Utilities Policy 91 (2024) 101854

Contents lists available at ScienceDirect

Utilities Policy

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

Full-length article

Pathways to a sustainable electricity sector in Kenya: Challenges and transformational factors

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ARTICLE INFO

Handling editor: Janice A. Beecher

Keywords:
Cross-impact balance analysis
Energy scenarios
Kenya

ABSTRACT

Which factors may enable a secure, affordable, and sustainable development of the Kenyan energy system? The present study aims to understand how the country's energy system could be structured in 2050, to unravel the main challenges, and to identify critical leverage points for policy action. To this end, we designed energy scenarios for Kenya using cross-impact balance and succession analysis, drawing extensively from expert judgments. The results highlight the importance of improving the quality of the grid, further reforming the electricity market structure, encouraging more competition, and promoting decentralization as the main leverage points for ensuring a secure and sustainable energy future.

1. Introduction

With a GDP of $110 billion in 2021, Kenya is classified as a lower-middle-income country (World Bank, 2022b). The country has a population of almost 55,000,000 inhabitants, the third largest in East Africa (World Bank, 2022c). Economic and population growth pose several challenges and opportunities for Kenya's energy sector. Although significant progress has been made in recent years, such as regarding energy access, inequality and poverty remain key challenges for Kenya (USAID, 2022). Therefore, despite often being termed a regional leader in socioeconomic progress, Kenya continues to face challenges similar to those of other countries in the region. The same holds for the country's energy sector.

Kenya is a pioneer in the sub-Saharan African region in terms of climate and renewable energy policies and outcomes. It has rapidly increased electricity access over the past decade, thanks to a robust on and off-grid renewable energy sector. The country plans to decarbonize and envisions a 32% reduction of emissions by 2030 against the business-as-usual scenario (Ministry of Environment and Forestry Kenya, 2020). Kenya's electricity is mainly generated from renewable energy, which made up 88% of installed power capacity in 2021. Supply is led by geothermal energy (41%), followed by large hydropower (30%) and wind energy (16%). There is also a rising solar PV sector (1%) (International Trade Administration, 2022), receiving a high share of new investments (UNEP, 2019). Thermal power plants still produce 10% of electricity, and the Kenyan industrial and transport sectors rely primarily on fossil fuels (EPRA, 2021). Determined policies promoting renewable energy include regulatory policies (e.g., a feed-in tariff and tendering) and some fiscal incentives (e.g., tax incentives) (REN21 2021). Despite these achievements, the electricity sector still faces several limitations. These include a lack of universal energy access, affordability problems, and transmission and distribution network challenges. By extension, this leads to a mismatch between demand and supply of electricity, resulting in a capacity surplus (Mbungu et al., 2021). Finally, discoveries of oil and gas reserves (Ngungi and Nzioka, 2021) put in question the continued reliance on renewables in the electricity sector unless the government remains committed to decarbonization.

Like many other African countries, the key challenge for the Kenyan energy sector is not achieving the energy transition. At least in the power sector, Kenya does not suffer from path dependencies that would favor fossil fuels. Instead, the question is whether the country can ensure its clean energy sector is developed further and its energy system remains mainly reliant on renewables (Kazimierczuk, 2019). Against this backdrop, our study aims to identify Kenya's main challenges and leverage points to ensure a sustainable energy future. Our method of choice is

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https://doi.org/10.1016/j.jup.2024.101854
Received 10 April 2023; Received in revised form 3 November 2024; Accepted 3 November 2024
Available online 11 November 2024

scenario modeling.

We are not the first to study Kenya; the country has received significant attention in energy research. Studies looked at the key challenges and opportunities the energy systems in Kenya are currently facing in integrating more renewables (Kazimierczuk, 2019) or changing the electricity market structure (Newell and Phillips, 2016). Other works focused on the implications of energy poverty (Njiru and Letema, 2018), the difficulties in improving energy access (Lee et al., 2016), and energy reliability (Taneja, 2017). Research also investigated attitudes regarding renewable energy (Oluoch et al., 2020). Finally, decentralized electricity has received attention. For example, Lay et al. (2013) looked at the drivers of decentralized clean energy adoption, focusing on solar home systems in Kenya. Moner-Girona et al., (2019) conducted spatial mapping to inform electrification policy for off-grid areas by identifying the optimal balance between grid extension and decentralization.

Several studies have also produced scenarios for Kenya's energy future. However, these are quantitative techno-economic studies that assess the cost-effectiveness of different combinations of technologies or policy measures and their respective costs and benefits, including their mitigation potential (Kehbila et al., 2021). The modeling here, therefore, only captures a small part of the whole picture. Currently lacking is scenarios analysis that also incorporates factors that potentially significantly impact Kenya's energy future but are hard to quantify, factors including political economy structure, technology transfer, technology acceptance issues, and energy security.

The unique contribution of the scenario exercise underpinning our study lies in the fact that it models factors captured as qualitative judgments using participatory cross-impact balance (CIB) (Weimer-Jehle, 2006). CIB allows for the formal assessment of energy system dynamics and systemic changes. This permits studying structural components that impact the future of energy systems and identifying their relevance in combination with other driving factors. In short, the interactions within a complex energy system are considered in a systematic way.

CIB has been used extensively as a scenario method in energy research for investigating issues as different as energy consumption (Vögele et al., 2017), innovation (Vögele et al., 2022), energy supply (Göllinger and Knauf, 2019; Venjakob et al., 2018), and decarbonization (Kunz and Vögele, 2017; Mier et al., 2020; Norouzi and Fani, 2021; Pruditsch and Zöphel, 2017; Shafiei Nikabadi et al., 2021). The geographic focus of this literature is predominately Europe (see, for example, Förster and Weimer-Jehle, 2003; Kunz and Vögele, 2017; Pruditsch and Zöphel, 2017), and studies from the Global South are scarce. Exceptions so far include investigations into Iran and Mexico (Marzban and Mohammadi, 2020; Norouzi and Fani, 2021; Shafiei Nikabadi et al., 2021; Oviedo-Toral et al., 2021). So far, there exists no CIB analysis of energy scenarios in the Kenyan context, and no study has taken this approach to analyze the systemic changes leading to a sustainable energy future for the country.

Filling this gap, we designed different energy scenarios for the Kenyan energy system by 2050 to identify the main challenges and the factors that can play a transformational role in sustainability. CIB is a method that produces internally consistent and plausible scenarios. Its strength lies in the fact that it can model quantitatively qualitative factors, which makes it open to co-creative approaches, whereby the factors used in the modeling stage are determined from expert opinions. Our study follows a participatory approach, drawing extensively from judgments collected in workshops and expert interviews. In order to identify the critical leverage points to transform the Kenyan energy sector, we used succession analysis (Weimer-Jehle, 2006).

The present study adds knowledge on the complex dynamics that can shape energy futures in non-OECD countries. Based on a formal modeling approach, it confirms some findings from other studies, for example regarding the challenges facing the Kenyan energy sector. At the same time, the study generates novel insights into the central factors shaping Kenya's energy future, how these factors interrelate, and what follows for policy intervention to achieve desirable outcomes. Moreover, relying extensively on expert judgments, the study offers novel insights into expert opinions concerning the most relevant factors and desirable outcomes for the Kenyan energy future.

In line with previous studies, our findings suggest that achieving access to affordable, reliable, and secure energy, which we refer to broadly as energy security, is the main challenge for the Kenyan energy sector. Our analysis shows that there, in fact, is no single scenario that produces the desired outcome, i.e., an end-state where energy security is fully addressed by 2050. We also identify the building blocks for addressing this challenge going forward. We find that transformational areas for action to enhance energy security and continue on a sustainable energy path include improving the quality of the grid, further reforming the structure of the electricity market, encouraging more competition, and promoting decentralized energy systems. Other identified areas include renewable energy value chain participation, international technology knowledge transfer, investment in renewable energy, and public perception of renewable energy. However, our modeling results show that these factors do not have the power to enable systems change.

With this, the paper adds to our understanding of the most important factors enabling a secure, affordable, and sustainable development of the Kenyan energy system. Doing so highlights the analytical power of the scenario approach in formally modeling alternative and normatively desirable futures in a structured way and in identifying policy pathways to achieve them so that the results also inform policy design.

The paper is organized as follows. Section 2 presents relevant background information on the Kenyan energy sector. Section 3 introduces the methodology and the data collection process. Section 4 presents and discusses the results, and Section 5 concludes with policy recommendations.

2. Structural challenges and opportunities for a sustainable energy future in Kenya

Kenya's support of alternative renewable energy sources has been mainly driven by energy security and development concerns and not so much by climate mitigation action. The country developed other renewable energy sources after changes in rainfall patterns in the 1990s challenged a continued reliance on large hydropower as a primary source of electricity generation.

Despite considerable progress during the last decades, it is currently unclear how much of Kenya's renewable energy potential will be further developed. This situation is due primarily to demand limitations regarding electricity, which occur while the country is still struggling to achieve universal energy access and address energy poverty. Reasons for this include a lack of affordability and problems in the transmission and distribution network (Mbungu et al., 2021). These cause a capacity surplus, which has had implications for the financial sustainability of the power sector as investments are deterred. Moreover, the Kenyan government, a majority shareholder and single buyer in the electricity sector, incurs additional financial burdens. Most power purchase agreements have a 'take or pay' clause, which means that the energy provided needs to be paid for, even if it is not being used (Eberhard et al., 2018).

Kenya plans to expand domestic thermal capacity. For example, the 2013 5000+ MW program, which eyed an increase in electricity generation capacity of over 5000 MW by 2016, also foresaw significant natural gas and coal capacity (Kenya Engineer, 2013). Although the ambitions of this program have been since reduced (The Kenyan Wall Street, 2017), there are still plans to develop thermal projects (Government of Kenya, 2021).

2.1. Quality of the grid

A critical limitation of the Kenyan electricity sector is its poor reliability and a national grid that does not cover many remote areas. There are significant technical losses in transmission and distribution, and power outages are frequent (Kazimierczuk, 2019). The situation is worse in rural areas where, in addition to short-term outages, sometimes there is no electricity access for months (Lee, 2023). This has several impacts. First, it creates economic losses (Takase et al., 2021). Second, the poor quality of the electricity supply makes it less attractive for households to have electricity installed or to purchase electrical appliances (Bajo-Buenestado, 2021), which leads to low demand and, subsequently, to economic losses for power producers. Third, the current grid infrastructure often faces limitations when integrating new renewable energy projects. Renewables contribute to grid instability due to intermittency, which adds to grid quality issues. The country has experienced significant delays in connecting new renewable energy projects to the grid, leading to excess capacity (Bajo-Buenestado, 2021). At the same time, there are also parts of the country with high potential in renewable energy whose development is currently not within the limits of the grid network.

2.2. Universal access to electricity

Kenya's electricity access rate rose from 19.2% in 2010 to over 75% in 2021 (World Bank, 2022a). However, a significant part of the rural population still lacks electricity access. One reason for this is limited grid coverage. In addition, affordability problems and rising electricity prices (Njeru et al., 2021) are responsible for lower-than-expected connection rates (Lee et al., 2016) and for the low electricity consumption of many electrified households (Taneja, 2018).

Decentralized power generation, based on renewables, has been highlighted as a potential solution. This technology can help overcome grid quality problems and improve sustainable energy access, especially in remote communities. Decentralized renewables constitute a tiny fraction of Kenya's total installed power capacity. However, the sector has experienced rapid growth in the last decade. In 2018, 24.523 MW of solar lights and solar home systems had been installed in Kenya, up from 0.408 MW in 2011 (IRENA, 2020). This capacity was the second highest in Africa, after Tanzania. Some Kenya-based companies emerged to target low-income households through innovative delivery models. Despite this potential, decentralized renewables face several challenges. These include unstable demand, lack of access to capital, and limited technical expertise of domestic companies (Bhamidipati et al., 2021).

2.3. Electricity market structure

Making the electricity market more competitive has been highlighted to address some of the challenges the Kenyan power sector faces. Encouraging competition and the participation of independent power producers (IPPs) through transparent competitive bids and least-cost planning can increase private sector investments. This approach introduces competitive prices and allows the power sector to expand successfully. Indeed, for more than two decades, the Kenyan electricity sector undertook several reforms to introduce competition and reduce inefficiencies. These reforms included competitive tendering in power generation based on least-cost criteria, cost-reflective pricing, and the restructuring and partial privatization of the national utility (Newell and Phillips, 2016). Despite these reforms, the electricity market remains mainly controlled by the state, which comes with political involvement on different matters that can cause market distortions (Godinho and Eberhard, 2019).

As a result of the reforms so far, the generation capacity by IPPs has grown. Indeed, Kenya has become a leader in sub-Saharan Africa in introducing IPPs in power generation (Eberhard, Gratwick, and Kariuki 2018). In June 2021, IPPs were responsible for 33.57% of effective generation capacity, which compares to a 65.8% share of KenGen, the state-owned entity for electricity generation with significant private shareholding (EPRA, 2021). However, IPPs are mainly involved in thermal or geothermal energy and have limited involvement in other renewables (Eberhard, Gratwick, and Kariuki, 2018). In addition, despite successful procurement through international competitive bids, there have been recent cases of direct assignment, especially for geothermal and wind energy projects. There also are no clear and transparent criteria for allocating projects between the public and private sectors. So far, private sector participation is limited to the instances in which KenGen cannot finance new investments (Eberhard, Gratwick, and Kariuki 2018).

To conclude, Kenya's energy system is facing several structural challenges and opportunities, which are complex and interdependent. It is, therefore, vital to systematically analyze the factors that affect the Kenyan energy system to determine pathways toward a sustainable future.

3. Methodology and data strategy

3.1. Participatory cross-impact balance

The present study uses participatory CIB (Kurniawan et al., 2022) to model the energy sector, produce plausible scenarios for the Kenyan energy future, and assess the main challenges and opportunities going forward. The study forms part of a broader research project (described in Kurniawan et al., 2022) that applied the same methodology in a number of countries, representing different regions, in order to study energy transition pathways (see Eicke et al., 2023; Schuch et al., 2024).

In CIB, scenarios are designed from the interactions of different influential factors (i.e., scenario variables) and the ways they can develop in the future (i.e., end-states) (Weimer-Jehle, 2006, 2009). This interdependence is crucial for the analysis of the dynamics of complex systems. Therefore, the CIB process requires to first identify the relevant factors of influence and their end-states, and then to determine the way these factors influence each other. These 'influence judgments' can be based on expert judgments or literature reviews (Schweizer, 2020) and are then inserted in the CIB matrix for modeling to produce scenarios for alternative futures.

We follow the standard steps of other studies applying the CIB method (see, for example, Vögele et al., 2017; Marzban and Mohammadi, 2020). However, to elicit influence judgments, we relied on expert inputs elicited in a participatory manner using qualitative expert interviews and three different workshops with international and Kenyan energy experts. More specifically, we followed the approach described in Kurniawan et al., (2022), which involves the use of influence diagrams. This participatory approach allows for extensive expert interaction during data collection. We also included additional methodological innovations to our approach that are conducive to enhancing the participatory elements of the CIB process. These include choosing ideal scenarios by experts and using succession analysis to identify main leverage points to reach such ideal scenarios (see also Eicke et al., 2023; Schuch et al., 2024). Fig. 1 schematically depicts the individual steps of the research strategy.

Workshop participants were chosen based on their expertise in energy transition and the region, using convenience and snowballing sampling. They represented a cross-section of sectors, including policy, research, finance, industry, civil society organizations, and development agencies. The sample of experts was relatively small; therefore, we ensured that they came from diverse backgrounds to minimize the possibility of bias in our results. We collaborated with a partner with a local presence in Kenya, the Konrad Adenauer Stiftung, and its Regional Programme for Energy Security and Climate Change in Sub-Saharan Africa. The local partner supported us in organizing and implementing the activities in Kenya and identifying experts in the Kenyan energy sector.

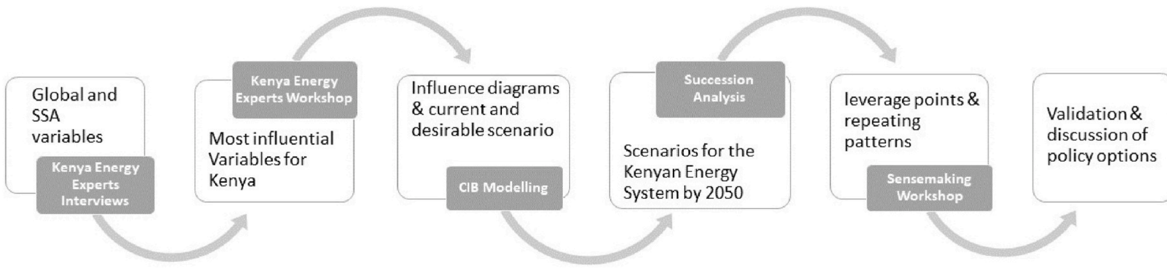


Fig. 1. Overview of the research process. Source: authors.

3.2. The most influential variables for the kenyan energy future and their end-states

As a first step, we identified the most influential factors for modeling the Kenyan energy future and their respective end-states (see Appendix A for a detailed description of the identification process). These include value chain participation, investment in renewable energy, international technology knowledge sharing, political economy structure, electricity market structure, types of energy projects, energy security concerns, quality of the grid infrastructure, and public perception of renewable energy. Table 1 lists the selected variables and their corresponding end-states. End-states refer to the way each of these factors (variables) could unfold in the future in a mutually exclusive way. For example, the variable 'participation in renewable energy value chains' was assigned the following end-states: (mostly) manufacturing, (mostly) R&D, (mostly) resources, combination of value chain segments and no participation. Detailed definitions of the end-states can be found in Appendix Table A.2.

In order to model the energy system properly and produce meaningful scenarios, it is essential to capture the interactions of the relevant factors in detail. We do this by restricting the number of factors, included in the analysis, to the most important ones, with direct impacts on the Kenyan energy sector. We therefore excluded other factors that may also play a role.

3.3. Identifying interactions between influential factors

The next step involved the identification of how the selected variables and their respective end-states interact with each other to produce influence judgments. We conducted a two-day workshop with 14 Kenyan experts on November 3–4, 2021, in Nairobi, Kenya. Participants chose the variable interrelations in several breakout sessions and plenary discussions.

On the first day of the workshop, we divided participants into three breakout sessions, ensuring a balanced representation of different sectors. We then asked participants to draw the connections they perceive between the different variables based on their knowledge and exchanges with other participants. Participants were requested only to draw enabling influences (e.g., end-state 1 of variable 1, enables end-state 2 of variable 2) and to highlight connections for which there was no consensus or some uncertainty within the group.

The second day of the workshop consisted of two plenary sessions and a breakout group session, where we confirmed the connections produced on the previous day. More specifically, experts deliberated on which connections to keep and which to remove. This concerned connections highlighted as uncertain in any of the breakout sessions. We only removed connections for which there was a unanimous decision during the plenaries. For two connections there was no unanimous decision, so they were modeled separately.

The final results produced the influence diagram (see Fig. 2) that we used in formal CIB modeling. The direction of the arrows indicates enabling influences.

Fig. 2 highlights the richness and complexity of the connections that emerged from the participatory process. For clarity, all the interactions are presented with numerical values in the cross-impact matrix in Figure B.1 in the Appendix. Fig. 3 breaks down the enabling connections drawn for a select variable: quality of the grid infrastructure. Some insights here are that good grid quality is connected with centralized renewables and bad grid quality with decentralized renewables. Another interesting connection is that poor grid quality leads to strong energy security concerns, whereas good grid quality leads to some energy

Table 1
The most relevant variables for the Kenyan energy future and their corresponding end-states.

Variable name	Variable definition	Variable end-states
V1: Participation in renewable energy value chains	The extent to which Kenya (Kenyan companies or companies located in Kenya) is part of a global value chain of renewable energy technologies, such as wind turbines or solar panels.	E1: (Mostly) Manufacturing E2: (Mostly) R&D E3: (Mostly) Resources E4: Combination of value chain segments that are equally important E5: No participation
V2: Investments in renewable energy	The amount of national and international, public, and private investments in renewable technologies in Kenya.	E1: High E2: Medium E3: Low
V3: International technology knowledge sharing	The degree to which the producers of renewable energy technologies engage in knowledge transfer with Kenya.	E1: No sharing E2: Some sharing of skills E3: Extensive sharing of skills and knowledge
V4: Political economy structure	The degree to which firms, collective actors, or state institutions shape Kenya's economic structure.	E1: Liberal market economy E2: Coordinated market economy E3: State-centered capitalism
V5: Electricity market structure	The organization of the electricity market is based on the number and structure of market participants.	E1: Monopoly E2: Oligopoly E3: Perfect competition
V6: Types of energy projects	The characteristics of energy installations are as follows: what kinds of fuel they use and how centralized they are.	E1: Mostly centralized fossil fuels E2: Mostly centralized renewable energies E3: Mostly decentralized renewable energies
V7: Energy security concerns	The degree to which energy resources are available, affordable, and accessible.	E1: No concerns E2: Some concerns E3: Strong concerns
V8: Quality of the grid infrastructure	The transmission capacity and coverage of the grid.	E1: Good E2: Bad
V9: Public perception of renewable energy	The existence or absence of public support of, or resistance toward, the deployment of renewable energy.	E1: Opposition to renewable energy E2: Neutral E3: Public support for renewable energy

See Table A.2 in the Appendix for detailed definitions of the different end-states (E).
Source: authors

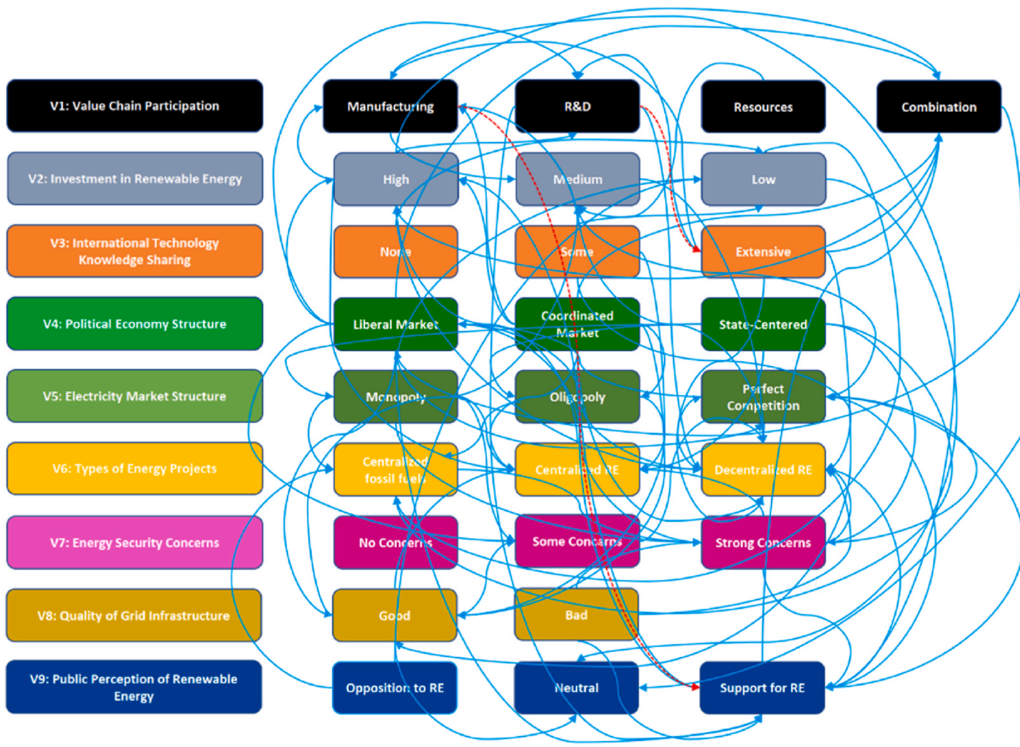


Fig. 2. Influence diagram produced. Connections with no unanimous decision were modeled separately and are marked in red. Source: authors.

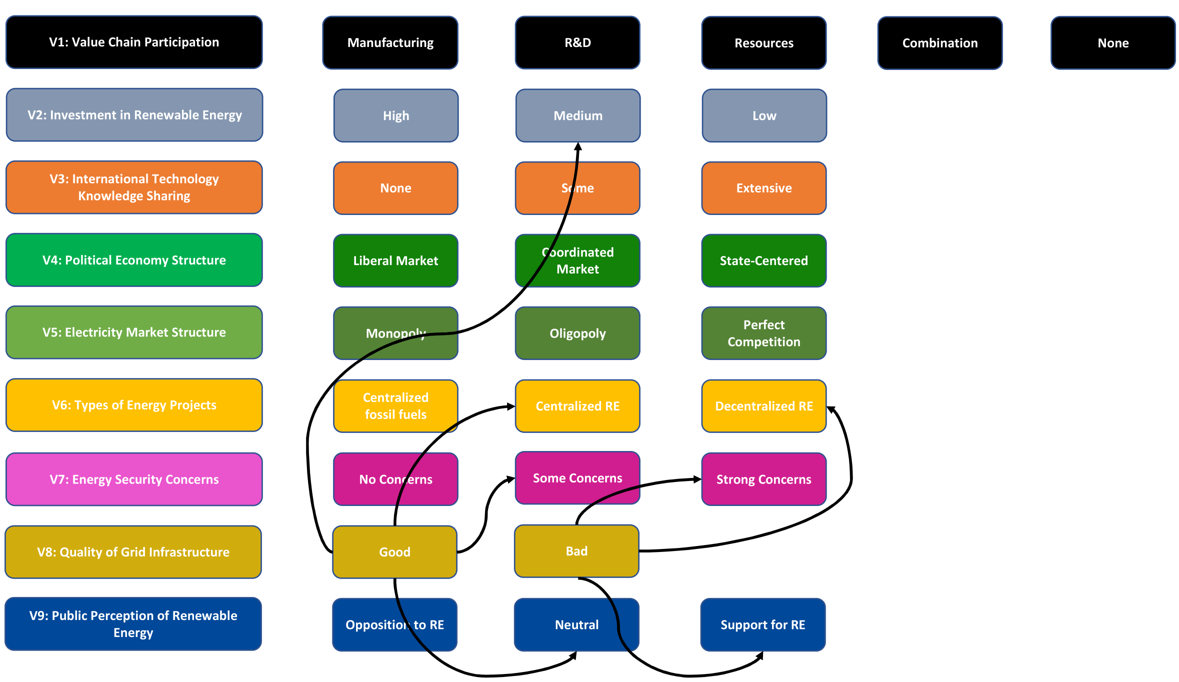


Fig. 3. Enabling connections highlighted for the variable: quality of the grid infrastructure. Source: authors.

security concerns. This perspective suggests that comprehensively addressing energy security concerns is not just a question of improving the quality of the grid.

After the workshop, we asked participants to vote through an email survey on which end-states of a pertinent variable best describe the current position of the Kenyan energy sector and which are, in their opinion, their desired end-states for the Kenyan energy future by 2050. This step enabled us to compare the scenarios resulting from our analysis with the current situation of the Kenyan energy sector and with the experts' view on an ideal Kenyan energy future.

3.4. Producing scenarios for the kenyan energy future and identifying leverage points and policy options

The influence diagram produced in the Kenyan expert workshop was then entered into a CIB matrix, the cross-impact matrix. This matrix documents how the variables in the rows influence the variables in the columns. The matrix entry is a numerical value that captures the interactions between the two end-states of different variables. Positive effects are balanced with inhibiting factors, represented with a negative number (see Figure B.1 in the Appendix). Scenario pathways were developed using the ScenarioWizard software (Weimer-Jehle, 2016). This software detects internally consistent scenarios based on the influences the different end-states have on each other, as described in the CIB matrix.

In CIB, consistency depicts the likelihood of the end-states of different variables materializing together. When this is highly likely, the end-states are considered to be self-reinforcing. Internally consistent scenarios comprise self-reinforcing end-states and are, therefore, plausible futures. CIB assesses the internal consistency of different variable end-state combinations expressed by the 'impact balance' score. This score is the columnar sum of all values in the matrix cells for a given scenario combination (see Figure B.2 in the Appendix for an example). The 'total impact balance score' (TIS) is the addition of all 'impact balance' scores for all end-states of each consistent scenario (Weimer-Jehle, 2016). The scenarios with the highest TIS are the most plausible.

After identifying all the internally consistent scenarios, we used succession analysis (Weimer-Jehle, 2006) to detect the leverage points to reach the ideal scenario for Kenya, as identified by the experts. For this, we started from the current scenario (as identified by the experts) and then changed the end-state of one of the variables of the model. This step triggers a domino effect as the end-states of other variables are changed too, until they settle on a new, internally consistent scenario. This process was repeated for all variables and all the different end-states to determine which changes in which variables result in a transformation close to the ideal scenario.

Finally, we collected feedback from 17 Kenyan energy experts on the policy implications stemming from the analysis. During a half-day workshop that took place online on March 14, 2022, participants were presented with the key results from the modeling exercise. In three breakout groups, they discussed the different policy options for achieving desirable energy futures. The discussion centered on the main challenges and the leverage points identified through CIB modeling.

4. Results and discussion

We start by summarizing experts' responses regarding the end-states that best describe the current state and the desired future of the Kenyan energy sector (Table 2).

The majority of participants agreed that ideally, by 2050, the level of investment in renewable energy will be high, the political economy structure will be a liberal or a coordinated market economy, the electricity market structure will reach perfect competition, there will be no energy security concerns and the quality of the grid infrastructure will be good. There was no consensus on the types of energy projects, although there is a clear preference for renewable energy. Some respondents opted for an ideal end-state where most energy installations are centralized renewables, and others for an end-state where most energy installations are decentralized renewables.

When it comes to the current situation, the experts indicated that Kenya has a moderate investment in renewable energy. The political economy structure is state-centered capitalism. The electricity market structure is a monopoly, there are strong (or some) energy security concerns, and the quality of the grid infrastructure is poor. Finally, the types of energy projects are primarily centralized renewables.

The experts agreed that there is no renewable energy value chain participation. In their opinion, ideally, by 2050, Kenyan companies will be active in a combination of segments, notably in the manufacturing of renewable energy technology components and in knowledge and innovation in the sector. In addition, international technology knowledge sharing should improve from the current state of some skill sharing to extensive knowledge sharing. Finally, according to the experts, public perception of renewable energy is now neutral. The desirable end-state by 2050 would consist of the majority of the population supporting the deployment of renewables.

Expert deliberations confirmed our prior expectations regarding the Kenyan energy sector's main strengths and challenges. On the one hand, Kenya already depends mainly on renewables for its power generation. It, therefore, is on the right path as far as decarbonization and sustainability are concerned. On the other hand, the country is still facing energy security problems, which persist due to affordability, infrastructural barriers, and grid quality limitations. The latter, in turn, hinder the adoption of more renewable energy. Kenya also needs to enhance competition in the energy market. Additional challenges highlighted were the need to increase investment in renewable energy, renewable energy value chain participation, and knowledge transfer.

The CIB modeling produced 28 scenarios on possible future developments of the Kenyan energy system by 2050. Table 3 summarizes all end-states for the different variables that appear at least once in these scenarios. There is no scenario in which most energy projects are centralized fossil fuels. There are only scenarios where the quality of the grid is good and only scenarios that exhibit some energy security concerns. Finally, when it comes to perceptions, no scenario was produced where most of the population resists deploying renewable energy.

On the other hand, there are scenarios entailing all levels of international technology knowledge sharing and value chain participation in renewable energy. The same holds for the electricity market structure. The political economy structure is either liberal or state-centered (no scenarios produced the in-between end-state of a coordinated market economy).

Table 4 details the 28 scenarios and their respective plausibility, as measured by the TIS. The scenarios with the highest plausibility have many end-states in common (Scenarios 3, 23, and 25 with a TIS of 72, followed by Scenarios 22 and 24 with a TIS of 62). More specifically,

Table 2
Current and ideal scenario for Kenya based on responses of Kenya energy experts.

Variables	Kenya's situation in 2022	Ideal scenario for Kenya by 2050
Value chain participation	No participation	Combination
Investment in renewable energy (RE)	Medium	High
International knowledge transfer	Some	Extensive
Political economy structure	State-centered	Liberal market/Coordinated market
Electricity market structure	Monopoly	Perfect competition
Types of energy projects	Mainly centralized RE	Mainly centralized RE/Mainly decentralized RE
Energy security concerns	Some concerns/ Strong concerns	No concerns
Grid infrastructure	Bad quality	Good quality
Public perception of RE	Neutral	Support

Source: authors

Table 3
Overview of all the end-states that appear in the 28 scenarios produced by CIB.

Variables	End-states: Scenario results
Value chain participation	Any
Investment in renewable energy (RE)	Any
International knowledge transfer	Any
Political economy structure	Liberal/state-centered
Electricity market structure	Any
Types of energy projects	Centralized RE/decentralized RE
Energy security concerns	Some
Quality of grid infrastructure	Good
Public perception of RE	Neutral/support

Source: authors

Table 4
Scenarios for the Kenyan energy future by 2050. Scenarios with high plausibility, as measured with the Total Impact Score (TIS), are highlighted in yellow. Scenarios closest to the ideal are highlighted in orange.

Scenario	Value chain participation	Investment in RE	Int. tech knowledge transfer	Political economy structure	Electricity market structure	Types of energy project	Energy security concerns	Quality of grid	Public perception of RE	TIS
1	Manufacturing	Medium	None	State-centered	Monopoly	Centralized RE	Some	Good	Neutral	15
2	Manufacturing	Medium	None	State-centered	Oligopoly	Centralized RE	Some	Good	Neutral	15
3	Manufacturing	Medium	Some	Liberal	Perfect competition	Decentralized RE	Some	Good	Support	72
4	Manufacturing	Medium	Some	State-centered	Monopoly	Centralized RE	Some	Good	Neutral	19
5	Manufacturing	Medium	Some	State-centered	Monopoly	Decentralized RE	Some	Good	Neutral	23
6	Manufacturing	Medium	Some	State-centered	Oligopoly	Centralized RE	Some	Good	Neutral	19
7	Manufacturing	Medium	Some	State-centered	Oligopoly	Decentralized RE	Some	Good	Neutral	23
8	Manufacturing	Medium	Extensive	State-centered	Monopoly	Centralized RE	Some	Good	Neutral	19
9	Manufacturing	Medium	Extensive	State-centered	Monopoly	Decentralized RE	Some	Good	Neutral	23
10	Manufacturing	Medium	Extensive	State-centered	Oligopoly	Centralized RE	Some	Good	Neutral	19
11	Manufacturing	Medium	Extensive	State-centered	Oligopoly	Decentralized RE	Some	Good	Neutral	23
12	Manufacturing	Low	None	State-centered	Monopoly	Centralized RE	Some	Good	Neutral	25
13	Manufacturing	Low	Some	State-centered	Monopoly	Centralized RE	Some	Good	Neutral	29
14	R&D	High	Extensive	State-centered	Monopoly	Centralized RE	Some	Good	Neutral	20
15	R&D	High	Extensive	State-centered	Oligopoly	Centralized RE	Some	Good	Neutral	20
16	R&D	Medium	Extensive	State-centered	Monopoly	Decentralized RE	Some	Good	Neutral	24
17	R&D	Medium	Extensive	State-centered	Oligopoly	Decentralized RE	Some	Good	Neutral	24
18	R&D	Low	Extensive	State-centered	Monopoly	Centralized RE	Some	Good	Neutral	24
19	Resources	Medium	None	State-centered	Monopoly	Centralized RE	Some	Good	Neutral	16
20	Resources	Medium	None	State-centered	Oligopoly	Centralized RE	Some	Good	Neutral	16
21	Resources	Low	None	State-centered	Monopoly	Centralized RE	Some	Good	Neutral	26
22	Combination	High	None	Liberal	Perfect competition	Decentralized RE	Some	Good	Support	62
23	Combination	High	Extensive	Liberal	Perfect competition	Decentralized RE	Some	Good	Support	72
24	Combination	Medium	None	Liberal	Perfect competition	Decentralized RE	Some	Good	Support	62
25	Combination	Medium	Extensive	Liberal	Perfect competition	Decentralized RE	Some	Good	Support	72
26	None	Medium	None	State-centered	Oligopoly	Centralized RE	Some	Good	Neutral	16
27	None	Low	None	State-centered	Monopoly	Centralized RE	Some	Good	Neutral	32
28	None	Low	None	State-centered	Oligopoly	Centralized RE	Some	Good	Neutral	26

Source: authors

they feature a competitive market structure for both the economy in general and the electricity market in particular. The types of energy projects are mostly decentralized renewable energy, and there is public support for renewable energy. In addition, like in all scenarios, there are some energy security concerns and a good grid quality.

The most desirable scenario, as described by the experts, was not produced by the CIB modeling, as none of the scenarios yields the ideal end-state (no concerns) for energy security concerns. This result can be explained by the fact that no direct connections exist between any of the variables in the model and the end-state 'no energy security concerns'. This also highlights the difficulty in addressing this problem altogether.

For example, the structure of the economy or the electricity market has some impact on energy security, with less competition being linked to greater energy security concerns (for the electricity market structure, a monopoly is linked with some or strong energy security concerns, and for the political economy structure, a state-centered market is linked with strong energy security concerns). Similarly, connections are drawn between the quality of the grid infrastructure, energy project types, and energy security concerns. The poor quality of the grid and centralized fossil fuels are linked with strong security concerns. No end-state is connected with a situation without energy security concerns.

Some scenarios come close to the ideal and are also highly plausible:

scenarios 25 and 23. All end-states of the ideal situation for the Kenyan energy system by 2050 are met in these two scenarios, apart from two instances. In scenario 25, the level of renewable energy investment is medium. Moreover, some energy security concerns exist in scenarios 25 and 23.

A key insight from the scenarios produced by CIB is that no cases exist with high availability, affordability, and accessibility of energy resources. Despite improvements in energy security concerns by 2050, these are not fully addressed. In all scenarios, the types of energy projects are mostly decentralized renewable energies or mostly centralized renewable energies. The absence of centralized fossil fuels from all scenarios depicts a future in which renewables will continue to play an important role in Kenya's energy system. Kenya should maintain growth in the renewable energy sector while successfully addressing energy security concerns.

TIS is a measure of the plausibility of the end-states of the different variables occurring together (as modeled based on their interdependencies) rather than the probability of specific end-states within these scenarios occurring by 2050. The fact that scenarios with mostly decentralized renewables have a higher plausibility than those with centralized renewables does not predict that they will dominate Kenya's energy sector by 2050. By contrast, it means that the different end-states of the variables comprising these scenarios will be more stable once and if they occur together. These combinations can be self-reinforcing, promoting each other through stronger causal interdependencies, as they receive more connections in the influence diagram, and they can be more transformational for the energy system.

As a next step, we conducted succession analysis to see which changes in variables yield the scenarios closest to the ideal ones. Through succession analysis, we identified repeating patterns that lead to desired changes. This approach allows insulating factors that are transformational for the Kenyan energy sector. We focused on the sequences that lead to improvements in energy security, as this is the most pressing challenge going forward.

Overall, the results of the succession analysis highlighted systems dynamics wherein energy security concerns improve after improvements in the quality of the grid infrastructure. Moreover, a competitive electricity market structure and political economy structure and decentralization consistently precede energy security improvements and grid quality improvements.

For example, starting from the current state scenario 25 can be reached by changing initially the end-state of the variable 'value chain participation' from 'none' to 'R&D' or the end-state of the variable 'intentional technology knowledge sharing' from 'some' to 'extensive'. In both instances, energy security concerns improve from 'strong concerns' to 'some concerns', after the quality of the grid infrastructure shifts from 'bad' to 'good'. This only happens after the system achieves decentralization and the economy, and the electricity market achieves perfect competition.

In all cases, regardless of the initial variable changes and the final scenario, we find that the process initiated always leads to improvements in energy security concerns via decentralization, perfect competition, and grid improvements.

Therefore, the results of the succession analysis emphasize that the main areas for policy intervention should be improving the grid quality, decentralization, and introducing more competition in the electricity market structure. This does not mean that improvements in renewable energy value chain participation and international technology knowledge transfer will not be beneficial. However, it suggests that these factors have less of a transformational impact on improving energy security concerns. The same holds for the other variables in our model, like the level of investments in renewables and public perceptions about renewables. In other words, if grid quality issues and market structure inefficiencies are not addressed, energy security concerns will not be improved regardless of whether there are improvements in the other factors entering our model.

5. Limitations

The CIB method has a number of limitations, due to the fact that it is a scenario modelling exercise based on qualitative judgements. Only a limited number of variables were used to model Kenya's energy future to facilitate a detailed discussion of their interconnections in a participatory workshop. This approach meant excluding some factors that could also be relevant. For example, the issue of carbon capture and storage was not included because participating stakeholders did not discuss it as being central to determining Kenya's energy future. Similarly, we excluded factors like regional cooperation and political stability.

Furthermore, the end-states of the selected variables were also restricted for a meaningful discussion of their interconnections. This method led to a simplification of the actual outcomes that could play out in reality. For example, there are only three end-states for the variable 'types of energy projects'. We could have added other end-states, such as a combined approach with centralized and decentralized renewable energy projects. Nuclear-based technologies could have been considered as another end-state. The final selection was based on the choices made by experts. Nuclear is not expected to play a major role in the energy future of Kenya, also considering energy planning. Moreover, adding balanced combinations of possible technology types would have complicated the analysis without offering additional benefits. The existing end-states permit drawing conclusions for each technology separately.

Overall, we ensured that we modeled the most important variables of the Kenya energy future and their end-states, by following a meticulous stakeholder engagement process. Moreover, our results conform with findings from the literature.

Another limitation of this study is that results are primarily based on expert deliberations, which can be subjective. In addition, the sample of the participating experts had to be relatively small to allow for meaningful discussions, which might have biased the results. To address this, we included experts from a cross-section of sectors, including international and Kenyan energy experts, and ensured their balanced participation in the discussions.

Finally, the data collection for this study was conducted from February 2021 until March 2022, and although participating experts were asked to focus on the long-term perspective, the results of the analysis could have been affected by certain particularities of this period that influenced both the global and the national context (e.g., the impacts of the COVID-19 pandemic, rising energy prices). It would, therefore, be relevant for future research to explore if and how developments since have affected expert perspectives on the energy future of Kenya.

6. Conclusion and policy implications

Our study models how Kenya's energy system could be structured in 2050 and identifies the main challenges and leverage points for the country to remain on a sustainable energy path. To this end, we analyzed scenarios for the Kenyan energy sector in 2050. We then tested which variables in the system can have a transformational effect on the sector. For this, we used the method of participatory CIB following a co-creative research process and resting on expert judgments on system dynamics. While previous research highlighted the importance of certain factors like energy access, grid quality, decentralization, electricity market structure, and public acceptance of renewables, for the Kenyan energy systems (Kazimierczuk, 2019; Njiru and Letema, 2018; Taneja, 2017;

Oluoch et al., 2020; Moner-Girona et al., 2019), our analysis is the first to model the interactions of both qualitative and quantitative factors of influence in a systematic way.

In a follow-up workshop, experts discussed policy options centered on the leverage points identified in our analysis: improving the quality of the grid infrastructure, further reforming the electricity market to introduce more competition and decentralization. Recommended policies and reforms are often built on existing efforts in place. Improvements in the quality of the grid infrastructure will require an update of the national grid code. Further regional grid integration, especially through the existing Eastern African Power Pool, and demand scheduling of different energy sources, are also crucial for grid quality improvements and grid stability. This will help deal with the intermittency challenges associated with renewable energy. It will also reduce the reliance on costly storage capacity and on backup thermal power plants. Demand-side management is vital to synchronize consumption with the availability of renewable sources. Digitalization will be generally key for Kenya to achieve these grid improvements. A smart grid would also allow for more accurate demand projections and the detection of quality problems (IEA, 2017).

Policies that will incentivize technology adoption through cost reduction and technology transfer will be instrumental in promoting digitalization and further integration of renewables into the grid and regional grid integration. For regional grid integration, it will be necessary to develop regulations at a regional level to ensure compatibility with technical requirements (ADB, 2021).

Kenya should invest in capacity building and focus on designing pertinent guidelines to ensure data protection and the integrity of the energy systems regarding digitalization (Nyabira and Muigai, 2022). Technology transfer will be achieved via cooperation at the international level for knowledge sharing. To introduce more competition in the electricity market structure and increase private sector involvement in power generation, the procurement process allocating investment in power generation should rely on competitive open tenders. This process should abide by transparent least-cost criteria (Eberhard et al., 2018). In addition, capacity building and a consultation process will be instrumental in supporting potential IPPs. This policy should be paired with others to strengthen the investment climate, including the availability of risk instruments and guarantees to mitigate investment risks and unlock private investment. Moreover, implementing net-metering programs and renewables auctions will draw more IPPs and investment in renewable energy (EPRA, 2022; Ministry of Energy Kenya, 2021).

Impartial techno-economic planning will be necessary to identify additional capacity needs and balance demand with supply accurately (Eberhard et al., 2018; Godinho and Eberhard, 2019). This will need to be done in parallel with improvements in the transmission and distribution system, also through private sector participation. The latter will require regulations supporting Independent Power Transmission (IPT) and competitive tenders for IPTs (World Bank, 2017).

Despite the need to make the electricity market more competitive the government should still maintain a central role. This is needed to implement the policies and reforms required in the power sector, to strengthen the investment climate and to support the renewable energy sector when necessary. The government's role is also crucial for promoting universal energy access and security, for example, through interventions that will ensure affordability for low-income households (e.g., lifeline tariffs, cross-subsidization, and connection subsidies).

To further promote decentralization and support the off-grid sector to reach scale, Kenya must improve its sustainable financing structures and tax incentives for technology development. Supply-side and demand-side subsidies (with transparent selection criteria) and results-based finance would help ensure cost recovery for suppliers and render systems more affordable to consumers. Such interventions will be relevant until the sector becomes viable without support. This depends on the presence of a robust investment climate, with available debt and equity financing opportunities supported by derisking instruments and guarantees (ESMAP 2020).

Going forward, the approach of our study is also relevant for the study of the energy future of other countries facing similar challenges like energy security. The conclusions and policy implications of the present study might not be directly generalizable beyond Kenya due to potential differences in the energy sectors. Nevertheless, our insights and proposed approach can inform similar analyses concerning the structural dynamics of the energy sectors of other countries in the Global South.

Funding statement

This research was funded by the Investigating the Systemic Impacts of the Global Energy Transition (ISIGET) project financed by the Federal Ministry of Education and Research (BMBF) under the "Make our Planet Great Again – German Research Initiative" grant number 57429628, implemented by the German Academic Exchange Service (DAAD). *The BMBF/*DAAD *were not involved in the design, analysis, writing, or publication of this academic work.* The two-day workshop with the Kenyan energy experts in Nairobi as part of the data collection process was funded by the Konrad-Adenauer-Stiftung Regional Program Energy Security and Climate Change in Sub-Saharan Africa, based in Nairobi, Kenya.

CRediT authorship contribution statement

Maria Apergi: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Laima Eicke:** Writing – review & editing. **Andreas Goldthau:** Writing – review & editing, Funding acquisition. **Jude Kurniawan:** Writing – review & editing, Methodology, Data curation. **Esther Schuch:** Writing – review & editing. **Silvia Weko:** 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.

Acknowledgment

The authors thank all interviewees, workshop participants, and the Konrad-Adenauer-Stiftung Regional Program Energy Security and Climate Change in Sub-Saharan Africa for support throughout the research process. Furthermore, we thank Maureen Otieno and Victor Otieno for their workshop support and Judith Hermann for valuable research assistance.

Appendix A. Identifying the most influential variables and their end-states

The first step of the data collection process entailed the identification of the most relevant factors for the energy transition, globally and for the sub-Saharan African region particularly. This was done in a two-day online workshop, which took place on February 10–11, 2021. The workshop included 22 international energy experts representing a variety of sectors and working in one or more regions of the Global South. Through an open discussion, the plenary session identified the most influential factors influencing the trajectory of the energy transition globally by 2050. This step was followed by breakout groups (each representing a different region), where participants were asked to narrow down the influential factors for this region and identify relevant factors that might have been missed in the global discussion. Then, participants were tasked to think of ways each of these factors could unfold in the future in a mutually exclusive way. This approach gave us the variables' end-states, for example, investments in renewable energy: high, medium, or low. One of the breakout groups focused specifically on the region of sub-Saharan Africa.

At the end of this first workshop, and with the help of qualitative coding of the transcripts (which refers to labeling and grouping the themes that emerged during the discussion), we identified the most relevant variables for the energy transition in sub-Saharan Africa as well as the different end-states for each of these relevant variables. This included 13 variables in total: 3 variables relevant for all regions (value chain participation, investment in renewable energy, international technology knowledge sharing), as indicated by the literature (Eicke and Goldthau, 2021; Zhang and Gallagher, 2016; Goldthau et al., 2020) and confirmed by workshop participants, and 10 variables specific to sub-Saharan Africa.

The next step was to identify which 9 of these variables were the most relevant for our case study, Kenya. To do so, we conducted 11 semi-structured interviews with Kenyan energy sector experts online between August 13 and October 12, 2021. Participants were presented with a list of the relevant variables identified previously. Then, they were asked to rate the importance of these variables (on a three-point scale) for the Kenyan energy future by the year 2050. Participants were also given the option to suggest additional variables they considered important (see Table A.1 for the exact interview questions). The six variables with the highest rating were chosen to model Kenya's energy future. These are political economy structure, electricity market structure, types of energy projects, energy security concerns, quality of the grid infrastructure, and public perception of renewable energy. To these we added the three variables flagged as important for all regions, both during the first workshop and in the literature.

Table A.1
Interview questions.

Nr.	Interviewer Question	Definition (read out if needed)
A1	Please consider the political economy structure of Kenya. How would a change in the **political economy structure** influence Kenya's energy future until 2050? -High influence -Some influence -Little or no influence	**Political economy structure:** The degree to which governments intervene in the economy, whether it is a liberalized free market, state-centered capitalism, or a coordinated market economy.
A2	Now consider the **electricity market structure.** How much would a change in the structure of electricity markets influence Kenya's energy future until 2050? -High influence -Some influence -Little or no influence	**Electricity market structure:** The organization of a market, whether many actors operate in a competitive market or whether the market is dominated by a single or very few utilities.
A3	Now consider the **political stability** of Kenya. How much would a change in political stability influence Kenya's energy future until 2050? -High influence -Some influence -Little or no influence	**Political stability** in the course of a country's energy transition. Political stability can refer to the stability of the political system, the absence of protest, and peaceful changes in government.
A4	Now consider the **types of energy projects** of Kenya. Here we are referring to whether installations consist of mostly centralized fossil fuels, mostly centralized renewable energies, or mostly decentralized renewable energies. How much would a change in the types of energy projects influence Kenya's energy future until 2050?: -High influence -Some influence -Little or no influence	**Types of energy projects:** The characteristics of energy installations related to whether these consist of mostly centralized fossil fuels, mostly centralized renewable energies, or mostly decentralized renewable energies.
A5	Now, consider **how closely Kenya cooperates** (politically or economically) with other countries in the region. How much would a change in the level of regional cooperation influence Kenya's energy future until 2050? -High influence -Some influence -Little or no influence	**Regional cooperation:** The intensity of political or economic cooperation between countries in the region.
A6	Now, consider **the role of Chinese investments and politics** in Kenya. How much would a change in Chinese investments and politics influence Kenya's energy future until 2050? -High influence -Some influence -Little or no influence	**The role of China** in driving and shaping the energy future in a country could be influenced by direct investments in energy projects (renewables or fossil fuels) or infrastructure or by economic pressure or political influence.
A7	Now consider **stranded assets**. How much will a change in stranded assets influence Kenya's energy future until 2050? -High influence -Some influence -Little or no influence	**Stranded assets:** The likelihood of equipment or resources being prematurely written off (that is, seized to be used before the end of their economic life) due to a transition to a low-carbon economy (e.g., distribution infrastructure, coal mines, utilities powered by fossil fuel).

(*continued on next page*)

Table A.1 (*continued*)

Nr.	Interviewer Question	Definition (read out if needed)
A8	Now consider the **energy security concerns** of Kenya. How much will a change in energy security concerns influence Kenya's energy future until 2050? -High influence -Some influence -Little or no influence	**Energy security concerns:** The degree to which energy resources are available, affordable, and accessible.
A9	Now, consider the **quality of Kenya's grid infrastructure**. How much will a change in the quality of the grid infrastructure influence Kenya's energy future until 2050? -High influence -Some influence -Little or no influence	**Quality of grid infrastructure:** This refers to the transmission capacity and coverage of the grid. (Good quality means accessible in rural areas, easy to integrate to neighboring countries grid for import/export energy. Bad quality means poor coverage and in physically dismal conditions (needing major upgrade when extending the grids).
A10	Now, consider the **public perception of renewable energy** in Kenya. How would a change in public perceptions impact Kenya's energy future until 2050? -High influence -Some influence -Little or no influence (don't know)	**Public perception of renewable energy:** The existence or absence of public support of or resistance toward the deployment of renewable energy.
A11	*If nearly all of the questions have been answered with "high influence," please ask:* "You rated the following factors as high influence: (LIST). Which of those do you think are the three most important?"	
A12	Do you think we covered all relevant factors that can influence Kenya's future energy system, or can you think of something we missed? *If yes, follow up: how important is it and why?*	

Table A.2
List of variables and end-states.

V1: Renewable Energy (RE) Value Chain Participation

This variable describes whether and how Kenya (Kenyan companies or companies located in Kenya) is part of a global value chain of renewable energy technologies, such as wind turbines or solar panels.

End-state 1: (Mostly) Manufacturing	**End-state 2: (Mostly) Knowledge (R&D)**	**End-state 3:(Mostly) Resource/raw material producers**	**End-state 4: Combination of segments**	**End-state 5: No participation**
Local companies manufacture some components of renewable energy technologies.	Knowledge-driven economic activities where public and private institutions focus on innovations as a value-added service in the renewable energy sector.	Resource-driven value chain participation in a form of extraction of raw materials (e.g., silica, ore) needed in the production of renewable technologies, or in the production of hydrogen.	Kenyan companies are active in two or more combinations of (1) manufacturing, (2) knowledge and innovation, and (3) resource extraction.	No local companies take part in the value creation of renewable energy technologies, which are all imported from other countries.

V2: Investment in Renewable Energy

The variable refers to the amount of national and international, public, and private investments in renewable technologies in Kenya.

End-state1: High	**End-state2: Medium**	**End-state3: Low**
There is a high level of investment in renewable energies compared to today.	The level of investment in renewable energies is at a medium level.	There is a low level of investment in renewable energies compared to today.

V3: International Technology Knowledge Sharing

The degree to which the producers of renewable energy technologies engage in knowledge transfer with Kenya.

End-state1: No skill or knowledge sharing	**End-state2: Some skill sharing**	**End-state3: Extensive knowledge sharing**
There is no engagement in skill or knowledge sharing of renewable energy producers from abroad with local firms in Kenya.	International renewable energy producers share some skills on how to install, maintain and operate renewable energy technologies with local firms in Kenya.	International renewable energy producers share skills and knowledge on how to reproduce and innovate on renewable energy technologies with local firms in Kenya.

V4: Political Economy Structure

The degree to which firms, collective actors, or state institutions shape the country's economic structure.

End-state1: Liberal market economy	**End-state 2: Coordinated market economy**	**End-state3: State-centered capitalism**
Liberal market economies are mainly shaped via the dynamics of supply and demand in free, competitive markets.	Coordinated market economies rely more on collaborative arrangements, often coordinated by business associations or trade unions.	The state actively intervenes in market structures, in the shape of regulation, business and commercial economic activities in state-owned enterprises.

V5: Electricity Market Structure

The organization of the electricity market, based on the number and structure of market participants.

End-state1: Monopoly	**End-state2: Oligopoly**	**End-state3: Perfect competition**
Monopolistic markets (including state-monopoly) are dominated by only one company and its product offerings.	Oligopoly refers to a market characteristic where a small number of product or service providers (two or more companies) dominate the market.	Perfect competition refers to a market characterized by many product and service providers, and these companies do not have significant influence on prices in the market.

V6: Types of Energy Projects

The characteristics of energy installations: what kinds of fuel they use, and how centralized they are.

End-state1: Mostly centralized fossil fuels	**End-state2: Mostly centralized renewable energies**	**End-state3: Mostly decentralized renewable energies**

(*continued on next page*)

Table A.2 (*continued*)

V6: Types of Energy Projects		
The majority of energy used in the country comes from large fossil fuel plants or projects, and is transported to where it is consumed. This could be in the form of electricity, or oil and gas pipelines.	The majority of energy used in the country comes from large renewable energy plants or projects, and is transported to where it is consumed. This could be in the form of electricity, or transforming energy to be used elsewhere such as batteries/hydrogen.	The majority of energy used in the country comes from smaller-scale renewable energies (such as rooftop PV or biomass), and is mostly used locally.
V7: Energy Security Concerns		
The degree to which energy resources are available, affordable, and accessible.		
End-state1: No concerns	**End-state2: Some concerns**	**End-state3: Strong concerns**
High level of availability, affordability, and/or accessibility of energy resources.	Medium level of availability, affordability, and/or accessibility of energy resources.	Low level of availability, affordability, and/or accessibility of energy resources.
V8: Quality of the Grid Infrastructure		
This refers to the transmission capacity and coverage of the grid.		
End-state1: Good	**End-state2: Bad**	
Good quality means high reliability, good geographic coverage and easy to integrate to neighboring countries' grid for import/export energy.	Bad quality means low reliability, poor geographic coverage and needing major upgrade in order to integrate to neighboring countries grid for import/export energy.	
V9: Public Perception of Renewable Energy		
The existence or absence of public support of, or resistance toward, the deployment of renewable energy.		
End-state1: Opposition to RE	**End-state2: Neutral**	**End-state3: Support for RE**
Majority of the population resists the deployment of RE.	Population does not actively support or oppose RE deployment.	Majority of the population supports the deployment of RE.

Appendix B. Cross-impact matrix for CIB analysis

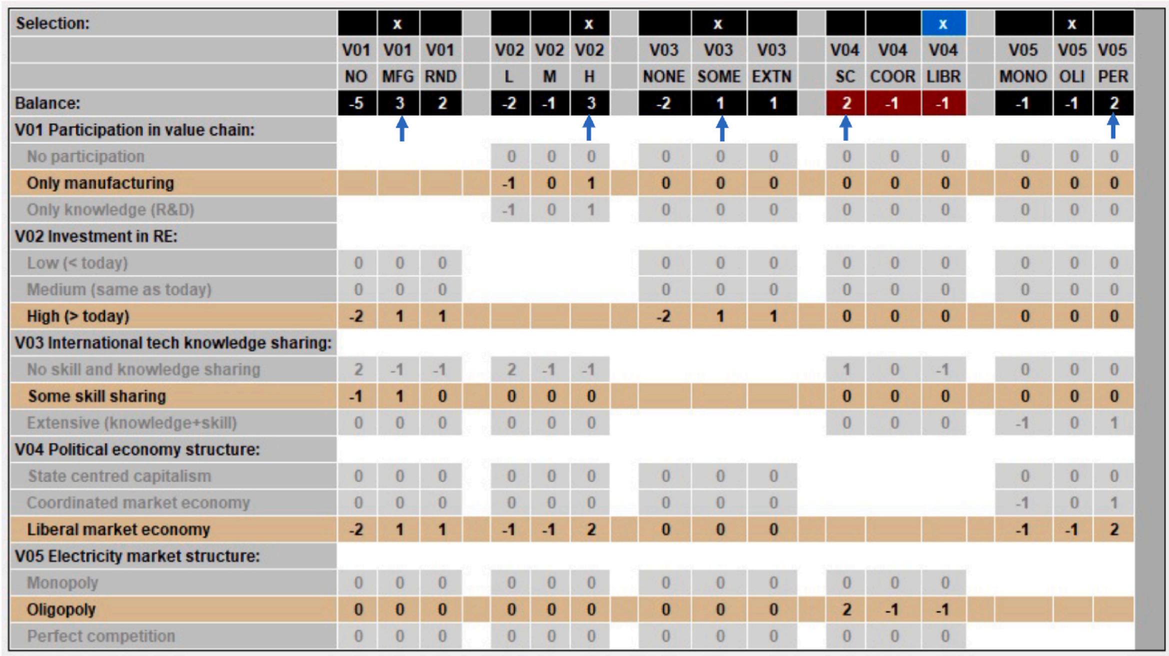
	V1 VC					V2 Invest			V3 Know			V4 Econ			V5 Elec			V6 EProj			V7 Secu			V8 Grid		V9 Percp		
	Mfg	RnD	Res	Com	Non	H	M	L	N	S	Ex	Libr	Coor	SC	Mon	Oli	Free	CenFF	CenRE	DecRE	No	Som	Stg	G	B	Opp	Neu	Sup
V1 Value chain participation																												
Manufacturing						-2	4	-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	-1	2
RnD						0	0	0	-1	-1	2	0	0	0	0	0	0	-2	-2	4	0	0	0	0	0	-2	-2	4
Resources						-2	4	-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Combination						4	-2	-2	0	0	0	4	-2	-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
None						0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-2	4	-2
V2 Investment in RE																												
High	2	2	0	2	-6				0	0	0	0	0	0	0	0	0	-4	2	2	0	0	0	0	0	0	0	0
Medium	0	0	0	0	0				0	0	0	0	0	0	0	0	0	-2	-2	4	0	0	0	0	0	0	0	0
Low	0	0	0	0	0				0	0	0	0	0	0	0	0	0	-2	4	-2	0	0	0	0	0	-2	4	-2
V3 International tech knowledge sharing																												
None	0	0	0	0	0	-2	-2	4				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Some	4	0	0	-2	-2	-2	-2	4				0	0	0	0	0	0	-2	-2	4	0	0	0	2	-2	0	0	0
Extensive	2	2	0	2	-6	0	0	0				0	0	0	0	0	0	-2	-2	4	0	0	0	2	-2	0	0	0
V4 Political economy structure																												
Liberal market	0	2	0	2	-4	4	-2	-2	0	0	0				-2	-2	4	-2	-2	4	-2	4	-2	2	-2	-2	-2	4
Coordinated market	2	0	0	2	-4	4	-2	-2	0	0	0				-2	4	-2	-4	2	2	0	0	0	2	-2	-2	-2	4
State-centered	0	0	0	0	0	0	0	0	0	0	0				2	2	-4	2	2	-4	-2	-2	4	0	0	0	0	0
V5 Electricity market structure																												
Monopoly	0	0	0	0	0	-2	-2	4	0	0	0	0	0	0				2	2	-4	-4	2	2	0	0	0	0	0
Oligopoly	0	0	0	0	0	0	0	0	0	0	0	0	0	0				2	2	-4	0	0	0	0	0	0	0	0
Perfect Competition	0	0	0	0	0	-2	4	-2	0	0	0	4	-2	-2				-2	-2	4	0	0	0	0	0	-2	-2	4
V6 Types of energy projects																												
Centralized FF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				-2	-2	4	0	0	0	0	0
Centralized RE	0	0	0	0	0	4	-2	-2	0	0	0	0	0	0	0	0	0				0	0	0	0	0	0	0	0
Decentralized RE	0	0	0	0	0	-2	4	-2	0	0	0	0	0	0	-2	-2	4				0	0	0	0	0	0	0	0
V7 Energy security concerns																												
No	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				0	0	0	0	0
Some	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-2	-2	4				0	0	0	0	0
Strong	0	0	0	0	0	0	0	0	0	0	0	4	-2	-2	-2	-2	4	-4	2	2				0	0	-2	-2	4
V8 Quality of grid infrastructure																												
Good	0	0	0	0	0	-2	4	-2	0	0	0	0	0	0	0	0	0	-2	4	-2	-2	4	-2			-2	4	-2
Bad	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-2	-2	4	-2	-2	4			-2	-2	4
V9 Public perception of RE																												
Opposition to RE	0	0	0	0	0	-2	-2	4	0	0	0	0	0	0	0	0	0	4	-2	-2	0	0	0	0	0			
Neutral	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
Support for RE	0	0	0	2	-2	4	-2	-2	0	0	0	0	0	0	-2	-2	4	-2	-2	4	0	0	0	0	0			

Fig. B.1. A cross-impact matrix for CIB analysis: influence diagram produced in the Kenya expert workshop in the form of CIB matrix (consolidated version including the two contested connections). The matrix entry is a numerical value that captures the interactions between the two end-states of different variables.

The CIB matrix documents how the different end-states of the variables in the rows influence the other variables in the columns (based on expert deliberations). The matrix entry is a numerical value that captures the interactions between the two end-states of different variables. We only collected information on positive effects, which are recorded with a positive number, and are subsequently balanced with inhibiting factors (assumed for the other end-states). The latter are represented with a negative number.

The values attributed to end-states with connections and to those without connections should add up to zero for the matrix to be balanced. If connections were drawn from one variable end-state to the other, we grade it as one (or higher, depending on the number of other end-states without connections). The rest of the end-states in the row (where there were no connections) can be given a negative number or a zero as long as the total number adds up to zero. The matrix in Figure B.1 is a consolidated matrix, also modelling two contested connections. Therefore, all coded values are doubled, apart from those of the two contested connections.

For example, for the variable 'quality of grid infrastructure' the end-state 'bad' was indicated to have an influence only on the end-state 'strong' for the variable 'energy security concerns'. For this, in the corresponding row, the end-state 'strong energy security concerns' was coded with a 4 and, to ensure balance within the different end-states (i.e., the sum of all should equal zero), the end-states 'no energy security concerns' and 'some energy security concerns' were coded with a −2 each.



	V01 NO	V01 MFG	V01 RND	V02 L	V02 M	V02 H	V03 NONE	V03 SOME	V03 EXTN	V04 SC	V04 COOR	V04 LIBR	V05 MONO	V05 OLI	V05 PER
Selection:		x				x		x				x		x	
Balance:	-5	3	2	-2	-1	3	-2	1	1	2	-1	-1	-1	-1	2
V01 Participation in value chain:															
No participation				0	0	0	0	0	0	0	0	0	0	0	0
Only manufacturing				-1	0	1	0	0	0	0	0	0	0	0	0
Only knowledge (R&D)				-1	0	1	0	0	0	0	0	0	0	0	0
V02 Investment in RE:															
Low (< today)	0	0	0				0	0	0	0	0	0	0	0	0
Medium (same as today)	0	0	0				0	0	0	0	0	0	0	0	0
High (> today)	-2	1	1				-2	1	1	0	0	0	0	0	0
V03 International tech knowledge sharing:															
No skill and knowledge sharing	2	-1	-1	2	-1	-1				1	0	-1	0	0	0
Some skill sharing	-1	1	0	0	0	0				0	0	0	0	0	0
Extensive (knowledge+skill)	0	0	0	0	0	0				0	0	0	-1	0	1
V04 Political economy structure:															
State centred capitalism	0	0	0	0	0	0	0	0	0				0	0	0
Coordinated market economy	0	0	0	0	0	0	0	0	0				-1	0	1
Liberal market economy	-2	1	1	-1	-1	2	0	0	0				-1	-1	2
V05 Electricity market structure:															
Monopoly	0	0	0	0	0	0	0	0	0	0	0	0			
Oligopoly	0	0	0	0	0	0	0	0	0	2	-1	-1			
Perfect competition	0	0	0	0	0	0	0	0	0	0	0	0			

Fig. B.2. A cross-impact matrix with impact balance scores for a hypothetical ('test') scenario combination. Source: Schuch et al., 2024.

In the hypothetical example (Figure B.2), the 'impact balance' score is calculated as the columnar sum of the values on the highlighted rows. Impact balance scores are indicated in this example under 'balance'. For example, in this combination of end-states, V01(MFG) receives an impact balance score of 3, adding up the matrix values of V02: High = 1, V03: Some skill sharing = 1, V04: Liberal market economy = 1 and V05: Oligopoly = 0. V01(No) receives an impact balance score of −5, adding up the matrix values of V02: High = −2, V03: Some skill sharing = −1, V04: Liberal market economy = −2 and V05: Oligopoly = 0.

If for a specific scenario combination, an end-state of a variable produces the highest impact balance score, compared with its other end-states, it means that the specific scenario is internally consistent. In the example of Figure B.2, the initial selection of a scenario combination is highlighted in the first row of this figure (x). Given this initial selection of a scenario combination, the system will choose the combination with the highest impact balance scores (highlighted here with the blue arrows). This combination is in this example: V01(MFG), V02(H), V03(SOME), V04(SC), and V05(PER). Therefore, the end-states V04(LIBR) and V05(OLI), which were in the initial scenario combination, are highlighted as inconsistent.

Data availability

The data that has been used is confidential.

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