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Tackling urban household energy transition: A systems approach

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2021

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Inaugural lecture delivered on 26 October 2021
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Biography of author

Josephine Kaviti Musango has been a professor at the School of Public Leadership at Stellenbosch University since 1 January 2020. She is the Trilateral SARChI Chairholder on Mainstreaming Gender for Energy Security in Poor Urban Environments. Josephine joined the School of Public Leadership in 2013. She previously served as a master's coordinator in the Sustainable Development Programme from 2014 to 2019. Josephine is a skilled resource economics and system dynamics professional researcher with over 16 years' experience. She was a senior researcher at the Gauteng City-Region Observatory and a resource economist at the Council for Scientific and Industrial Research. She also served as a deputy director at the former Department of Energy, where she was responsible for grid-renewable energy. Josephine is one of the founding members of the South Africa System Dynamics Chapter and serves on the International System Dynamics Society Policy Council. She has supervised 27 master's, five PhDs and four postdoctoral candidates. Josephine has published over 60 articles in accredited journals, three books, nine book chapters and 80 papers in international and national conference proceedings. Josephine's research interests entail using a systems approach in managing change and policy-related challenges in energy transition, the green economy, urban African energy issues and gender mainstreaming. Josephine was recently appointed to serve on the Energy Sector Gender Ministerial Advisory Council. She has four sisters and three brothers.

TACKLING URBAN HOUSEHOLD ENERGY TRANSITION: A SYSTEMS APPROACH

Prof Josephine Kaviti Musango

ABSTRACT

Although energy transition processes are observed to work partly through urban transformation and urban practices, energy is hardly the main concern in urban planning. Urban areas are expected to play a crucial role in energy transition. With urbanisation in Africa expected to be the fastest between 2030 and 2050, when done out of context, urban energy transition assessments could result in unsustainable interventions that bring about unintended outcomes. Urban energy transition is a systemic issue embedded within technological and sustainable development. Systemic problems such as urban energy transition are complex, dynamic, uncertain and do not have a single solution, because they affect the entire system. This study explored how a systems approach could serve as a decision support tool in urban household energy transition planning. First, the study conceptualised urban energy transition as a systemic problem. Second, the study developed a generic framework termed a 'systems approach to sustainable energy transition assessment' (SASETA) to support measures relevant to urban energy planning. Third, the study demonstrated the application of the SASETA framework within urban household energy transition, using Drakenstein Municipality as a case study. Key insights from the study show that well-intended positive interventions to support household energy transition, such as energy subsidies, may result in socio-environmental impacts that increase inequality and impair human health. Complementary interventions that consider the cross-sector effect, such as off-grid power solutions and energy efficiency, are necessary. Future work entails integrating urban energy transition assessments through the perspective of gender equality.

INTRODUCTION

Energy transition is a global challenge of the 21st century, but the concept is still conveyed ambiguously. In general, energy transition is a radical, systemic and managed change towards the sustainable or effective provision and use of energy [1,2]. Some studies consider energy transition as a change in the composition of energy supply [3], a change in fuels [4], a shift from one socio-technical regime to another [5] and a change in the state of the energy system as opposed to a single energy technology [6]. Despite the various interpretations, the concept of energy transition unfolds at multiple levels, including global, national, urban, sector and household [7]. Energy transition processes are observed to work partly through urban transformation and urban practices.

Urban energy transition research and policy practice have largely focused on transformation towards a low-carbon economy based on transition concepts in the context of the global North [8,9]. Attention has been given to energy transition that evolves as homogenous grid-connected electricity or heterogeneous constellations in poor urban environments [8,10]. Urban energy transition frameworks fail to consider the systemic issues emerging from urbanising Africa [11].

More than half of the world's population live in urban areas, estimated at 56.16% in 2020 [12]. In sub-Saharan Africa, the level of urbanisation remains low at 41% [12]. However, of the 54 African nations (see Figure 1), 22 countries are over 50% urban, of which six are over 60% and eight are over 70% [12]. The African urban population is expected to grow the fastest between 2030 and 2050 [13], and the majority of the people who migrate from rural to urban areas end up in informal settlements. In 2018, 54% of the urban population in sub-Saharan Africa lived in informal settlements [12]. Empirical evidence shows that the majority of the population in urban informal settlements are women [14], requiring consideration of energy and gender issues [10]. In South Africa, the share of the population in informal urban settlements was 26% in 2018, translating to approximately 10 million people [12].

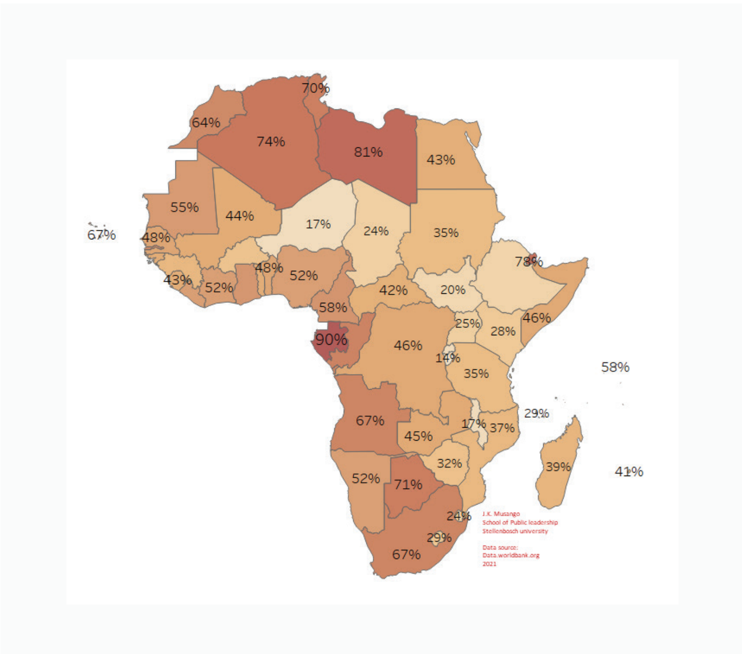

Figure 1: Share of urban population in Africa countries

The changing urban population dynamics challenges urban planners to provide basic services, including housing, water, sanitation and energy [9,11]. In addition, cities have become areas of focus in addressing the global challenge of climate change through transition to low-carbon, clean and efficient energy systems [15,16]. However, energy is hardly the main concern in urban planning and is generally treated as a field that brings together multiple stakeholders to mediate existing dilemmas and interests [15]. Urban planning needs to consider energy transition measures in transport, households, industry and commerce, agriculture and public services consumption as well as their relationship with other domains in supporting urban and global agendas.

At a household level, energy is an essential socio-economic input not for its own sake, but because of its contribution to the energy services consumed to support the city economy and household well-being [17]. Energy is linked with biophysical and societal structures that relate to energy conversion value chains, governance, economy, cultural perceptions as well as household functions, services, benefits and values related to energy consumption [17].

Energy services are "functions performed using energy to obtain or enable desired end states" [18]. The energy services indicate the level of household satisfaction in consuming different energy services [19] such as lighting, cooking, washing and mobility, rather than fuel type [20,21] or energy technology. A household energy service is therefore the desired state or satisfaction parameter that is neither predetermined nor fixed [22]. It can therefore change over time and depends on people's changing expected energy service, which is influenced by factors such as accessibility, affordability, reliability, health and safety, dwelling type and the gender of the head of the household. For example, if a household moves from a wooden shack to a formal building, the desired energy service may change. The gender of the head of a household also has an influence on the desired energy service. Factors outside a household, including policy frameworks and institutional factors, also influence the consumption of household energy services.

Connecting energy services with energy sources and technological devices can support understanding of household energy behaviours [23,24]. Furthermore, depending on the level of satisfaction with the household energy services, households can be viewed as energy-secure or *energy-insecure*. Household energy security is the "amount of energy needed to meet the basic needs of the daily life of the individual and household in terms of cooking, lighting, washing, warming and cooling the house" [25]. This implies that the security of energy services is "the extent to which a household can access affordable, environmentally and socio-culturally acceptable energy services of adequate quality" [10].

In tackling energy insecurity in urban households, various factors continuously influence energy services satisfaction, making it challenging to understand the processes of energy demand and the social processes that trigger them independently. It is on this basis that the study argues for a systems approach in understanding urban household energy transition to support synergies between energy technology development and socio-economic and environmental aspects. This idea echoes the argument that technological development continuously affects the different aspects of the socio-economic, socio-political and socio-ecological regime and vice versa [26]. As an example, the provision of housing (technical regime) to informal settlements to meet the housing service (social regime) triggers the need for the energy services (social regime), which then influences the need for developing energy infrastructures and devices (technical regime) to meet these services.

Household energy transition in urban Africa is crucial to achieving sustainable energy for all, as stipulated in Sustainable Development Goal (SDG) number 7. Household energy planning overlooks demand-led assessments [16]. The implication is that household energy services are not clearly understood to support urban energy planning. Without frameworks and decision support tools for urban policy interventions, household energy transition can have unintended effects on energy affordability, access and equity issues.

This study therefore explored how a systems approach can serve as a decision support tool in urban household energy transition in three ways. First, the study conceptualised energy transition from a systems perspective and developed a generic framework relevant to urban energy transition. Second, the study developed an urban energy transition assessment framework to translate the general concept to practice within the urban planning process. Third, the study demonstrated the assessment framework using a case study of Drakenstein Municipality.

METHODOLOGY

The study used three methods, namely a narrative review, a case study and simulation. Narrative reviews can be systematic or non-systematic and address broad research questions with the aim of contributing to the state of knowledge, themes, research agendas and theoretical models [27]. The non-systematic narrative review was applied in the development of the generic framework for urban energy transition and in translating the concept into an assessment framework.

A case study was used to demonstrate the application of the assessment framework. A case study is useful when an in-depth investigation is required [28]. Although a single case study was used, the generic framework developed can be customised and tested in other case studies. The choice of Drakenstein Municipality was due to ongoing research to provide gendered energy solutions to energy-related issues in informal settlements.

Simulation was applied in populating a model for urban energy transition assessment in Drakenstein. Simulation is a computer-aided method that provides a simplified representation of real-world systems to help understand and manage issues according to desired needs [29]. It involves specifying input variables, decision variables and external parameters. The simulation approach utilised was system dynamics, which describes the causal relationship of key system variables and is explicitly defined as differential equations [29]. System dynamics helps in assessing the effects of interventions on key indicators.

CONCEPTUALISING URBAN ENERGY TRANSITION FROM A SYSTEMS APPROACH

Although no consensus on a single conceptualisation of urban energy transition exists, at the global or national level, scholars, industry and policymakers discuss it from the context of technological development and sustainable development, and as a complex challenge. The New Urban Agenda adopted in 2016 places sustainable urban development at the centre of urban planning. However, with energy considerations only integrated into the later stages of urban formation (e.g. housing) or infrastructure development, such integration is technology-driven and affects socio-economic and environmental aspects.

Similarly, one of the aims of the 26th session of the Conference of Parties (COP26) of the United Nations Framework Convention on Climate Change, themed ‘energy transition’, is to find solutions to the technological, economic and social aspects of transition to low-cost, low-carbon, inclusive and resilient power systems, as specified in SDG7 [30]. A dedicated Energy Transition Council was set up to bring together ministers, senior officials, intergovernmental agencies, investors, scholars, businesses and industry to engage in a series of dialogues relating to energy transition challenges and to find solutions for clean power technologies. The focus of the Energy Transition Council is on technological development through new capacity or improved energy efficiency. The challenge is to ensure that technological development is just, inclusive and equitable. Urban environments play a crucial role in supporting energy transition; hence, it is necessary to develop a framework that puts energy at the core of urban planning.

The development of the generic urban energy transition conceptual framework was supported by the narrative review and informed by two general frameworks applied at global, national and sub-national levels that consider a systems approach. The first is the Threshold 21 (T21) framework that supports comprehensive, integrated planning for the medium to long term [31]. The T21 framework illustrates the interdependencies between energy and other aspects of the economy, society and the environment, mostly applied at national scale. The second framework is based on the earlier work of Musango and Brent [32]. They developed a systems approach for technological development for sustainability and support technology assessment measures and applied it at the sub-national level to assess biodiesel technology development. These frameworks were adapted into the generic urban planning cycle developed by Cajot and Schüler [15], constituting five phases: initiative and vision, strategic planning, design, implementation, and operation and monitoring.

The generic energy transition conceptual framework was discussed from the perspectives of technological development and sustainable development, and also as a dynamic system to show interactions in sustainable energy transition and to support sustainable energy transition assessment and energy technology transition assessment at the urban scale (see Figure 2). The 'systems approach to sustainable energy transition assessment' (SASETA) is therefore aimed at placing energy at the centre of the urban planning process.

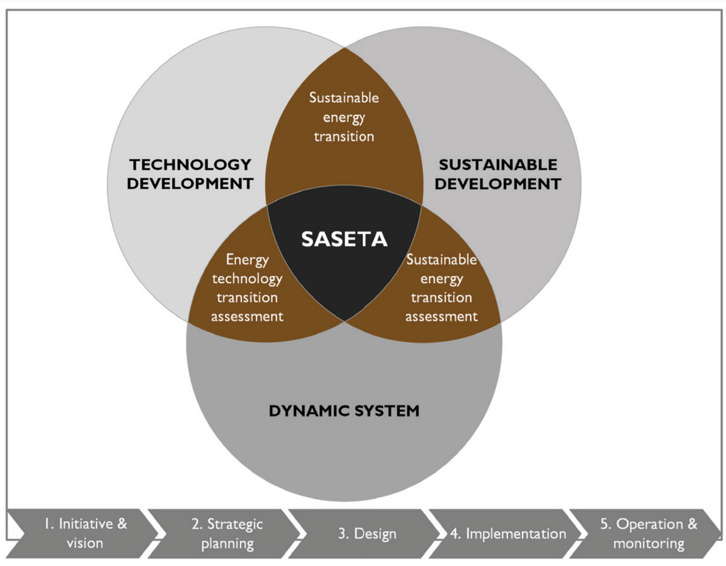

Figure 2: Generic energy transition conceptual framework integrated within urban planning phases

Source: Adapted from Musango and Brent [32] and Cajot and Schüler [15]

ENERGY TRANSITION IN THE CONTEXT OF TECHNOLOGICAL DEVELOPMENT

Technological development affects society in several ways [32] through advancing economies and society or generating wastes that affect the environment and society. The last 300 years have experienced rapid technology changes, referred to as the "age of technology" [33]. The role of technology in shaping society and cultures has been a core interest of philosophers, historians and anthropologists. Schumpeter [34] pioneered the thinking of technology as endogenous in the economy. Technology change arises from the economy and is seen as perceived opportunities to address desired needs [33].

Energy transition conceptualised in the context of technological development focuses on moving from dependence on conventional dirty energy technologies to cleaner energy technologies or improving energy efficiency to minimise the extraction of energy resources. From an economic perspective, energy transition means switching from a coal-powered economy to a renewable energy economy. Technological development, however, is not an easy task. Grübler [33] identified four characteristics of technological development: it is uncertain, dynamic, systemic and cumulative [33,35]. Governance issues also influence technological development [36].

At the urban planning level, relationships between energy and other domains are lacking [15,37]. Placing energy at the core of urban planning can support energy efficiency interventions to reduce public or private spending or to improve the affordability of renewable technologies by increasing local supply and improving air quality [15,38].

At the household level, the energy ladder is a dominant framework that argues that household energy transition involves a switch from fuel sources such as wood to modern energy sources such as gas and electricity as income levels increase [39,40]. However, empirical evidence in urban contexts has challenged such linear movement and showed that households tend to fuel-stack rather than make a complete technological switch [41]. The energy ladder also fails to integrate factors outside a household, such as the availability of the technologies or policies that favour specific technologies.

Tackling urban household energy transition, therefore, goes beyond switching from one technology to another. It requires a thorough understanding of technological development from an energy service requirement or household demand and consumption, rather than only focusing on the supply side, to inform sustainable energy transition. Further, consideration of socio-cultural, socio-political, gender and equity issues related to sustainable urban development is essential.

ENERGY TRANSITION IN THE CONTEXT OF SUSTAINABLE DEVELOPMENT

The concept of sustainable development has been widely discussed in the energy transition field since the Brundtland report, "Our Common Future" [42] and the Energy for a Sustainable World report [43]. Sustainable development focuses on the shift of perspective from economic development to consideration of economic growth as affecting society and the environment. Sustainable development is also neither a fixed nor a final state, but inherently a dynamic process [44].

Energy transition in the context of sustainable development has become important. The core argument in this conceptualisation is ensuring that low-carbon technology development is just, equitable and inclusive [45]. Meeting the targets of SDG7 on universal access to clean, affordable and modern energy requires assessing technology, not for its own sake, but as a clean energy technology to achieve energy justice related to distribution, recognition and procedures [46]. Some scholars have warned that low-carbon energy transition may not be any fairer or more just than the conventional energy systems they displace and may still constitute persistent inequalities, thereby inhibiting sustainable development [47].

Energy transition interventions should provide the energy needs of the current generation without compromising the ability of future generations to meet their needs. Measures relevant to supporting the monitoring and evaluation of sustainable urban energy transition interventions and their effect on equity, access and other justice-related issues become relevant. The International Renewable Energy Agency (IRENA) [38] highlights six drivers of municipal action on energy, namely (i) secure and affordable energy, (ii) economic development and jobs, (iii) social equity, (iv) climate stability, (v) air quality and health, and (vi) governance.

Other relevant concepts used to refer to sustainable energy transition include “net-zero economy” [48], green economy transition in which energy is a key sector, circular economy at industry and city level, smart cities, the Fourth Industrial Revolution and the Internet of Things. These concepts, although described from global and national contexts, tend to influence the urban planning vision, demonstrating the dynamic nature of energy transition.

ENERGY TRANSITION IN THE CONTEXT OF A DYNAMIC SYSTEM

Energy transition is inherently a dynamic system that is complex and governed by several cycles of feedback and long delays. Major uncertainties exist relating to individuals, energy technology, the entire system and policy-/decision-makers in the energy field [49].

The energy transition process is also characterised by nonlinear shifts that depend on endogenous factors. Further, energy policy developments, demand changes, political instability and dependency on energy increase the complexity of energy transition.

Energy transition needs to consider assessment methods that dynamically capture fragmented aspects in the urban planning context. Cajot and Schüler [15] highlight two assessment methods, namely simulation and optimisation, that support urban planning. The benefit of the simulation method is the ability to mimic the behaviour of a system and assess the effects of key indicators before actual implementation takes place. Although optimisation methods are also useful, this study proposes system dynamics to capture the dynamic aspects of urban energy transition.

Cajot and Schüler [15] highlight that simulation is only applied at the design phase of urban planning. However, it is possible to apply systems thinking and system dynamics throughout the urban planning process.

System dynamics, founded by Jay Forrester in the 1950s, is a computer-aided approach for strategy and policy design. Its overall objective is to make better decisions when confronted with complex dynamic systems. It provides the theory, methods and tools necessary to analyse dynamic problems arising in complex social, economic, managerial or ecological systems [50,51]. System dynamics is the same approach used in Meadow’s et al. [52] study on the limits to growth that showed the collapse of the global socio-economic system sometime in the 21st century if steps are not taken to lessen the demand on the earth’s carrying capacity.

Research on managing energy transition using system dynamics is not new. This kind of work dates back to the 1970s with the work of Naill [53] on managing energy transition in the US economy to search for alternatives to oil and gas. Much of the earlier work focused on a national scale or electric systems at a national level [e.g. 54-56] or the industry level [57], with a specific focus on the processes in electricity market liberalisation and deregulation [58]. Few system dynamics studies examined energy issues at an urban scale [59,60], especially to inform the expansion of energy infrastructures to improve access while reducing resource consumption through energy efficiency for urban households [61]. The developed SASETA shows the dynamic interactions relevant to support urban energy transition measures and inform urban energy planning.

URBAN ENERGY TRANSITION ASSESSMENT FRAMEWORK

The study developed a generic urban energy transition assessment framework to translate the concept described in Figure 2 into practical application, consisting of the SASETA, integrated with the urban planning and using systems approach. The SASETA consists of two phases: sustainable urban energy transition and urban energy transition assessment. Urban planning consists of the five phases described by Cajot and Schüler [15] and the systems approach consists of systems thinking and system dynamics (see Figure 3).

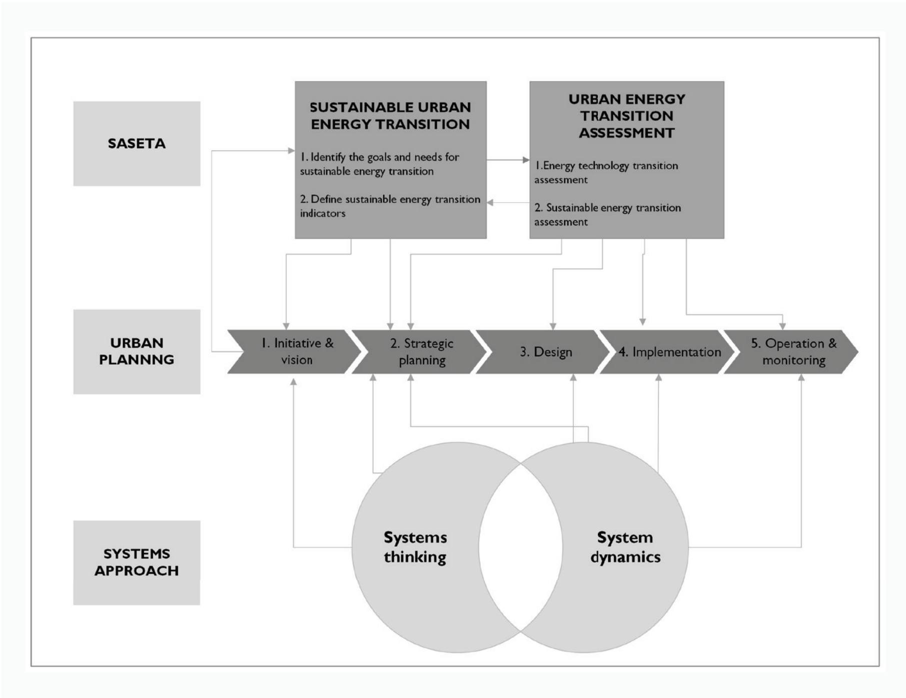

Figure 3: Generic urban energy transition assessment framework

Various authors have shown different steps of the system dynamics process [e.g. 51,62-66]. This study adapted Moxnes's [66] system dynamics process constituting two cycles. The first cycle consists of problem identification, hypothesis analysis and policy design, and supports the first three phases of urban planning, while the second cycle consists of implementation, supporting the last two phases of urban planning.

SASETA: SUSTAINABLE URBAN ENERGY TRANSITION PHASE

The sustainable urban energy transition phase in SASETA, constitutes identifying the goals of and needs for urban household energy transition and defining sustainable energy transition indicators to monitor the measures. The sustainable urban energy transition phase can be achieved using systems thinking tools to inform the initiative and vision, and the strategic urban planning phases.

At household level, although the needs and goals of technology choice are to fulfil energy services, these are also influenced by policy intervention in the provision of basic services. A particular concern of urban decision-makers in energy transition is to improve access, provide affordable and clean energy, and address socio-political aspects related to basic service provision, including gendered issues for the population living in informal urban settlements.

Indicators to define sustainable energy transition need to be relevant to the urban context and need to consider national and global policy trends driving energy transition. Sustainable cities' energy indicators, such as Energy Cities Sustainable Indicators [67], support measures for urban energy transition. However, coordination of the economy, society and environment with urban energy plays an important role in integrating energy at the core of urban planning. The generic energy transition assessment framework is aimed at identifying the urban energy indicators using the T21 framework, which makes energy explicit. With increasing awareness of societal aspects contributing to the success of energy transition [68], social, environmental and economic indicators need to be considered simultaneously.

Specific indicators that are related to urban household energy transition include (i) economic indicators such as gross value added (GVA), investment and employment, and energy affordability; (ii) societal indicators such as population, households and share of households by dwelling type; (iii) environmental indicators such as air emissions and health costs related to energy consumption; (iv) distributional social equity indicators such as categorisation of energy consumption by households or population group; and (v) access measures including households with access to electricity and use of other fuel types [38].

SASETA: URBAN ENERGY TRANSITION ASSESSMENT PHASE

The urban energy transition assessment phase in SASETA, aims to support two assessments. The first is energy technology transition, involving system dynamics model development to support strategic urban planning in the context of energy technology. The second assessment, sustainable energy transition assessment, incorporates the potential new technology, policy or intervention to support energy transition. It assesses the effects of the integration of the new technology or policy. This assessment involves the analysis and policy design phase of system dynamics modelling to support the design phase of urban planning. Further, the urban energy transition assessment phase supports the implementation and the operation and monitoring phases of urban planning using the adapted Moxnes [66] implementation phase that consists of planning action, taking action steps and continuously evaluating actions.

APPLICATION OF THE SASETA FRAMEWORK TO URBAN HOUSEHOLD ENERGY TRANSITION: DRAKENSTEIN MUNICIPALITY

Translating concepts into practice is essential for any framework to be useful as a decision support tool. The study demonstrated the application of the SASETA framework to support measures for urban energy transition. The focus was on a policy perspective to influence household energy transition within Drakenstein Municipality.

SUSTAINABLE URBAN TRANSITION FOR THE DRAKENSTEIN MUNICIPALITY CASE STUDY

Drakenstein Municipality is the largest economy in the Winelands district with a GVA of R19.8 billion in 2016 [69,70]. The Municipality had 300 991 people and 71 686 households in 2016 [71]. Approximately 90.3% of these households resided in a formal structure and the proportion of female-headed households was 34.1% [72]. Although 98.4% of Drakenstein Municipality households had access to electricity in 2016 [71], approximately 2 200 households[1] in informal settlements were still not connected to the grid. Energy needs in these households remained based on traditional fuels. A particular concern was the increasing illegal connections and the need to seek alternative energy technology solutions to improve access.

Drakenstein Municipality is one of the six municipalities in the Western Cape that can generate or buy its own electricity. The Municipality has a policy for embedded electricity generation adopted in June 2019 and has a co-generation tariff of 0.5077 rand/kWh [73]. The energy transition opportunities seen as key at the municipal level include small-scale embedded generation, energy storage and energy efficiency [74].

The Drakenstein Municipality policy documents incorporate national-, provincial- and local-level mandates and global trends. These documents include Vision 2032, the Integrated Development Plan, the Spatial Development Framework, Western Cape OneCape Vision 2040, the National Development Plan 2030 aimed to eliminate poverty

[1] Information from Mr Moses Mlangeni, Manager: Economic Growth and Development, Drakenstein Municipality.

and reduce inequality, and global trends related to energy transition such as urbanisation, technology, rising inequality and sustainability [69]. Although Drakenstein's economic growth strategy indicates the use of the systems approach [70], the consideration of energy is missing except when highlighted in the financial incentive and capital investment in electricity and gas, which were the fourth-largest investments in 2016. This seem similar to how the South African energy sector has historically focused mostly on the supply side of energy, with minimal attention given to the demand side and sustainability issues, such as where energy is being used, by whom, for what and how these needs or interventions impact social, economic and environmental sustainability [75].

Sustainable energy transition indicators depend on the economic, environmental, social and political context where energy transition is implemented. The indicator identification was informed by Drakenstein policy documents, IRENA [76], energy transition indicators and previous research on urban Africa indicator development [11]. Data limitations are often a significant obstacle to generating urban indicator sets, and this study was no exception. The following four criteria were used for final indicator selection:

- Indicators that were most relevant to urban energy transition
- Indicators that reflected South Africa and Drakenstein Municipality urban energy transition issues[2]
- Indicators encompassing environmental, social and economic spheres of sustainability
- The ability to quantify the indicators and data availability.

Ten indicators were compiled for the sustainable urban household energy transition assessment and are presented in Figure 4. They included three social indicators, namely population, households and share of households by dwelling type; economic indicators, namely GVA, cost of energy and household energy consumption; and four environmental indicators, namely total cost of fires, health cost of paraffin use, health cost of paraffin burns and health cost of paraffin ingestion.

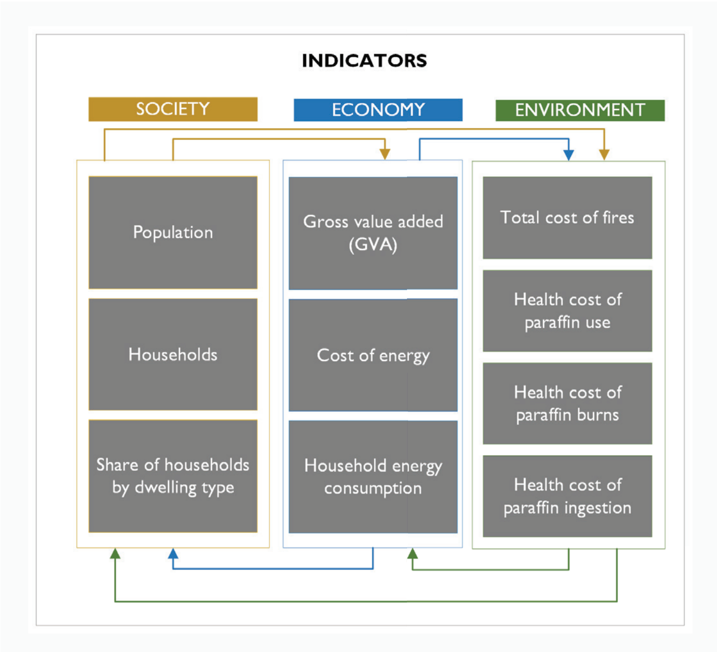

Figure 4: Illustration of relevant urban household energy transition indicators

[2] For example, the socio-economic profile provides indicators related to demographics, education, health, poverty, basic service delivery, safety and security, the economy and public infrastructure. There is no dedicated reporting on energy balance like the one on Cape Town.

URBAN HOUSEHOLD ENERGY SUSTAINABILITY ASSESSMENT IN DRAKENSTEIN MUNICIPALITY

To generate the indicators depicted in Figure 4, VENSIM software was used to develop a system dynamics model, with an adapted model structure in Bassi [77], consisting of six sub-models: economy, population, households, energy demand and consumption, energy affordability and socio-environmental impact.

Description of the sub-models

The economy sub-model consists of the GVA of Drakenstein Municipality. The economy sub-model generates indicators that relate to GVA, GVA per capita, electricity price and investment in electrification. In the South African context, the electricity price is exogenously determined. The economy sub-model influences the electricity demand and consumption and energy technology transition options either through investment in technological development and energy efficiency, or through subsidies/tariffs to motivate households to generate their own electricity.

The population sub-model provides demographic information about Drakenstein Municipality, which is crucial for urban planning and development related to energy transition. The population sub-model is broken down by age and sex, which both influence household energy behaviour patterns.

Households are a main driver of energy demand and the economy of the urban area. The household sub-model was categorised into five classes: formal electrified, formal not electrified, informal electrified, informal not electrified and backyarders. The factors that influence changes in households are both internal growth and migration from rural to urban areas.

The energy demand and consumption sub-model represents household energy requirements and consumption by dwelling type, energy services and energy fuel types. According to Sustainable Energy Africa [16], the residential sector in Drakenstein Municipality consumes 15% of the total energy. The household energy services evaluated were lighting, electronics, white appliances, heating, water heating and cooking. The energy sources in the model include biomass, paraffin, gas and electricity. The potential demand that can be serviced from off-grid renewables is built into the sub-model.

The energy affordability sub-model is crucial in supporting energy transition. The South Africa energy sector is characterised by high rising energy prices and a decreasing cost of renewables [74]. This observation is somewhat conflicting, but it is because the energy market price in South Africa is exogenously driven, rather than determined by energy market dynamics.

The socio-environmental impact sub-model represents the effects of energy transition on society and environment-related indicators. These impacts relate to health costs, carbon emissions, fires and job losses in other economic segments. Estimating the net effects of socio-environmental impacts indicates whether the energy transition interventions generate positive or negative overall effects.

Data sources and collection criteria

Data at an urban scale is a challenge, and this study was no exception. However, Sustainable Energy Africa [16] has been attempting to provide demand-led data, and Drakenstein was one of the secondary cities considered. The criteria for data collection in this study were the following:

- Drakenstein Municipality data would be used as a starting point. The population, economy and household indicators were based on Drakenstein Municipality data.
- If Drakenstein data were unavailable, relevant information from other Western Cape municipalities would be used. Parameters related to the demand for energy per household used measures from both Drakenstein and the City of Cape Town.
- If no data were available from Western Cape municipalities, South African-based data would be used.
- If no data were available for South Africa, international data would be used; if no data at all were available, calibration to estimate parameters would be used. The benefit of the modelling is that the structure is determined endogenously, and parameters whose data are missing can be added when it becomes available or validated through stakeholder engagements.
- The criteria used provided a balance between realistic and idealistic perspectives to demonstrate the application of the SASETA framework.

Validation

The model was validated and tested following Barlas's [78] three classes of validity tests: (i) structural validity tests, (ii) behaviour validity tests and (iii) policy implication tests. This study utilised the three validity tests. The model was further subjected to three questions proposed in [79,80] to validate the model structure and behaviour: (i) Are the structure of the model, its underlying structure and its parameters contradictory to the observed reality and/or obtained from expert opinion?, (ii) Is the behaviour of the model system consistent with the observed/hypothesised behaviour of the real system? and (iii) Does the model fulfil its designated task or serve its intended purpose?

Policy design

The scenarios developed were motivated by the need for achieving SDG7, which aim is to ensure access to affordable, reliable, sustainable and modern energy for all. However, estimating context-specific energy demand and consumption will be essential to provide insights into various options to achieve this goal.

Three scenarios were tested. The first was the business as usual (BAU) in which the current policy situation prevails. Economic development is emphasised, which in some ways does not favour sustainable transition. Relevant urban policy measures that relate to population, households and GDP for Drakenstein Municipality were presented.

The second scenario was an introduction of the energy subsidies policy. Energy subsidies can be pursued to achieve specific policy goals such as providing affordable energy for low-income members of society, correcting markets for unpriced externalities, inducing technology learning and driving down the costs of new technologies, reducing import dependence, enhancing energy security and creating new economic activity and jobs [81]. The energy subsidy hypothesis used in this study was informed by the COP26 Energy Transition Council, which aims at finding speedy solutions to support clean technology transition in the power sector by 2030. The hypothesis proposed the introduction of a 20% energy subsidy in 2022 and removal of this subsidy in 2025.

The third scenario was energy efficiency of an additional 1% implemented in 2022 and removed in 2025.

A model simulator was developed that could allow urban planners to interrogate the model features and energy transition dynamics.

WHAT HAPPENS TO POPULATION, HOUSEHOLD AND GROSS VALUE ADDED IN THE BUSINESS-AS-USUAL SETTING?

The population of Drakenstein Municipality is projected to reach 456 465 people in 2040, representing a 29.7% increase from 2021 (see Figure 5). The increased population implies that if the current situation prevails, the Municipality long term planning for household energy is for an additional 29.7% people.

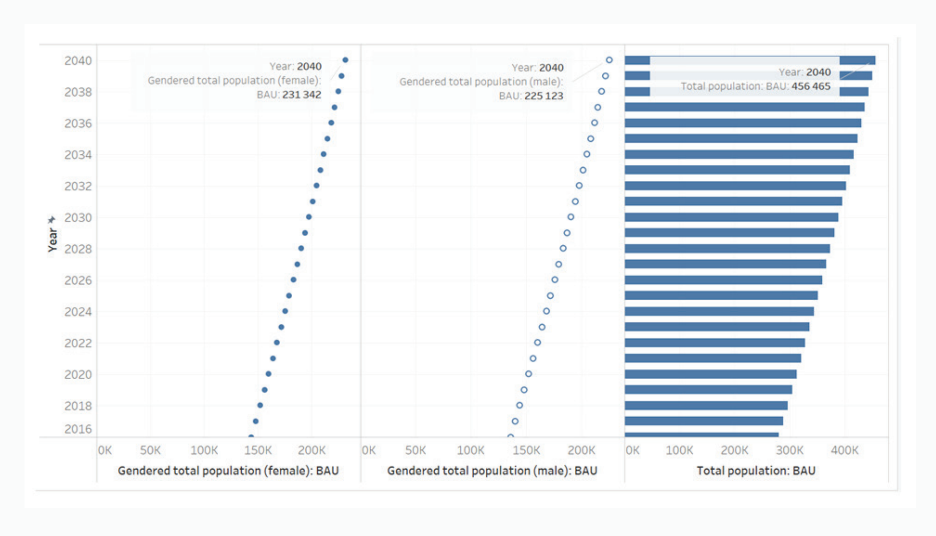

Figure 5: Population dynamics in BAU scenario, Drakenstein Municipality

Urban energy planning is generally informed by the number and types of households that exist. The results estimate the households to reach 110 344 by 2040, representing a 28.7 increase (Figure 6). All five dwelling types, namely formal electrified, formal not electrified, informal electrified, informal not electrified and backyarders, are increasing over the simulation period. However, the highest growth is observed in formal electrified (30.3%) and informal electrified (19.8%) dwellings.

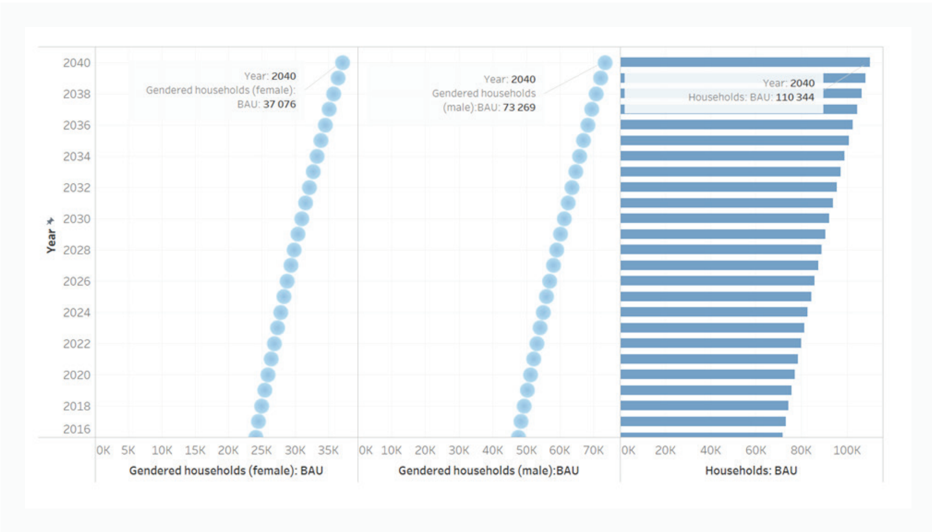

Figure 6: Household dynamics in BAU, Drakenstein Municipality

Similarly, the GVA increases by 28.7% between 2021 and 2040, reaching approximately R30.47 billion (Figure 7). Understanding the changes in the population, household and urban energy context informs policy in terms of whom to plan for and the financial ability of the urban economy to invest in clean energy technologies. In addition, measures of households by gender and household dwelling types support interventions that are gender-conscious.

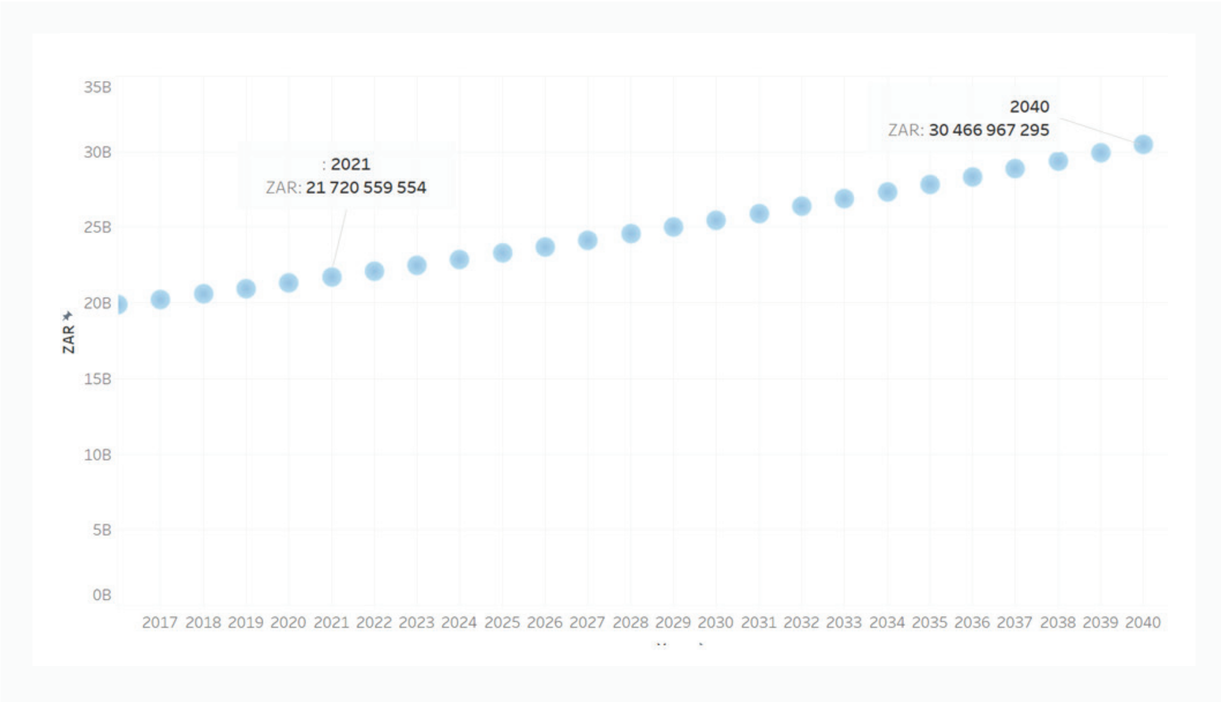

Figure 7: GVA dynamics, Drakenstein Municipality

HOW DO ENERGY SUBSIDY AND ENERGY EFFICIENCY INTERVENTIONS AFFECT HOUSEHOLD ENERGY TRANSITION?

Introducing energy subsidy or energy efficiency interventions has implications for energy costs and affordability, changes in household dynamics, energy consumption and externalities.

Energy costs and affordability by household dwelling type

The cost and affordability of energy are crucial to supporting energy transition. The introduction of an energy subsidy improves the affordability of energy sources in the short term, which in turn reduces the energy costs incurred by the different household dwelling types. However, electrified households benefit more from the energy subsidy than households without a grid connection (Figure 8). Such an intervention therefore results in increasing inequality and potentially rising illegal connections to fulfil unmet energy services. In the long term, the energy subsidy results in higher costs relative to the BAU scenario. In contrast, the energy efficiency scenario reduces the overall costs of energy relative to the BAU scenario.

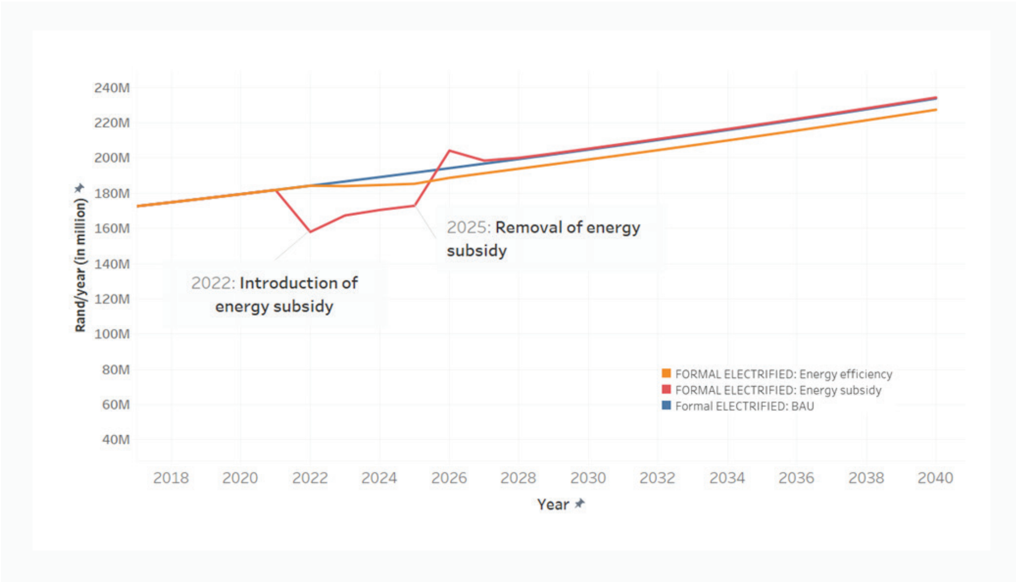

Figure 8: Effect of energy subsidy on energy cost and affordability on households in formal electrified dwellings, Drakenstein Municipality

Changes in households by household dwelling type

The introduction of an energy subsidy marginally changes the total number of households relative to the BAU scenario. However, an intra-dwelling shift in households occurs, whereby the share of households in formal electrified dwellings increases while it decreases in the other dwelling types (Table 1). The energy efficiency scenario marginally increases the share of households in formal electrified dwellings.

Table 1: Percentage changes in the share of household by dwelling type

Time (year)	2016	2017	2021	2022	2023	2024	2025	2030	2040
Share of households by dwelling type									
[FORMAL ELECTRIFIED]									
Energy subsidy	90.30%	90.31%	90.52%	90.68%	91.07%	91.30%	91.43%	91.54%	92.09%
BAU	90.30%	90.31%	90.52%	90.59%	90.65%	90.71%	90.78%	91.09%	91.70%
[FORMAL NOT ELECTRIFIED]									
Energy subsidy	0.10%	0.10%	0.10%	0.10%	0.09%	0.09%	0.09%	0.09%	0.08%
BAU	0.10%	0.10%	0.10%	0.10%	0.10%	0.10%	0.10%	0.09%	0.09%
[INFORMAL ELECTRIFIED]									
Energy subsidy	1.00%	1.00%	0.98%	0.96%	0.92%	0.90%	0.88%	0.87%	0.82%
BAU	1.00%	1.00%	0.98%	0.97%	0.96%	0.96%	0.95%	0.92%	0.86%
[INFORMAL NOT ELECTRIFIED]									
Energy subsidy	7.80%	7.79%	7.62%	7.50%	7.18%	7.00%	6.90%	6.80%	6.36%
BAU	7.80%	7.79%	7.62%	7.57%	7.52%	7.47%	7.42%	7.17%	6.68%
BACKYARDERS									
Energy subsidy	0.80%	0.80%	0.78%	0.77%	0.73%	0.72%	0.70%	0.69%	0.65%
BAU	0.80%	0.80%	0.78%	0.77%	0.77%	0.76%	0.76%	0.73%	0.68%

The implication is that the energy subsidy intervention creates attractiveness in the Municipality for the households to move to formal electrified dwellings, which ultimately generates a demand for formal households and energy needs.

The intra-dwelling household transition results in an increase in the demand for other fuel types, particularly the unclean fuel types, even though the proportion of households in informal dwellings and backyarders declines by 2040. Examining households by dwelling type can be useful in understanding household energy demand behaviours and requirements and can reveal better paths towards sustainable household energy transition.

Changes in total energy consumption

The changes in total energy consumption Table 2 indicate that the household energy services are not met with electricity. In the short term, the energy subsidy scenario leads to an increase in consumption of all energy sources – biomass, electricity, gas and paraffin – because energy affordability is improved. It also illustrates that urban households generally tend to fuel-stack and that improving affordability increases energy consumption. In the long term however, consumption of paraffin continue to increase after the removal of the energy subsidy. Although the Drakenstein Municipality statistics indicate 98.4% access to electricity, it is not fulfilling the household energy services, because grid connection does not equate to fulfilled energy services. A shift from grid connection as an indicator for sustainable energy for all to fulfilled household energy services requires exploration in energy transition research and practice.

Table 2: Changes in total energy consumption by energy source in terajoule per year

Time (year)	2016	2021	2025	2030	2040
TOTAL BIOMASS CONSUMPTION					
Energy subsidy	34.62	36.47	38.95 ↑	39.37	43.78
BAU	34.62	36.47	38.03	40.06	44.50
TOTAL ELECTRICITY CONSUMPTION					
Energy subsidy	548.52	583.86	685.41 ↑	658.03	750.53
BAU	548.52	583.86	615.16	656.78	749.22
TOTAL LPG CONSUMPTION					
Energy subsidy	10.41	11.04	12.60 ↑	12.28	13.91
BAU	10.41	11.04	11.60	12.33	13.96
TOTAL PARAFFIN CONSUMPTION					
Energy subsidy	15.37	16.15	16.87 ↑	17.24	19.05
BAU	15.37	16.15	16.79	17.64	19.45

In contrast, the energy efficiency scenario leads to an overall reduction in energy consumption relative to the BAU scenario. For example, paraffin consumption decreases by 5% relative to the BAU scenario, while electricity consumption decreases by 2.86%.

Socio-environmental impacts and externalities

The major socio-environmental impacts include the cost of fires and health costs related to paraffin use. These results in Table 3 highlight the concerns that the transition to clean energy technologies may not be fairer and may result in inequalities. Although the total cost of fires decreases the most in 2025, the health costs related to paraffin use, burns and ingestion increase.

Table 3: Socio-environmental impacts and externalities in Rand per year

Time (year)	2016	2021	2025	2030	2040
Externalities					
TOTAL COST OF FIRES					
Energy subsidy	422962	443837	456755	470773	517908
BAU	422962	443837	460820	482945	530416
HEALTH COST OF PARAFFIN USE					
Energy subsidy	68825	72330	75536	77232	85316
BAU	68825	72330	75216	78987	87120
HEALTH COST OF PARAFFIN BURNS					
Energy subsidy	46103	48451	50599	51734	57149
BAU	46103	48451	50384	52910	58358
HEALTH COST OF PARAFFIN INGESTION					
Energy subsidy	57626	60561	63245	64665	71434
BAU	57626	60561	62978	66135	72944

The implication for urban energy planning is that energy access for all is not well understood and is systemic. Some indicators that rely on energy access based on the supply side may not be a correct representation of the observations in households. Further, interventions aimed at supporting improvement in achieving energy access for all might result in unintended socio-environmental impacts. Urban energy planning would require examining the cross-sector effect of interventions to support just energy transition. In addition, understanding household behaviours within a household boundary is essential.

POLICY INSIGHTS FOR URBAN HOUSEHOLD ENERGY TRANSITION

Subsidies are promoted to support energy transition [80], and their positive effect is the reduction of household energy costs. However, the benefit is largely more observed in households that have access to electricity than in households without electricity access. Subsidies may therefore exacerbate rather than improve inequality. As an example, within the South Africa context, free basic electricity mostly applies to households that are connected to the grid.

In addition, the reduction in energy costs in the energy subsidy scenario improves affordability, which increases energy consumption and higher externalities – this is the rebound effect. For households that are not electrified, improved affordability increases consumption of unclean energy fuels. In contrast, an increase in spending improves the Municipality's economic growth, which in turn can lead to the attractiveness of the Municipality for migration and hence an increase in backyarders – an unintended consequence.

Applying a single solution may not be favourable to sustainable urban household energy transition. The study recommends combining different policies to promote inclusive, just and sustainable household energy transition. For example, combining energy efficiency with off-grid solutions can minimise reliance on subsidies for electricity, increase affordability and reduce the rebound effects.

CONCLUSIONS

Achieving sustainable energy for all is an immediate and a future challenge in urban households, especially with massive urbanisation expected to take place in Africa between 2030 and 2050. The current and expected change in urbanisation presents a complex challenge to urban policy- and decision-makers in energy transition pathways. Providing scientific support to urban energy planning requires consideration of the systemic nature of energy transition in the context of technological development and sustainable development.

This study developed a generic conceptual framework, SASETA, to support sustainable energy transition assessment in an urban context. The main contribution of the framework was the consideration of social, economic and environmental factors concerning sustainable energy transition indicators in a manner that could be customised to and applied in different urban case studies. The study further demonstrated how to translate the SASETA into practice using Drakenstein Municipality as a case study. Key insights relate to understanding the context in which urban energy transition is taking place, developing relevant indicators to support policy and providing insights into interventions that produce counterintuitive results.

The policy implication for urban energy transition planning in Africa is to consider the systemic nature of the interactions between energy technology development and sustainable development. Approaches that provide decision support to urban policy are necessary in monitoring indicators related to SDG7 on energy and SDG11 on building sustainable cities and communities.

The developed system dynamics model is not without limitation. For Drakenstein Municipality, the major limitations related to missing data regarding household energy consumption and socio-environmental impacts. In addition, the demonstration of the application of the SASETA would require further engagements with Drakenstein Municipality to test it application within the entire urban planning phases. Despite these limitations, the study attempted to demonstrate how a systems approach could support measures for urban household energy transition. Future work will involve testing the integration of the entire urban planning phases and application to other urban case studies. A key aspect is also extending the gendered energy transition measures.

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