Interdisciplinary Description of Complex Systems 22(6), 666-683, 2024

AN INFORMAL SETTLEMENT CASE STUDY – A SYSTEMS THINKING LOGIC APPLIED TO ENERGY POVERTY SITUATIONS

Perpetua I. Okoye*

University of Pretoria – Faculty of Engineering, Built Environment and Information Technology
– Department of Engineering and Technology Management
Pretoria, South Africa

DOI: 10.7906/indecs.22.6.3
Regular article

Received: 16 January 2023.
Accepted: 28 November 2024.

ABSTRACT

This article applies a systems thinking logic to analyse energy poverty situations, using the Sofia informal settlement, a representative energy-poor community in South Africa, as a case study. Energy poverty in such communities transliterates into three interrelated energy poverty systems – material cultures, cognitive norms, and energy practices. The study investigates energy-related parameters and elements contributing to energy poverty in Sofia and similar informal settlements across South Africa. By adopting the systems thinking, these elements are identified and integrated into subsystems within the Energy Poverty Systems, modelled into the energy poverty model. The synergistic interactions influencing energy poverty are captured using causal loop diagrams. These diagrams offer a systems perspective on energy poverty analysis, providing actionable insights into critical gaps and intervention opportunities. The findings are intended to inform policies and tailored, inclusive interventions motivating sustainable energy access in informal settlements across South Africa.

KEY WORDS

energy poverty systems, energy poverty model, informal settlements, systems thinking, causal loop diagrams

CLASSIFICATION

JEL: N77, O13, Q41

*Corresponding author, η: pokoye04@gmail.com; -;
Department of Engineering and Technology Management, University of Pretoria, Private Bag X20, Hatfield 0028, South Africa

INTRODUCTION

Energy poverty is commonly defined as a lack of access to modern energy sources or reliance on inefficient fuels such as paraffin and charcoal, which limits households' ability to meet basic energy needs like lighting, cooking, space heating, and cooling [1]. While frequently linked to income poverty, energy poverty is a multifaceted socioeconomic issue shaped by a complex interplay of factors, including sociocultural environments that influence household energy-use patterns and behaviour [2]. Effectively analyzing energy poverty requires comprehensively evaluating the physical, sociocultural, economic, environmental, and institutional dynamics affecting an energy-poor group. Consequently, energy poverty analysis must go beyond technical algorithms and consider the diverse conditions and resources that define the realities of energy-poor communities.

South African cities have traditionally developed low-density suburban areas, often known as informal settlements or shacks – makeshift dwellings constructed without adherence to approved architectural plans – sprawling across the city's periphery [3, 4]. These settlements are predominantly inhabited by low-income households with limited access to essential utilities, such as energy, water, sanitation, and suitable housing [5]. Regardless of wether connected to the electricity grid, these households often rely on less efficient fuels [6] and adopt energy mixes, such as the concurrent use of electricity and paraffin for space heating in winter [7]. As such, these settlements serve as domains for understanding energy poverty situations in the region [8].

The situational analysis of energy poverty requires evaluating the diverse variables and their synergistic interactions that shape these situations in any energy-poor community [2]. These variables include elements central to energy poverty systems (EPSs), even at the subsystem level, describing energy use patterns, efficiency, preferences, productivity, affordability, and appliances. The synergistic analysis mainly involves mutual assemblages of these elements operating within these systems. Bridging the synergies between systems is critical to understanding energy poverty dynamics and necessitates the application of systems thinking (SsT) logic [9]. Classically, SsT is a set of analytical and synergistic skills designed to improve the ability to identify and understand systems, predict their behaviours, and implement modifications to generate the desired outcomes [10]. The core processes of SsT begin with identifying elements in a system, recognizing system purpose, and understanding the interconnections among its components [11]. These processes may include adding or removing elements to refine the knowledge of system behaviours, which can be reinforcing or dynamic. This further involves analyzing elements, flows, and non-linear interactions to gain an improved understanding of system behaviours. SsT views different facets of a system as single but different entities and bridges synergies using arrays of causal loops, linkages, and interactions. Central to SsT is the principle that a system is greater than the sum of its parts and should, therefore, be studied holistically. By modelling complexity - whether at the system or subsystem level – SsT helps elucidate behaviours and causal influences, encouraging a deeper understanding of patterns. With SsT, one can understand the primary causes of complex behaviours to enable adjustments of outcomes in energy poverty analysis.

The concepts of SsT [12, 13] and energy poverty [14, 15] have distinctive theories and operational needs. However, the evolution of SsT has shifted from product design to encompass systems of production and consumerism and a wide range of concerns across physical, sociocultural, economic, technical, and institutional domains [16]. Globally, energy poverty has been studied, [17-19], including in developing countries [20, 21] and specific South African regions [2, 3, 22-24], with its impacts extending across socioeconomic spheres, ethics [2], and the environment [25]. SsT has been applied [26-31] and recognized as an effective multi-criteria decision-support tool for energy access planning [10, 32]. As it is, informal settlements serve as perfect sceneries where energy poverty mitigation can be promoted based on networking elements operating within the EPSs [33]. This underscores the importance of designing an autogenous, model-based SsT framework that describes system elements as integral components in analyzing energy poverty in informal settlements. The model's utility is to be committed to a place (in this case, informal settlements) by leveraging elements alleged to be activities within that place's spatial context integrable into modeling EPSs.

This article applies SsT logic to energy poverty by identifying and engineering elements in EPSs and their subsystems in the Sofia informal settlement as a case study. The goal is to provide a systems perspective highlighting interactions driving energy poverty situations in such contexts. In sequence, the article: 1) recognizes and integrates elements and subsystems into mutualistic EPSs and the energy poverty model (EPM) using SsT logic; 2) investigates energy-related parameters and elements in the settlement through empirical methods; 3) demonstrates the model's utility by empirically grounding significant elements and modeling system synergisms using causal loop diagrams (CLDs). The analysis offers a holistic understanding of energy poverty and insights to inform interventions addressing the challenges informal communities across South Africa face.

MATERIALS AND METHODS

APPLYING SYSTEMS THINKING: ENERGY POVERTY SYSTEM AND MODEL DEVELOPMENT

EPSs, comprising material cultures, cognitive norms, and energy practices, have been deconstructed into subsystems surrounding energy use [34], individual performance [35], and prospects for change in behaviour [36], Figure 1. These systems supported the goal of transformative change by simplifying the complexities of energy poverty dynamics and enabling flexibility in system configurations to observe potential impacts. SsT modeling of EPSs clarified the complexity of system behaviours and causal relationships embedded in the energy poverty model (EPM). The model development was guided by the need to ensure interoperability among physical, sociocultural, economic, institutional, and technological influences of energy poverty situations [37], promoting cohesive system operations toward shared goals. Each system can be analyzed in isolation but within the wider EPM modularity. The interfaces of these systems are critical as they interact dynamically to define the system functions, direct the system's purpose, and align with the model's overarching goals. The model aims to provide a systems perspective on energy poverty analysis, uncovering interactions that drive energy poverty in informal households and providing actionable insights for enabling energy access.

To capture the dynamics of energy poverty, diverse yet interrelated elements influencing behaviour were identified and integrated into the subsystems. The material culture system's subsystems encompass elements that describe energy poverty's physical, economic, and institutional influences, Figure 1. The energy use and sources subsystem represents all available forms and sources of energy within a target community. The house characteristics subsystem includes elements, such as dwelling types, house insulations, and renovations, directly impacting energy-use efficiency. The household income subsystem reflects income levels and the financial burden of energy costs on households. This system primarily shapes energy-use patterns and efficiency, and its interface significantly influences cognitive norms and energy practices.

The cognitive norms system comprises elements within subsystems that contribute to understanding the values, beliefs, and sociocultural, economic, and environmental inclinations shaping household energy choices, Figure 1. The expected comfort levels subsystem includes entertainment and meeting the minimum baseline of energy services required for daily living.

The social aspirations subsystem encompasses education/learning and entrepreneurship, reflecting aspirations that influence energy decisions. The respect for tradition subsystem evaluates the socio-cultural inclination toward energy choices, while the environmental and health concerns subsystem assesses awareness of poor energy-use practices and their impacts on well-being and the environment. This system largely shapes energy preferences and productivity, and its interface strongly influences material cultures and energy practices.

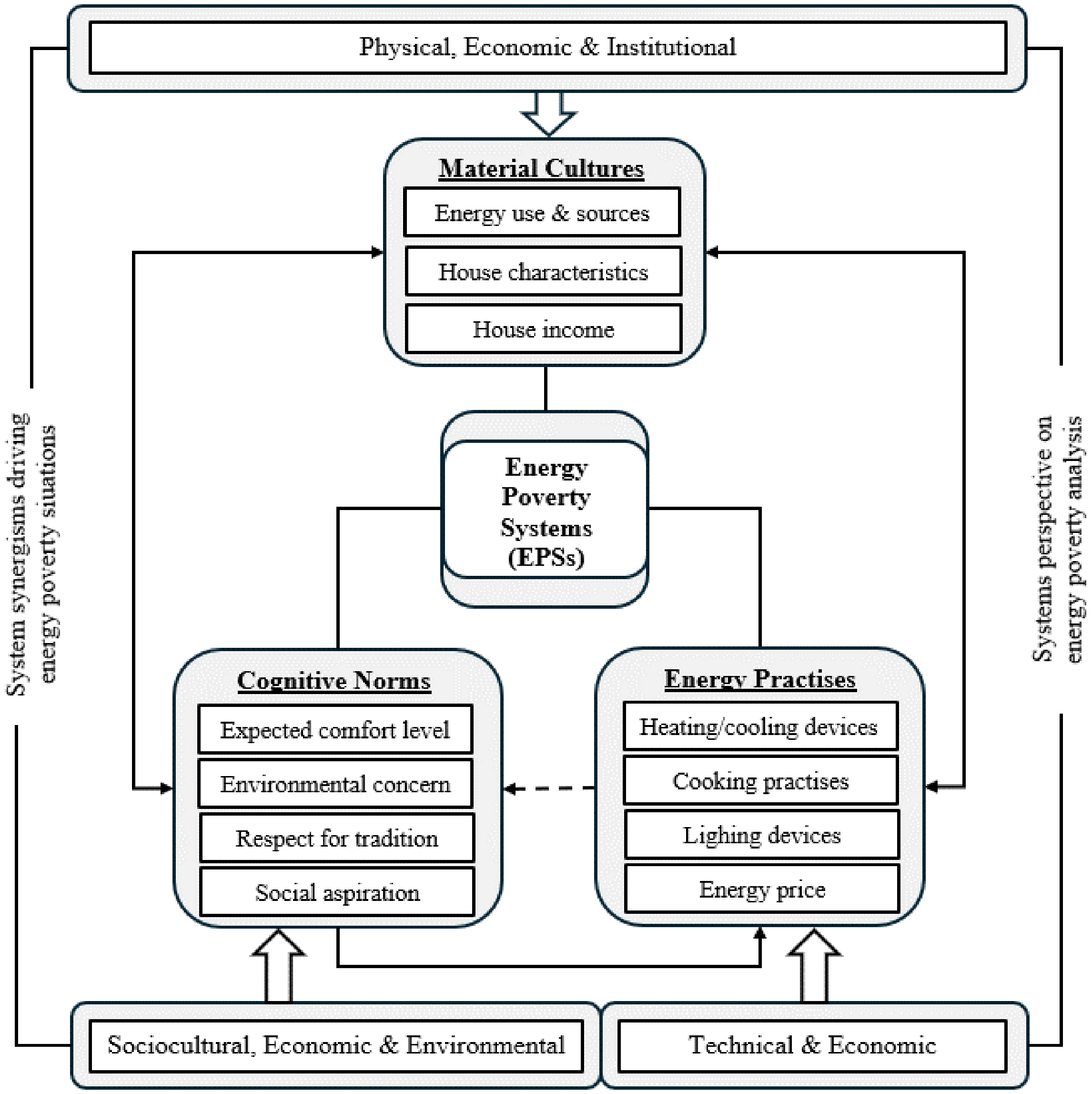

Figure 1. Energy Poverty Model Comprising Energy Poverty Systems. Strong (bold lines) and weak (dotted lines) connections represent high-level and low-level system dependency.

The energy practices system encompasses elements within subsystems that describe the technical and economic factors influencing energy poverty situations, Figure 1. The energy price structure subsystem is central in determining household adoption of clean energy fuels. The subsystem of heating devices includes paraffin and charcoal heaters, gas portable units, heat pumps, etc. Similarly, the cooling devices subsystem comprises window and door units and electric fans. The lighting choices subsystem involves paraffin lamps, candles, and light bulbs, while the cooking practices subsystem includes elements like paraffin stoves, gas stoves, and other cooking appliances. This system significantly shapes household decisions regarding energy appliances and pricing. While they strongly influence material cultures through system interfaces, their impact on cognitive norms is relatively limited.

CASE STUDY METHODOLOGY

The case study focuses on the Sofia informal settlement, a representative energy-poor community typically of many in Africa and Asia, located in the western part of South Africa, Figure 2. The settlement comprises about 200 to 220 informal households, predominantly occupied by low-income, black residents who are mainly unemployed and dependent on government grants. Despite being near the grid electricity, the settlement lacks access to electricity, a condition common in many informal settlements across South Africa. To understand energy poverty situations in the settlement, we conducted a primary survey using household questionnaires and semi-structured short interviews with local energy product vendors to investigate energy-related parameters and elements recognized within the EPSs and subsystems. The survey approach and analytical techniques used in this study are comprehensively detailed in [6].

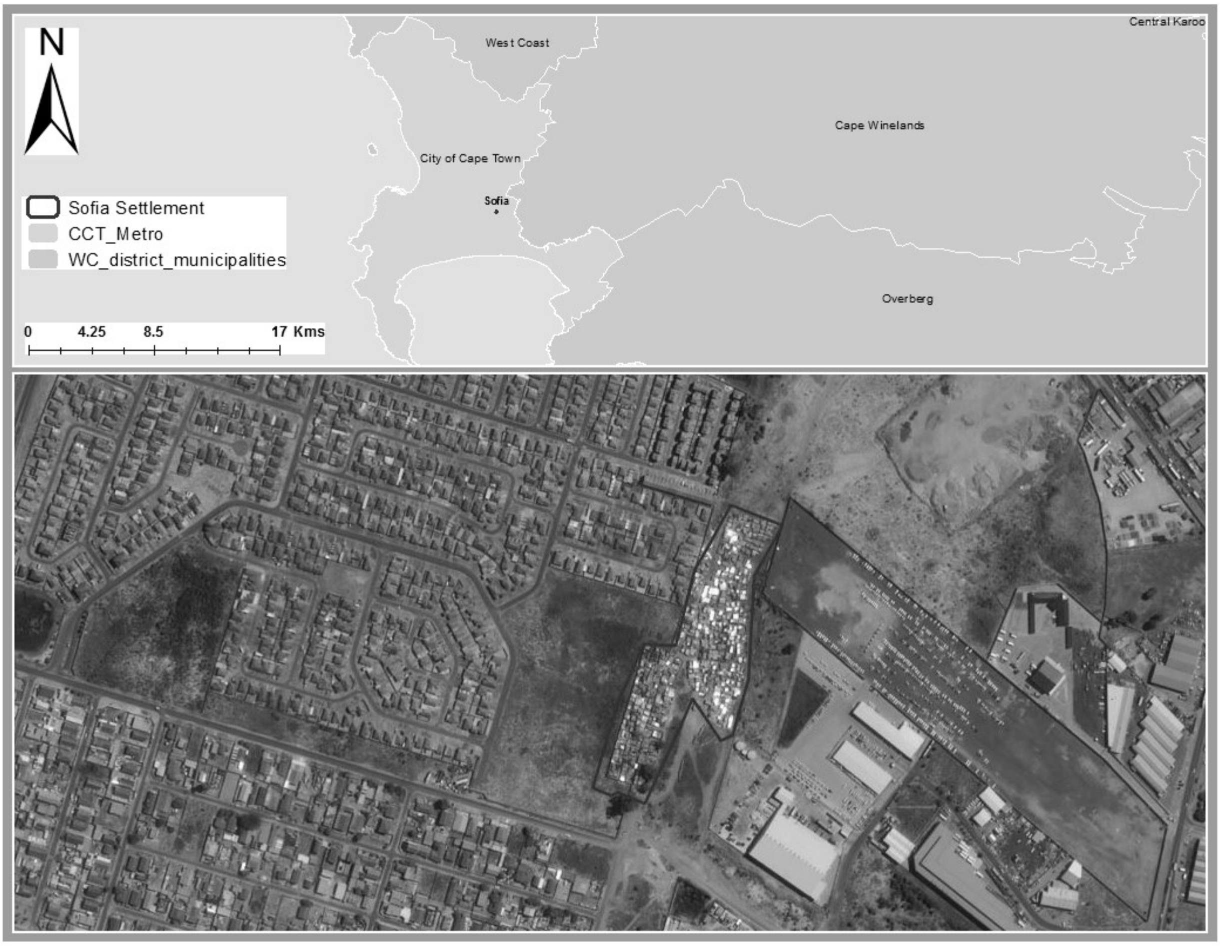

Figure 2. Case Study Area – Sofia Informal Settlement [6].

CAUSAL LOOP DIAGRAMS

Causal loop diagrams (CLDs) align with SsT in identifying, interacting with, predicting, and adjusting systems and behaviours, facilitating the modeling of variables operating within a system [33]. CLDs serve as illustrative descriptions of system synergisms, providing causal depictions, influences, and analyses while incorporating quantitative details about the nature of these influences [38]. CLDs were developed for distinct EPSs by connecting elements and subsystems through arrows, represented as causal loops and links [33]. Causal links, represented by single arrowheads and grounded on significant empirical outcomes from the case study, illustrate the basic mechanisms between subsystem elements. Causal loops, depicted with double arrowheads, reflect the reinforcing patterns (positive or negative) within and between EPSs, emphasizing their systemic interactions. Connections in CLDs are categorized as strong (bold lines) or weak (dotted lines) and marked with + or - signs to denote high-level or low-level system dependency, respectively. Strong causal influences indicate that changes in one system are analogous to a similar change in another system, highlighting strong system coupling. Weak causal influences suggest that changes in one system induce changes in another with less intensity. While weak influences may not always drive system behaviour, they were treated as step inputs to broaden the understanding of elements and interactions influencing behaviour.

Using the Insight Maker online software, CLDs for individual EPSs were successively designed and built into the EPM. Annotations were employed to represent the systems: MCs – material cultures, CNs – cognitive norms, and Eps – energy practices. Causal loops within a system were labeled with the system's annotation, followed by a numeric identifier (e.g., MCs1), incrementing sequentially to reflect the total number of loops in that system. Loops spanning system interfaces were marked with annotations corresponding to all connecting EPSs linked by a hyphen (e.g., MCs-CNs). Significant and accurate data inputs, especially from a typical energy-poor community such as the Sofi settlement, were critical to ensuring the validity of insights generated in the model. The iterative CLD designs ensured the representation of EPSs evolved logically, focusing analyses on individual systems and capturing additional interactions at each step. The CLD development began with:

- Developing MCs; the initial step involved creating a simple CLD of a material culture system based on causal influences, including causal loops and links, to analyze the synergisms within the system.
- Incorporating CNs; the second step expands the diagram by integrating cognitive norms, resulting in additional causal loops and links and allowing for the analysis of synergisms within the CNs system and at the interface between MCs and CNs.
- Adding EPs; the final step involved integrating energy practices into the diagrams, generating further causal loops and links, and enabling the analysis of interactions within and across all three interfaces, progressively building these diagrams into the EPM.

RESULTS AND DISCUSSIONS

Table 1 in Appendix summarizes the case study data analysis, which organizes empirical findings by Okoye [6] under various energy-related categories. Each CLD design for distinct EPSs draws on sampled parameters and their significant outputs grounded in empirical evidence to update elements and causal influences in the EPM.

MATERIAL CULTURES

Figure 3 illustrates the initial step in mapping causal influences within the MCs system in a simple CLD. The diagrams highlight the interplay of subsystems and elements, revealing both strong and weak causal loops and links directed to influence CNs and EPs systems. In links, the MCs system was strongly defined by:

- Low-income households with no electricity access; predominantly used, separately and concurrently, less efficient energy fuels such as paraffin and gas (transitional or cleaner fuels) or candles (traditional or less clean fuels) for lighting. These fuels were:
  - readily available and accessible through local vendors,
  - consumed at monthly rates of less than 100 *l* for paraffin and within 100-250 *l* for gas.
- Monthly energy costs of about 50 % and 40 % (high) and 10 % and 5 % (low) of household income; however, low-income status and reliance on government grants [7] queried the high energy costs.
- Shacks, i.e., poorly constructed housing structures, mostly self-built, lacked insulation, rarely underwent renovations, and scarcely maintained warm temperatures in winter.

The first causal loop – MCs1, captured the synergistic interactions between energy use and sources subsystem and house characteristics subsystem, Figure 3. This loop, further influenced by MCs2 loop activities, revealed that significant influences of elements captured in links resulted in poor energy-use patterns (e.g., less efficient fuels and low energy demand levels) and efficiency (e.g., poor housing structures). The MCs2 loop linked energy use and sources with the household income subsystem, indicating how low-income status reinforced the adoption of less efficient fuels, primarily instigated by a lack of electricity access in the settlement. The MCs3 weak loop connected house characteristics and household income subsystems, indicating that the impact of one system does not equal the same effect on another. For instance, improving house efficiency does not equal household income and vice versa. However, the MCs3 strong loop was generated, driven by strongly linked elements such as household low-income and non-insulated homes, showing a positive reinforcing pattern between the subsystems. These causal loops jointly shaped the MCs system's overall behaviour, emphasizing the subsystems' interconnectedness in driving energy poverty situations within the settlement.

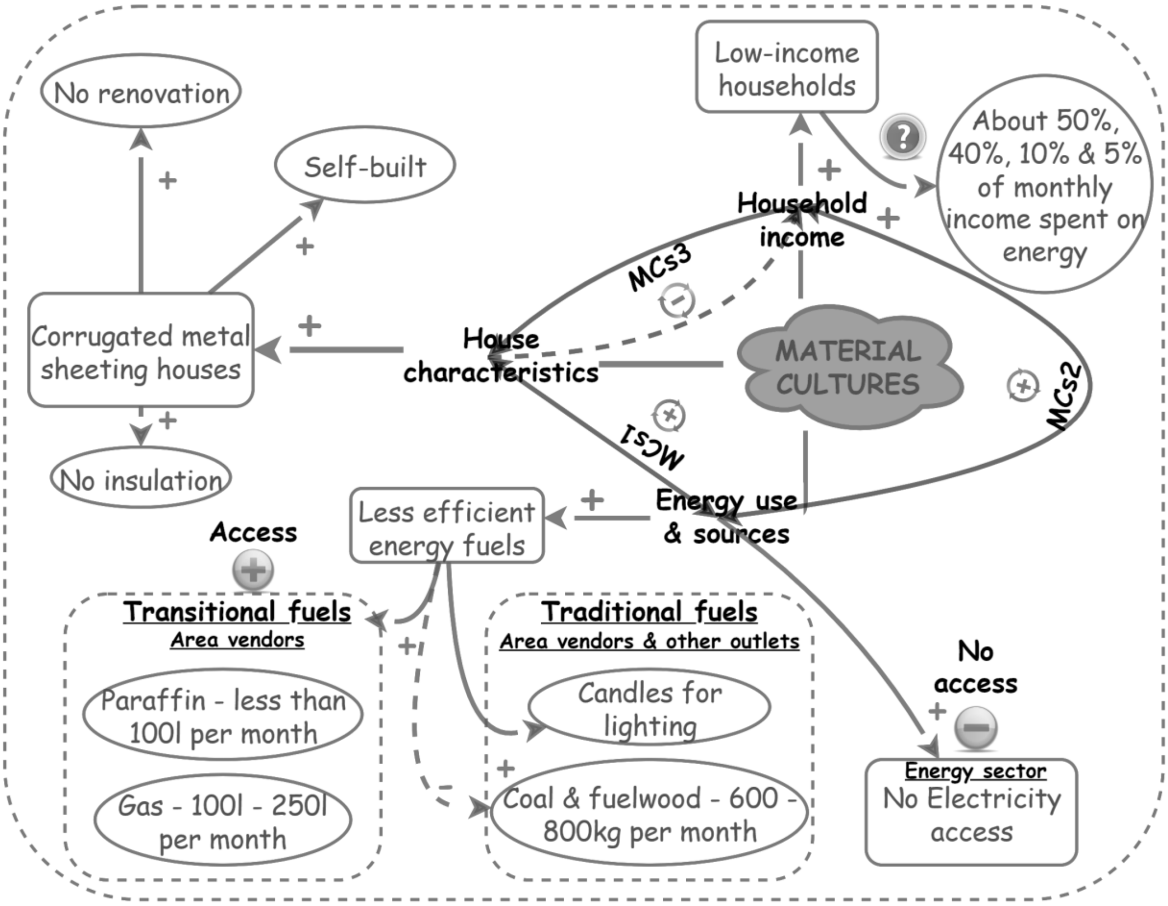

Figure 3. First Step: A simple CLD of MCs. Causal loops (in black) and links (in grey) are represented in strong (bold lines) and weak (dotted lines) connections, indicating high-level (marked with + signs) and low-level (marked with – signs) system dependency, respectively.

COGNITIVE NORMS

In the second step, the CNs system was added with a new set of causal loops and links to examine why households use energy the way they do, Figure 4. Interactions within the CNs system influenced both MCs and EPs systems while simultaneously being shaped by them. In links, CNs were defined by:

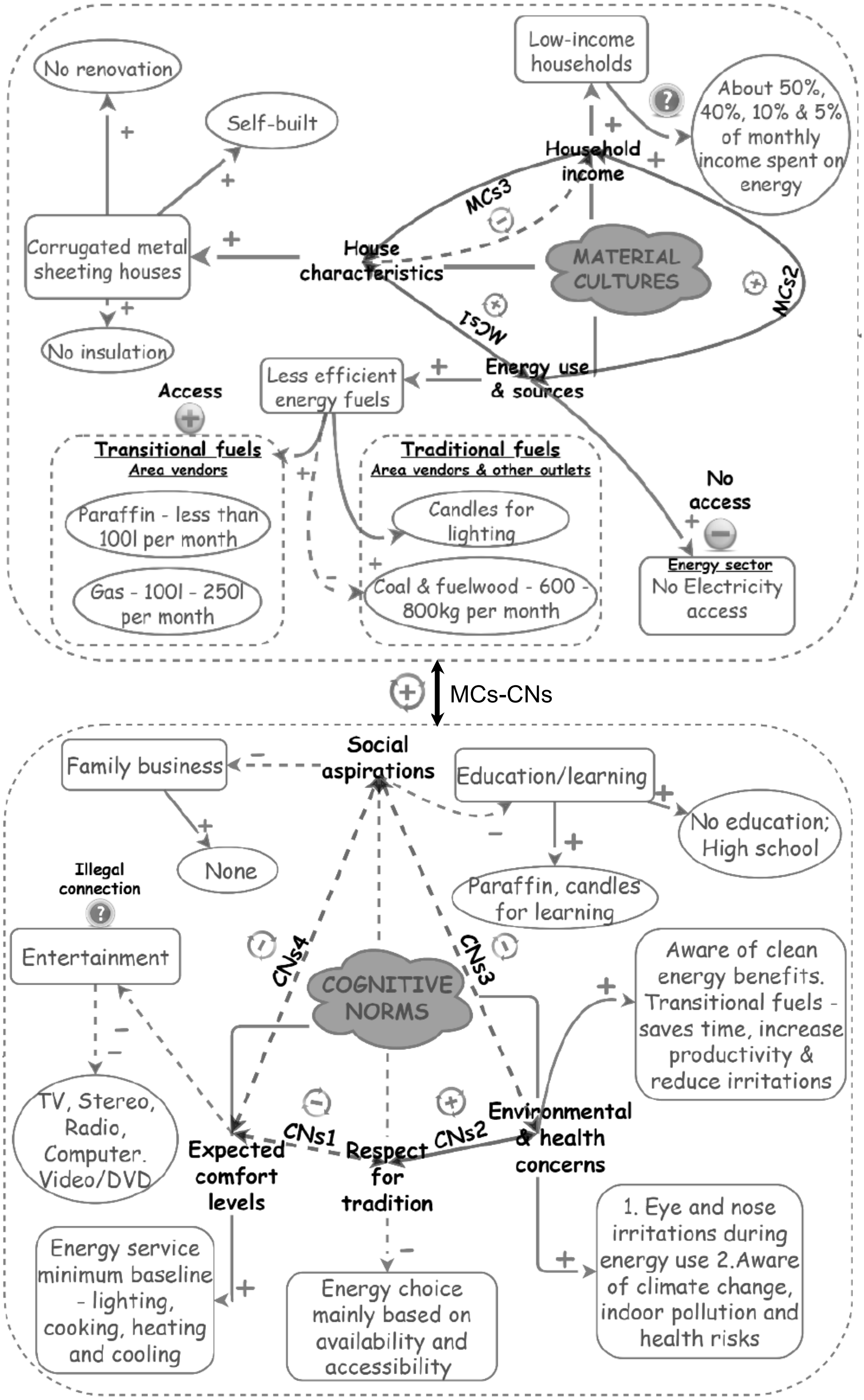

Figure 4. Second Step: Inclusion of CNs CLD design. Causal loops (in black) and links (in grey) are represented in strong (bold lines) and weak (dotted lines) connections, indicating high-level (marked with + signs) and low-level (marked with – signs) system dependency, respectively.

- Meeting the minimum baseline of energy services and entertainment in the form of recorded electrical appliances (which also queried the lack of electricity access in the settlement), although this interaction had low-level system dependency.
- Energy choices were not significantly driven by traditional values but rather by product availability and accessibility and not a strong determinant of system behaviour.
- Awareness of the negative impacts of poor energy use and the benefits of cleaner energy options informed some preferences, albeit weakly.
- Education was limited to high school certificates, using paraffin and candles for learning, and poor socioeconomic activities, such as small family businesses, also contributed weakly to defining system behaviour.

The CNs1 loop highlighted weak interactions between the subsystems, which, in turn, were dependent on CNs3 and CNs4 loop activities, with negative reinforcing patterns observed across all three loops, Figure 4. The CNs2 loop, however, showed a positive pattern, where respect for tradition enormously strengthened environmental and health awareness and vice versa. The combined synergisms between the four loops (CNs1-CNs4) produced positive behaviour toward energy preferences, primarily influenced by the disregard for tradition and heightened environmental and health concerns. These interdependencies further resulted in poor energy productivity, characterized by poor socioeconomic or low entrepreneurial activities, limited education, and an inability to exceed the minimum baseline of energy services.

Causal loops at the MCs – CNs system interfaces revealed reciprocal influences, Figure 4. Fundamental synergisms (not visually illustrated in the figure) defining system behaviour includes:

- MCs – CNs1 loop; weak CNs1 loop activities were strongly impacted by all MCs loops, particularly in querying the possibility of electricity theft in the settlement[39].
- MCs – CNs2 loop; the energy use and sources subsystem (captured in MCs1 and MCs2 loops) strongly impacted CNs2 loop activities.
- MCs – CNs3/CNs4; similar to CNs1 loops, all MCs loop activities strongly influenced CNs3 and CNs4 loops through their linked elements.

ENERGY PRACTICES

In the third step, causal links and loops were included to analyze the interrelationships within the EPs system, Figure 5. This step marked the development of the EPM, tailored to the case study energy poverty analysis. Central to the energy price structure subsystem, EPs were defined in links by:

- Lighting choices – dominated by paraffin and candles, with light bulbs present but not widely used.
- Cooking practices – using mainly paraffin, gas stoves, and fuelwood with minimal use of electric stoves.
- Heating devices – predominantly using paraffin and charcoal heaters, with fewer gas portable units and heat pumps.
- Cooling practices – involving more traditional methods like opening windows and doors with limited use of modern cooling technologies.

The system's four casual loops (EPs1-EPs4 loops) indicated positive reinforcing patterns, strengthening the energy price structure's relationships with other subsystems in shaping behaviour, Figure 5. The loops between the system interfaces demonstrated that EPs' activities were not self-contained but influenced by MCs and CNs' system behaviours. Conversely, EPs had a limited role in shaping behaviours within the CNs system. For instance, using paraffin stoves for cooking (EPs) cannot successfully motivate any aspect of social aspirations (CNs) in households. Key interactions from coupled interfaces (not) visually depicted in the figure are highlighted as follows:

- MCs – EPs loops; all MCs loops influenced the EPs1 strong loop, reinforcing the causal influence between the energy price structure and lighting choices within the EPs system. Similar influences were evident in MCs - EPs2, MCs - EPs3, and MCs - EPs4 loops, suggesting the EPs' strong system dependency on MCs.
- CNs – Eps; all CNs loops strongly impacted all EPs loops, except for the CNs2 – EPs inverse but a weak loop. This inverse weak loop stemmed from CNs2 linked elements (which, in turn, were strongly determined by MCs loops) that showed no impact on mitigating poor energy practices or encouraging the use of the finest appliances in households.

Figure 5 presents the EPM elucidating systems perspective on energy poverty analysis and describing energy poverty situations in the settlement based on significant synergisms within and across the systems (MCs – CNs – EPs), highlighted as follows:

- **Poor energy-use patterns and efficiency (MCs)** in informal households were driven by poor energy use and sources, inadequate housing characteristics, and low household income. These limitations contributed to reliance on local energy devices (EPs), poor social aspirations, the minimum baseline of energy services, and heightened environmental and health concerns (CNs).
- **Poor energy productivity (CNs)** in households rooted in constrained social aspirations, influenced by inefficient energy use and sources, low income (MCs), and dependence on local devices (EPs). While the minimum baseline of energy services was met (which aligned with acceptable standards [1]), energy productivity remains optimal. Furthermore,
  - **Positive behavioural patterns toward energy preferences (CNs)** were reflected in a disregard for tradition and a heightened awareness of environmental and health concerns, as indicated by the CNs2 loop. Despite these positive aspects, the CNs2 loop potential was limited by the solid causal influences flowing within and between the three systems, reinforcing inefficiencies.
- **Local energy appliances and affordable energy prices (EPs)** in the settlement. The availability and accessibility of paraffin and gas (MCs) strengthened the use of local devices and the affordability of local energy products (EPs). In addition, reliance on less efficient fuels and the lack of electricity access (MCs) perpetuated poor energy practices (EPs) despite awareness of environmental and health concerns (CNs).

INSIGHTS AND POLICY IMPLICATIONS

The synergistic analyses revealed that inefficiencies in MCs directly impacted CNs and EPs, collectively contributing to the overall poor model performance, highlighting the need for targeted solutions addressing structural barriers (e.g., housing conditions, income disparities), behavioural shifts (e.g., improving energy preferences), and accessibility to cleaner energy sources while fostering collaborative and integrated policy approaches. These analyses effectively identified system elements that exponentially drive energy poverty and enable sustainable energy access (SEA). For instance, the energy use and sources subsystem was pivotal in meeting the baseline of energy services, poor energy productivity, and the widespread use of local energy devices in the target settlement. These outcomes show consistency with the literature on informal settlements in South Africa [3, 24]. However, despite these limitations, this subsystem harbors integral elements capable of catalyzing transitions toward clean energy access, improved energy productivity, and affordable energy practices in target settlement.

The EPM further revealed no laid-out procedure for mitigating energy poverty in any local settings [40]. For example, households utilized less efficient fuels (MCs) and only met the essential energy services (CNs) while continuing to use local energy devices (EPs). Another instance is that household low-income status (MCs) indirectly influenced the energy price

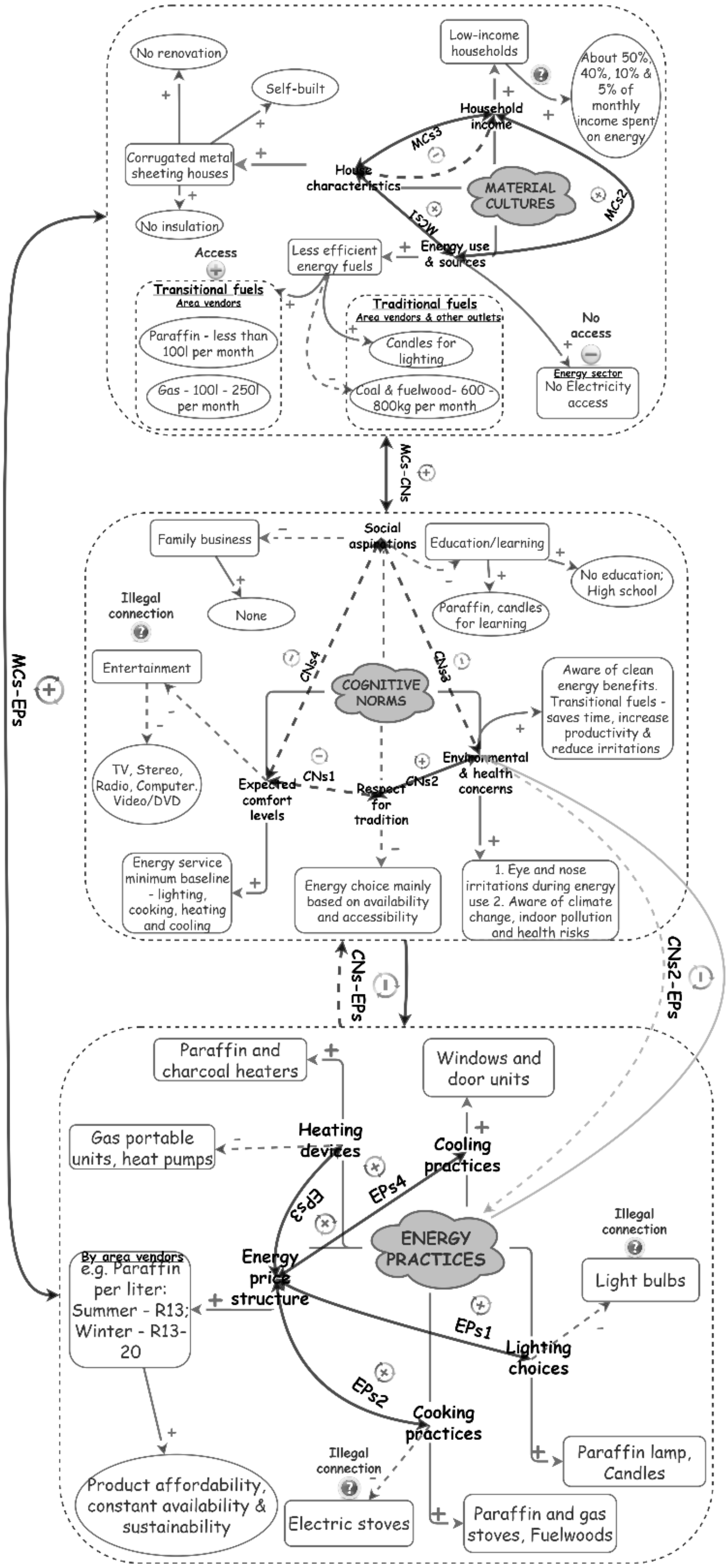

Figure 5. Third step: The EPM development. Inclusion of EPs CLD. Causal loops (in black) and links (in grey) are represented in strong (bold lines) and weak (dotted lines) connections, indicating high-level (+ sign) and low-level (– sign) system dependency, respectively.

influenced structure to be affordable (EPs), although it limits education and social aspirations (CNs). These highlight the system interconnectedness, where interventions in one element inadvertently trigger counterproductive influences in another, diminishing the practicality of policy initiatives or interventions. Instead of implementing actions that narrowly target a single element, such as workshops to promote positive behaviour without addressing the foundational energy-use patterns (MCs), the model reveals the importance of identifying actionable elements within the systems with multiple exponential impacts. For instance, providing access to electricity or cleaner energy options (such as renewables or transitional fuels like paraffin) displaces traditional fuels like charcoal, significantly improving energy-use patterns and efficiency (MCs), as well as energy preferences and productivity (CNs) in informal households. As another instance, promoting local entrepreneurial activities (CNs) can directly elevate household low incomes (MCs) to support better energy practices (EPs).

The common assumption in energy access programs is that households readily adopt a new energy technology once provided, disregarding factors acting singly or in groups that oppose such immediate adoption in a given place and time [41]. However, the model showed the intricate interactions among system elements that could initiate delayed technology use in an energy-poor community. For instance, even with future access to electricity (MCs), adoption delays are likely due to low-income status (MCs) exacerbated by electricity price hypes [3] limiting affordability and persistent reliance on less efficient energy products influenced by their immediate availability and accessibility in the target settlement. The institutional landscape is critical in enabling new technology use and should employ a multifaceted approach involving community stakeholders to address system interactions and barriers more proficiently. In contexts like the case study area, institutional challenges, such as delays in grid electrification, often hinder energy access progress. However, stakeholder-driven initiatives can bridge gaps by promoting free and subsidized transitional fuels (see Table 1) to displace traditional fuels, such as charcoal and fuelwood, reducing health risks from harmful emissions and enhancing productivity (CNs) while building capacity for future clean energy adoption. These strategies address immediate energy needs and create pathways for sustainable energy transitions, fostering social acceptance and long-term adoption of clean energy technologies. Once again, stimulating aspects of one system may be less effective in producing change than stimulating another, with more significant influences on elements within and between the system interfaces. For instance, promoting educational and entrepreneurial opportunities (CNs) can shift household behaviour and perceptions, increasing openness to adopting new energy technologies once provided in the study area.

The energy access process frequently faces constraints when the target group's needs and strengths are not adequately identified or addressed [42]. The model provides the platform to help planners understand current conditions and design effective, context-sensitive external interventions. Regrettably, sociotechnical decisions in energy access plans are made without sufficient input from the target communities. Nonetheless, much attention should be focused on addressing energy poverty based on the context of a place and responses generated when designing solutions pertinent to that place. This can be achieved by holistically viewing the interactions of MCs, CNs, and EPs in conditioning certain elements from opposing sustainability and, ultimately, promoting a willingness to a behaviour change. There are certain conditions where CNs, for example, are favourable but are compromised by inefficient MCs or another situation where CNs favour MCs but are weakened by poor EPs. Addressing these systems' lop-sided components through appropriate interventions while targeting a place's socioeconomic and cultural settings can conveniently improve situations. Besides, resolving the problem systems may require revoking some causal influences to motivate interventions. Essentially, the prime understanding of elements prolonging the system problems can lead to developing context-sensitive interventions and policy strategies.

The success of system synergies in invoking the right solutions relies on the robustness of existing policies [43-46]. Policies addressing MCs' elements have cascading effects, improving CNs, EPs, and overall model performance [43-46]. However, the simultaneous resolution of all problem systems remains challenging due to the limitations of current policy frameworks. At the time of this study, policy challenges exacerbated energy poverty in the target settlement [2, 47, 48]. These challenges included a focus on addressing energy inequality and supply shortages in the broader energy sector, often overlooking the nuanced realities of informal settlements [2, 48]. Such settlements are typically neglected in initial energy access planning due to their architectural volatility and lack of standardized infrastructure. These communities are often disproportionately linked to energy poverty without sufficient consideration of how policies could propel household-level sustainability. New place-based policy strategies should promote energy-use techniques at the household level through better technologies and practices. Alternative energy access options, such as renewable energy and localized microgrids, must be explored to sustainably balance demand and supply factions. Encouraging input from affected communities and relevant organizations further guarantees policies align with local needs and realities. Given that the EPM platform identifies the root causes of energy poverty grounded in the target group's specific conditions and resources, policymakers can design solutions that directly address energy inequality while avoiding unsustainable mitigation efforts. The model insights generate a worthy rotation motivating cross-sectoral collaboration to ensure that policy initiatives align with broader social, economic, and environmental goals. By leveraging these model insights, policymakers can circumvent the traditional exclusion of informal settlements from energy planning, bridging the gap between high-level policy intentions and on-the-ground realities and fostering resilience and inclusivity in energy access planning schemes. On balance, the model can promote policy cohesiveness and design of tailored interventions, promoting SEA in informal settlements at large in South Africa.

CONCLUSIONS AND LIMITATIONS

Energy-related issues in informal settlements [22, 24] and other similar communities [20, 21] have been widely documented, but none have been formalized in the field of SsT. The author adopted SsT to present a different but cohesive outlook on the complexities of energy poverty dynamics in informal settings. CLDs, synced with SsT and built into the EPM, have been shown to allow the integration of diverse elements into broader system configurations. The model utility generated multiple spectra of outcomes, facilitating the understanding of synergistic interactions and identifying critical gaps and required assets within the problem systems. The model further validated the synchronicity of actions necessary to address energy poverty problems, substantiating the potential of existing policies and initiatives to mitigate situations. However, policy support must be carefully scrutinized, and with a broad vision, several EPM insights must be considered. While these insights are promising, policymakers must remain adaptive, recognizing that the distinct characteristics of target communities require flexible and multidimensional approaches.

Despite its robustness, the model may display complexity when addressing energy poverty situations in a case-to-case scenario. Introducing new elements or accounting for unknown factors may generate varied responses, potentially complicating understanding the problem systems. This limitation is not unique but reflects the inherent complexity of any societal design. Emerging factors such as disruptive technologies, sociocultural changes, or collective traits of target groups may influence the model's outcomes. Future iterations of the model should recognize and incorporate the impacts of disruptive technologies, gradual societal changes, or new causal influences, such as grid electricity access or improved supply chain competence. These adaptations will not fundamentally alter the model but enhance its inclusivity and precision to enable effective interventions, ensuring its continued relevance and effectiveness in diverse settings.

APPENDIX

Table 1. Empirical observations of sampled parameters/elements in distinctive EPSs in the case study area.

Category	**Parameters/Elements (*n* – Number of respondents)**
Dwelling Types and Household Sizes	**a)** Dwellings (n = 117) are mainly shacks, built with corrugated metal sheeting (98,51 %); Mobile homes (1,49 %) ✓ Self-built (83 %) dwellings (n = 114); built by the local authority (26 %). ✓ Non-insulated (n = 77); poorly insulated (n = 19). ✓ Not renovated (63 %) dwellings (n = 120); unsure of renovating (5 %); renovated (31 %).
	b) Household sizes range from one to nine; with at least one member over 18 years (n = 101).
Electricity Access and Energy Use	**c)** Households (n = 96) indicate no electricity access (95,83 %); Few indicate access (4 %) ✓ Primary energy use is paraffin - for lighting (46 %, n = 186); cooking (66 %, n = 139); and heating (59 %, n = 128) ✓ Followed by candles (40%) for lighting; gas (14 %) and fuelwood (12 %) for cooking; and fuelwood (18 %) and coal (14 %) for heating
	d) Energy (paraffin) preferences (n = 117); are due to affordability (52,14 %), accessibility and availability (36,75 %); convenience (7.69%); environmentally friendly (2,56 %); and respect for tradition (0,85 %)
	e) Households (n = 97) obtain paraffin and gas from the area vendors; fuelwood and charcoal obtain from woodlots and other outlets (n = 7).
	f) For space heating, households use paraffin (about 40 %; n = 67), charcoal heaters (39 %); electric portable (4 %) and gas portable units (10 %); heat pumps (6 %).
	g) Traditional incandescent and LED light bulbs (n = 39); and some electrical appliances (n = 84) are recorded
	h) For space cooling, windows and door units (97 %; n = 71); and electric fans and evaporative coolers (3 %).
Energy costs on household income	**i)** Households (n = 127) mainly use less than 100 *l* (n = 34), 100-250 *l* (n = 17), and more than 250 *l* (n = 12) of paraffin in winter (n = 64) than in summer (n = 63). **j)** Gas consumption rates decline from summer (n = 13) to winter (n = 8); fuelwood and coal rates increase across seasons.
	k) One-third of households (n = 78) have energy costs of 0,5 of household income, monthly; others have 0,4 (17%), 0,2 (4%), 0,1 (15%), and less than 0,05 (23%). **l)** Most household sizes (n = 99) spend less than R300 (50 %) and R301-R999 (41 %) on energy products
Energy Productivity and Expected Energy Benefits	**m)** About future energy price hype, among n = 100 households: 83,33 % worry a lot; 3,92 % worry a fair amount; 1,96 % do not very much and 10,78 % do not worry at all. **n)** About the impact of using less efficient fuels on the climate, households (n = 104) worry: a lot – 90,57 %; a fair amount – 2,83 %; not very much – 2,83 %; not at all – 3,77 %. **o)** Households (n = 96) have eye and nose irritations using energy products as follows: ✓ when using (n = 40): very much – 80,00 %; not too much – 17,50 %; not at all – 2,50 %. ✓ immediately after using (n = 36): very much – 86,00 %; not too much – 13,89 %; not at all – 0,00 %. ✓ a long time after using (n = 20): very much – 85,00 %; not too much – 5,00 %; not at all – 10,00 %. **p)** Households (n = 110) visit a hospital or clinic one or two times a month (~ 35 %); others (~ 47 %) have zero visits. **q)** Households (n = 100) have no kind of family business (~ 93 %); others (~ 5 %) run businesses such as fashion, food vending, and hair salons **r)** Households (n = 98) have at least one member with a high school certificate (68 %); no education (22 %); a diploma (6 %); and degree certificates (3 %). **s)** For improved energy use, households (n = 104) suggest solar PV (n = 7) [43]; external (n =17) and internal thermal insulation (n = 14); replacement of windows, doors (n = 18), and roofs (n = 24); pre-paid meter installations (n = 24) [46]; free delivery of paraffin [45] and Reconstruction and Development Programme (RDP) houses [48].
Local Energy Supply and Sustainability	**t)** Two area vendors – one sells 1 *l* of paraffin at R13 in summer and R13-R20 in winter; the other sells 5 kg of gas for R120 and 9 kg for R220 regardless of seasonality. **u)** Both vendors confirmed product affordability, availability, and sustainability, except in a few winters when demand is high.

REFERENCES

[1] Practical Action: *Poor People's Energy Outlook 2010*.
http://practicalaction.org/ppeo2010,

[2] Mehlwana, A.M.: *The anthropology of fuels: situational analysis and energy use in urban low-income townships of South Africa*.
Energy for Sustainable Development **3**(5), 5-15, 1997,
http://dx.doi.org/10.1016/S0973-0826(08)60208-2,

[3] Sustainable Energy Africa: *Tackling Urban Energy Poverty in South Africa*.
https://cityenergy.org.za/uploads/resource_77.pdf,

[4] Chidhindi, P.; Belelie, M.D.; Burger, R.P.; Mkhatshwa, G. and Piketh, S.J.: *Assessing the impact of Eskom power plant emissions on ambient air quality over KwaZamokuhle*.
Clean Air Journal **29**(1), 29-37, 2019,
http://dx.doi.org/10.17159/2410-972X/2019/v29n1a2,

[5] Zerihun, M.F. and Mashingo, M.P.: *The quest for service delivery: The case of a rural district municipality in the Mpumalanga province of South Africa*.
Africa's Public Service Delivery & Performance Review **10**(1), No. a512, 2022,
http://dx.doi.org/10.4102/apsdpr.v10i1.512,

[6] Okoye, P.I.: *A novel systems approach to energy poverty in sub-Saharan Africa: A South African informal settlement case study*. Ph.D. Thesis.
University of Pretoria, Pretoria, 2021,
https://repository.up.ac.za/handle/2263/77373,

[7] Statistics South Africa: *Household Services Sub Place*.
http://www.statssa.gov.za, accessed 17th October 2018,

[8] van Niekerk, A.; Kimemia, D.; Seedat, M. and Annegarn, H.: *Energy impoverishment and burns: The case for an expedited, safe and inclusive energy transition in South Africa*.
South African Journal of Science **118**(3/4), 2022,
http://dx.doi.org/10.17159/sajs.2022/13148,

[9] Tejeda, J. and Ferreira, S.: *Applying systems thinking to analyze wind energy sustainability*.
Procedia Computer Science **28**, 213-220, 2014,
http://dx.doi.org/10.1016/j.procs.2014.03.027,

[10] Arnold, R.D. and Wade, J.P.: *A definition of systems thinking: A systems approach*.
Procedia Computer Science **44**, 669-678, 2015,
http://dx.doi.org/10.1016/j.procs.2015.03.050,

[11] Australian Prevention Partnership Centre :*What is Systems Thinking and How Does It Apply to Prevention in TAPPC*?
http://preventioncentre.org.au/wp-content/uploads/2015/02/Systems-thinking-paper1.pdf,

[12] Buede, D.M.: *The Engineering Design of Systems: Models and Methods*. 2nd edition.
Wiley & Sons, 2009,
http://dx.doi.org/10.1002/9780470413791,

[13] Biahmou, A.: *Systems Engineering*.
In: Stjepandić, J.; Wognum, N., Verhagen, W.J.C., eds.: *Concurrent Engineering in the 21st Century*. Springer, Cham, pp.221-254, 2015,
http://dx.doi.org/10.1007/978-3-319-13776-6_9,

[14] Karásek, J. and Pojar, J.: *Programme to reduce energy poverty in the Czech Republic*.
Energy Policy **115**, 131-137, 2018,
http://dx.doi.org/10.1016/j.enpol.2017.12.045,

[15] O'Sullivan, K. and Howden-Chapman, P.: *Mixing methods, maximising results: Use of mixed methods research to investigate policy solutions for fuel poverty and energy vulnerability*.
Indoor and Built Environment **26**(7), 1009-1017, 2017,
http://dx.doi.org/10.1177/1420326X17707327,

[16] Vezzoli, C., et al.: *Product-service system design for sustainability*, 1st edition.
Routledge, 2017,
http://dx.doi.org/10.4324/9781351278003,

[17] Maxim, A., et al.: *Implications and measurement of energy poverty across the European Union*.
Sustainability **8**(5), No. 483, 2016,
http://dx.doi.org/10.3390/su8050483,

[18] Pye, S., et al.: *Addressing Energy Poverty and Vulnerable Consumers in the Energy Sector Across the EU*.
L'Europe en Formation **378**(4), 64-89, 2015,
http://dx.doi.org/10.3917/eufor.378.0064,

[19] Sovacool, B.K.: *The political economy of energy poverty: A review of key challenges*.
Energy for Sustainable Development **16**(3), 272-282, 2012,
http://dx.doi.org/10.1016/j.esd.2012.05.006,

[20] Khennas, S.: *Understanding the political economy and key drivers of energy access in addressing national energy access priorities and policies: African Perspective*.
Energy Policy **47**(SUPPL.1), 21-26, 2012,
http://dx.doi.org/10.1016/j.enpol.2012.04.003,

[21] Sokona, Y.; Mulugetta, Y. and Gujba, H.: *Widening energy access in Africa: Towards energy transition*.
Energy Policy **47**(SUPPL.1), 3-10, 2012,
http://dx.doi.org/10.1016/j.enpol.2012.03.040,

[22] Musango, J.K.: *Assessing gender and energy in urban household energy transitions in South Africa: A quantitative storytelling from Groenheuwel informal settlement*.
Energy Research & Social Science **88**, No. 102525, 2022,
http://dx.doi.org/10.1016/j.erss.2022.102525,

[23] Housing Development Agency: *South Africa: Informal settlements Status (2013)*.
http://www.thehda.co.za/uploads/files/HDA_South_Africa_Report_lr.pdf, accessed 26th December 2018,

[24] Mdluli, T.N. and Vogel, C.H.: *Challenges to achieving a successful transition to a low carbon economy in South Africa: Examples from poor urban communities*.
Mitigation and Adaptation Strategies for Global Change **15**(3), 205-222, 2010,
http://dx.doi.org/10.1007/s11027-009-9195-4,

[25] Gulati, M. and Scholtz, L.: *Socio-enviro-economic impacts of biofuels: Weighing the risks and benefits for southern Africa*.
In: *Roadmap for sustainable biofuels in southern Africa*, Nomos Verlagsgesellschaft mbH & Co. KG, pp.85-110, 2017,
http://dx.doi.org/10.5771/9783845277585-85,

[26] Shrubsole, C., et al.: *Bridging the gap: The need for a systems thinking approach in understanding and addressing energy and environmental performance in buildings*.
Indoor and Built Environment **28**(1), 100-117, 2019,
http://dx.doi.org/10.1177/1420326X17753513,

[27] Laimon, M.; Yusaf, T.; Mai, T.; Goh, S. and Alrefae, W.: *A systems thinking approach to address sustainability challenges to the energy sector*.
International Journal of Thermofluids **15**, No. 100161, 2022,
http://dx.doi.org/10.1016/j.ijft.2022.100161,

[28] Silvast, A. and Foulds, C.: *Whole Systems Thinking and Modelling in the UK*.
In: *Sociology of Interdisciplinarity*. Palgrave Macmillan, Cham, pp.23-47, 2022,
http://dx.doi.org/10.1007/978-3-030-88455-0_2,

[29] Hassmiller Lich, K.; Urban, J.B.; Frerichs, L. and Dave, G.: *Extending systems thinking in planning and evaluation using group concept mapping and system dynamics to tackle complex problems*.
Evaluation and Program Planning **60**, 254-264, 2017,
http://dx.doi.org/10.1016/j.evalprogplan.2016.10.008,

[30] Haines, S.: *The systems thinking approach to strategic planning and management*.
CRC Press, 2000,
http://dx.doi.org/10.5860/choice.38-2242,

[31] Roychoudhury, A., et al.: *The Need to Introduce System Thinking in Teaching Climate Change*.
Science Educator **25**(2), 73-81, 2017,

[32] Richmond, B.: *Systems thinking/system dynamics: Let's just get on with it*.
System Dynamic Review **10**(2-3), 135-157, 1994,
http://dx.doi.org/10.1002/sdr.4260100204,

[33] Romero-Castro, N.; Miramontes-Viña, M. and López-Cabarcos, M.Á.: *Understanding the Antecedents of Entrepreneurship and Renewable Energies to Promote the Development of Community Renewable Energy in Rural Areas*.
Sustainability **14**(3), No. 1234, 2022,
http://dx.doi.org/10.3390/su14031234,

[34] Stephenson, J., et al.: *Energy cultures: A framework for understanding energy behaviours*.
Energy Policy **38**(10), 6120-6129, 2010,
http://dx.doi.org/10.1016/j.enpol.2010.05.069,

[35] Ishak, M.H.: *Modelling energy consumption behaviour using 'energy culture' concept for student accommodations in Malaysian public universities*.
Facilities **35**(11-12), 658-683, 2017,
http://dx.doi.org/10.1108/F-12-2015-0084,

[36] Asian Development Bank: *Sustainable Energy Access Planning.*
https://www.adb.org/publications/sustainable-energy-access-planning-case-study,

[37] INCOSE: *INCOSE Systems Engineering Handbook*.
John Wiley & Sons, 2023,

[38] Pâslaru, V.: *Causal and Mechanistic Explanations, and a Lesson from Ecology*.
In: Pârvu, I.; Sandu, G. and Toader, I., eds.: *Romanian Studies in Philosophy of Science*. Boston Studies in the Philosophy and History of Science **313**. Springer, Cham, 2015,
http://dx.doi.org/10.1007/978-3-319-16655-1_17,

[39] Geldenhuys, K.: *Electricity theft: The struggle to keep the lights on*.
Servamus Community-based Safety and Security Magazine **115**(3), 28-33, 2022,
https://journals.co.za/doi/abs/10.10520/ejc-servamus_v115_n3_a10,

[40] Süsser, D.; Döring, M. and Ratter, B.M.W.: *Harvesting energy: Place and local entrepreneurship in community-based renewable energy transition*.
Energy Policy **101**, 332-341, 2017,
http://dx.doi.org/10.1016/j.enpol.2016.10.018,

[41] Rahut, D.B.; Behera, B. and Ali, A.: *Factors determining household use of clean and renewable energy sources for lighting in Sub-Saharan Africa*.
Renewable and Sustainable Energy Reviews **72**, 661-672, 2017,
http://dx.doi.org/10.1016/j.rser.2017.01.080,

[42] Broto, V.C., et al.: *A research agenda for a people-centred approach to energy access in the urbanizing global south*.
Nature Energy **2**, 776-779, 2017,
http://dx.doi.org/10.1038/s41560-017-0007-x,

[43] Department of Energy Republic of South Africa: *Non Grid Electrification Policy Guidelines*.
http://www.cityenergy.org.za/uploads/resource_88.pdf,

[44] Nuclear Energy Advisory Committee: *Integrated National Electrification Programme (INEP) Plan to Achieve Universal Access to Electricity by 2012: Masterplan/Business Plan*.
https://www.cityenergy.org.za/uploads/resource_86.pdf,

[45] Department of Minerals and Energy Republic of South Africa: *Free Basic Alternative Energy (Households Energy Support Programme)*.
Government Gazette 29760, 1-21, 2007,
https://www.gov.za/sites/default/files/gcis_document/201409/29760.pdf.

[46] Department of Minerals and Energy Republic of South Africa: *White Paper on the Energy Policy of the Republic of South Africa*.
Government Gazette 19606, 1-110, 1998,
https://gazettes.africa/akn/za/officialGazette/government-gazette/1998-12-17/19606/eng@1998-12-17,

[47] Department of Energy Republic of South Africa: *Policy guidelines for the electrification of unproclaimed areas*. http://www.cityenergy.org.za/uploads/resource_72.pdf,

[48] Njekelana, S.: *Free Basic Energy; Free Basic Alternative Energy; Integrated National Electricity Programme (INEP): update*. https://pmg.org.za/committee-meeting/16037, accessed 9th January 2019.