAm-EM5, WAfr-EM3). In some cases, cross-checking and verification of data was necessary, as exemplified by a participant who encountered a dataset that made assumptions about building structures and their associated energy use, presuming the presence of only high-rise buildings when, in reality, there was a mix of high- and low-rise structures (WAfr-EM3). Context-specific knowledge was also noted to be important for data collection, particularly in SSA, where data availability and accessibility may be limited (see also [5,23]). For instance, in South Africa's KwaZulu Natal province, specific data on household energy behaviour in remote villages was collected by IO-EM1 to understand area-specific energy demands. This required a deep understanding of the local context, including village locations and accessibility (IO-EM1). Furthermore, participants emphasised the importance of using country-specific data, such as technology costs, grid efficiencies and losses, differences in rural and urban energy demands, and the availability of technologies and services such as internet connections. This underscored the need to adapt models not only to the unique characteristics of LMICs (as described in the introduction) [11,23], but also to each individual country and its circumstances [62]. Participants were critical of external modellers who build models based on inappropriate data and which therefore failed to reflect local realities:

> '*One major problem we also have in Africa is the lack of data. And then people are building models for us. And sometimes I look at these models and I ask myself, 'how did you know that this is what happens here?' Because definitely it wouldn't work*.' (WAfr-EM3)

Other participants (LAm-EM5, IO-EM1, IO-EM2, IO-EM4, IO-EM5, IO-EM6) also cautioned that external modellers often lacked specific contextual knowledge to use appropriate assumptions and data, as well as navigate stakeholder expectations. To address this, participants emphasised the importance of involving local experts in the modelling process in order to enhance the credibility of inputs and outputs, particularly for policymakers. They suggested that engaging local experts could help verify and collect relevant data, as well as design more country-specific modelling approaches. As external modellers will not know everything about a country's context, '*stakeholder engagement is very important because then you might just find out that there's something that you don't know about*' (SAfr-PM1). This echoes findings of previous studies [1,41,63], including Mutiso [5], who argues that non-African modellers often fail to approach energy modelling from a relevant perspective, and advocates for early engagement of in-country decision-makers to '*ensure that their assumptions make sense on the ground*' (p.1). IO-EM6 argued that local experts may generally be better suited to conduct the modelling than externals because they have better knowledge of the circumstances:

> '*I think it's easier to train people which come from, for example, the Africa continent in general, from specific countries, which know (…) what are the assumptions that should be integrated (…) than having people which could actually be super skilled in modelling but don't have any clue of what's the reality there and sometime use, let's say, overall assumptions, which are the same for the entire continent, forgetting that Nigeria is not the same as Mozambique*' (IO-EM6)

Furthermore, insufficient engagement of in-country stakeholders was identified as leading to a lack of ownership over modelling processes and outputs. Decision-makers who based their commitments on externally developed models might not have been '*fully aware of what such commitments mean*' (IO-EM6).

Generally, a lack of high-quality, accurate data is a critical obstacle in designing modelling approaches, especially in LMICs [57]. This imbalance in data availability represents a risk of perpetuating injustices and inequalities in energy planning [57]. One participant spoke to the issue of data being collected by international organisations, depriving countries both of access to that data and of decision-making power about what happens with the data:

> *"The problem (…) has been created by the international [organisations], (…) all the energy data and information on energy in Africa is [with] [name of intergovernmental organisation]. The country has nothing. The region has nothing. [Name of intergovernmental organisation] are collecting data. And this is to feed the system rather than helping the countries."* (IO-PM1)

This relates to the wider issue of data being extracted from LMICs, particularly local communities, by external parties [64,65]– referred to as digital colonialism [66] or algorithmic colonialism [67]. Ways of collecting and sharing data that are equitable and inclusive, and that put the rights of communities in which data is collected first, must be found and implemented. Moreover, investment in data collection and sharing is essential to tackle the unequal distribution of and access to data [57].

3.4. Stakeholder engagement in modelling

The political economy of each country played a defining role as to whether, and how, stakeholder engagement in the modelling process was pursued. For instance, Latin American countries emerged as leaders in participatory modelling processes. Their approaches typically involved comprehensive stakeholder consultation from the outset. In countries including Brazil, Chile, and Panama, industrial and societal stakeholders were able to submit online responses to consultation calls on modelling processes and energy plans (IO-EM9, LAm-EM5). In Brazil, the Energy Research Office, a governmental institution operating under the Ministry of Mines and Energy, demonstrated '*a whole engagement plan where they put the modelling process [out] for consultation and get thousands of responses of what people think*' (LAm-EM5). This exemplified the long-standing tradition of energy modelling in Latin America wherein institutional processes support stakeholder participation, in contrast to regions with less modelling experience. In such regions, communication and engagement structures may not be as well established, resulting in limited stakeholder involvement. A lack of trust in modelling by policymakers (see 3.1) is likely to affect their willingness to engage in the process. In one instance, a poor relationship between government and academia led to a lack of stakeholder engagement in university-led modelling projects (EAfr-EM1). While in another, a think-tank-based modeller attributed the lack of stakeholder engagement in a government-commissioned project to their '*hands-off*' attitude during the process (SAsia-EM1). However, this lack of engagement of stakeholders in modelling processes can pose challenges, as expressed by one participant:

> *'The less you involve people in the modelling that you do, the more opposition you risk triggering with your results.' (IO-EM4)*

Meaningful stakeholder engagement must reflect on which stakeholders are consulted and whether the needs of affected and underrepresented groups are adequately addressed. In modelling, it is essential to critically assess what kind of scenarios are being created, and who is able to make decisions [68]. In circular economy modelling, for example, concerns have been raised regarding the lack of democratic formulation that favours certain perspectives over others [69]. Genuine participation must go beyond passively including stakeholders in meetings and overcome social, cultural, and structural barriers to include the voices of underrepresented groups and enable them to shape the process [38,70]. Engaging stakeholders at various levels of governance, from the municipal to national level, can effectively address the multiple scales of energy issues and support more meaningful policymaking [59].

3.5. Balancing stakeholder priorities and independence

A theme that has featured throughout this discussion, and especially in relation to stakeholder engagement discussed in Section 3.4, is how independent, or detached from interests and influences, modelling processes could and should be. Modellers often face a fine balance between following requirements by government versus conducting more independent modelling (i.e. which considers energy futures and scenarios that might deviate from official government positions). Some authors call for greater attention to stakeholder interests in modelling projects so that the views of policymakers are considered earlier on in the process [1,41,63] thus enhancing the political relevance of modelling. While Keppo et al. [71] argue that political relevance of modelling is critical, they also contend that too close an influence of policymakers on the modelling process may create concerns regarding scientific integrity. Due to the risk that model outputs can be made to fit with the wishes of politicians, a level of independence in the modelling process is needed [1,60,72]. However, it needs to be caveated that these considerations may hinge on the funding structure of projects, with the source of funding being an influential factor in driving modelling scope and objectives.

Generally, modelling conducted by non-governmental bodies can provide scenarios of alternative energy futures. One participant (WAfr-PM1), in a country where no extensive in-country modelling capacities had been established yet, advocated for building modelling capacity in universities and linking it to the government:

> *"My preference is always to embed (…) [modelling capacity] in the university. Then you can have the economics department involved with the engineering department, with the specific energy faculty. Then you (…) link it to government. My worry is that when you put it in the ministry itself, in our small economies, it doesn't survive. (…) Individuals get spirited off to do other (…) political stuff or bureaucratic stuff, and we just don't focus on the modelling aspect."* (WAfr-PM1)

In countries where modelling activities were already ongoing in the government, a potential scenario might be to combine this capacity with an open-mindedness to independent modelling results which explore alternative scenarios. For example, EAfr-PM2 welcomed growing interest in modelling in academia in addition to governmental activities, as the university teams '*can look at other scenarios that we ourselves are not really looking at (.) [and] help us inform the future.*' In Zambia, Tembo et al. [60] similarly recommend the establishment of institutions that can uphold the necessary independence while enabling energy modelling to support policy processes. A participant discussed their hope to strike a balance between staying objective while still meeting stakeholders' needs:

> *'So the idea is to have [the model] certainly tailored to meet [the country's requested] objectives, but also trying to (…) keep some independence of thought within the group on how to approach these issues because (…) in some countries there's a very great reluctance to say something, even if it's not for publishing, even if it's just a look at different perspective than the official ones.' (IO-EM9)*

Similarly, two modellers highlighted that they deliberately model '*even the unpopular scenarios*' (SAfr-EM2), because such futures would otherwise remain invisible. In this way, they could use modelling as a '*sort of advocacy (…) to see certain change*' (SAsia-EM2). Specific strategies employed to maintain independence while meeting stakeholder needs were not discussed, which warrants further research to explore approaches that maximize value for all stakeholders. The extent to which there will be opportunities to conduct modelling studies that deviate from government plans will vary from country to country. However, an advantage of modelling is the ability to explore different future pathways for energy systems, transition options, demand and supply dynamics, and energy-related policies [1], so policymakers are encouraged to see energy modelling as a tool to enrich debates by creating multiple scenarios and incorporating different perspectives. Rarely can one model fulfil all policy needs, hence a diversity and variety of methodological approaches is critical (IO-EM2, IO-EM3, SAsia-EM1, LAm-EM5) [57]. More targeted funding that supports a modelling ecosystem with international and geographically dispersed teams of different sizes, drawing on multiple models, is needed [57].

3.6. The role of modelling in policymaking

Once modelling results were generated, their uptake and use in policymaking again differed across countries, reflecting each country's unique vantage point. Many interviewees argued that the results were used, at least to some extent, in policymaking. Modelling was described as fundamental for energy planning in some countries of Latin America and East Africa, as having some policy influence in countries of Southern Africa and South Asia, and as not being widely used in still other countries of East and West Africa, and West and South Asia. However, opinions on the uptake or impact of modelling differed even within the same region or country. For example, SAsia-EM1 stated that energy modelling had been used to inform energy and climate targets, while SAsia-EM2 was of the opinion that it has had only limited use. This difference of opinions may be related to the extent and strength of each participant's relationships with decision-makers, levels of collaboration and communication with model users, and thus different perspectives on how modelling outputs are used in practice.

Generally, the participating modellers pointed to the difficulty of understanding *how* exactly modelling feeds into policymaking, and *when* and *where* the results were used. Many modellers found it challenging to assess this, presumably because they were not directly included in the policymaking process. One modeller argued that as soon as a number or a target from their modelling activities was published in a policy document, such as NDCs or an updated energy policy, they defined this as having policy impact (IO-EM11). The communication of specific numbers from modelling in policy documents was therefore taken as a sign that modelling efforts had influenced decision making. One policymaker (SAfr-PM1) offered some insights from a planning perspective, describing how the model they used was helping them to assess the implementation timelines of different energy projects, prioritise them accordingly, and structure the process better while also securing investment more efficiently. This shows that it is not necessarily only a number that feeds into policymaking, but that there are also structural and management advantages for the process of policymaking itself. In another case, energy modelling was a key tool for assessing demand growth projections and consumer tariff impacts, as well as determining how to integrate more renewable energy into the grid in the future (EAfr-PM2). More subtle and harder-to-capture ways in which modelling may influence policymaking represent an interesting topic for future research.

Interviews revealed that policymakers drew on modelling results in diverse ways. Some participants claimed that policymakers chose to only acknowledge modelling studies that seemed relevant for achieving their goals (see 3.2), showed results that they liked, or were done by organisations which had a good standing with the government. Moreover, some interviewees lamented that policymakers overstated the relevance of modelling results, by being over-confident in the outcomes and not taking other factors into account in decision making. For example, policymakers might not have questioned or interpreted modelling results appropriately because they were keen to use any quantitative outputs to support decision-making (SAfr-EM1, SAsia-EM1). This could lead to premature communication of results without adequate reviewing or cross-checking, failing to place these numbers in context.

However, there were country examples where policymakers did not use modelling results at all. This went beyond a lack of engagement in the process, as discussed in 3.4, but referred to the actual utilisation of modelling results by policymakers, regardless of the extent of engagement in the process. A modeller shared insights into a project they conducted together with governmental stakeholders, who had not used the results (IO-EM3). The participant speculated on why the results were not used, perhaps due to a potential misalignment with policymaker needs, or a limited capacity to engage with the model once the project finished, and the dissolution of the responsible political entity (IO-EM3). This suggests that longer-term partnerships, which incorporate project evaluation, would enable an understanding of how and why modelling outputs are or are not used. Moreover, it highlights that local modellers are better placed to maintain longer-term relationships with policymakers. As discussed in 3.2, differences between governmental actors were cited as another reason modelling results were not taken up (IO-EM4). Policymakers would not use results that supported the standpoint of another person who they may not get along with. They could even dismiss or override modelling results, or amend them to say something that they want to see:

> *'What tends to happen is some modelling gets done and then this sort of policy adjustments overlay is applied to it which is really the Minister saying 'That's the wrong answer. We need more gas.' (SAfr-EM2)*

Similarly, in the context of HICs, Süsser et al. [1] point out that political uncertainties, as well as the number of different actors involved, can impair the use of modelling results in policymaking. This implies that stakeholder engagement processes need to be well thought through and carefully designed. In the context of Africa, Sterl et al. [62] point out that barriers for energy transition analyses to influence policymaking may include low contextualisation, a disconnect between science and policy, and lacking agency to translating action points into reality.

4. Conclusions

This paper examined the experiences and perceptions of those involved in energy modelling and policymaking in LMICs. It investigated how modelling is currently being undertaken in LMICs, what factors shape modelling processes, and, vice versa, how modelling results shape policymaking in LMICs.

The research revealed that energy modelling is increasingly being applied in LMICs, addressing different objectives which range from planning for universal electricity access to decarbonising energy systems, energy security and trading. Awareness of and interest in energy modelling is increasing among policymakers in many LMICs - facilitated by a growing awareness for the need for climate action and evidence-based decision-making, such as Paris-Agreement-aligned NDCs. However, the interviews revealed a mixed picture, with policymakers in some other countries being described as indifferent or even sceptical about modelling. This may be due to an underlying lack of trust, especially towards externally-led modelling projects. The research illustrated that countries are at fundamentally different starting points not only regarding perceptions of modelling, but also modelling capacities, stakeholder influence and engagement, and utilisation of modelling outcomes in policymaking.

Furthermore, the factors shaping energy modelling processes varied given different country- and project-contexts. Stakeholder engagement ranged from limited to extensive, with governmental stakeholders in particular shaping data assumptions and objectives. This diversity called for modellers to have good knowledge of the contexts in which they were working, and highlighted the importance of fostering equitable partnerships with local experts and stakeholders throughout modelling processes.

Finally, the diversity of country contexts again became clear in the process of examining the extent to which modelling influences policymaking and the ways in which results are used. While some countries fundamentally based their energy planning processes on modelling, others drew on modelling insights only minimally, and still others not at all. However, participants cautioned that it was difficult to ascertain how modelling results were used in policymaking, which suggests a need for longer-term project evaluation and greater support for ongoing and equitable partnerships. This research therefore advocates for modellers to be aware of the contexts in which they are working, and to collaborate with local experts. Additionally, building and maintaining in-country capacity, and investing into modelling teams, will enable modelling projects to be driven and owned by local stakeholders.

Several knowledge gaps have been identified which warrant further investigation. This research had greater participation from modellers, and further research should deepen the investigation into how modelling results feed into policymaking processes from the perspective of policymakers. For example, it would be relevant to investigate policymakers' reactions to, and opinions on, statements made by modellers regarding disinterest or fluctuating demand for modelling. This could help to identify further action points to facilitate a better connection with modelling for policymakers, based on what they identify as critical points for improvement. An enabling environment for modelling in policymaking depends on several factors in LMICs, as much as it does in HICs. The breadth of experiences that participants described, representing the diversity of stakeholders and their priorities, suggest that ideal approaches will look different in every country. Country case studies may be appropriate for understanding the political economy of a country in greater depth, how modelling is embedded into it, and what players are central.

Given global multifaceted energy- and climate-related challenges, energy modelling will remain important in providing quantitative information, in exploring the costs and benefits of different energy pathways, and representing a diversity of stakeholders. At the same time, modelling efforts need to be dynamic and responsive to changes in both geopolitics and national politics. If interpreted in the appropriate context, modelling can play a vital role in energy planning, but this should take place alongside other, more qualitative methods. Building capacity, especially in-country, and designing projects that establish equitable partnerships between modellers and stakeholders from HICs and LMICs, can facilitate the deep changes needed in energy systems worldwide.

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CRediT authorship contribution statement

J.L. Fuchs: Conceptualization, Methodology, Data collection, Formal analysis, Writing – original draft, Writing – review & editing. **M. Tesfamichael:** Supervision, Conceptualization, Methodology, Formal analysis, Writing – review & editing. **R. Clube:** Formal analysis, Writing – review & editing. **J. Tomei:** Supervision, Conceptualization, Methodology, Formal analysis, Writing – review & editing.

Declaration of competing interest

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

Data availability

The data that has been used is confidential.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2024.114726.

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