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When justice narratives meet energy system models: Exploring energy sufficiency, sustainability, and universal access in Sub-Saharan Africa

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ABSTRACT

This study presents a socially sustainable energy system narrative that is based on two pillars: energy sufficiency as the universal energy system goal and the energy-justice-based principles of energy access provision. The constructed narrative provides an operational theoretical foundation for choosing energy provision technologies that can be considered socially sustainable and offers an alternative to prioritizing the cost-minimization mindset. Through a case of household electricity provision in Sub-Saharan Africa, the narrative is applied as a set of theoretical assumptions for energy system modelling. The presented model explores to what extent different combinations of centralized, decentralized, fossil-fuel-based and renewables-based electricity access provision are compatible with the principles of socially sustainable energy system design. Comparing three different scenarios of electricity access provision using centralized and decentralized fossil-fuel-based and renewables-based electricity generation technologies, this study concludes that decentralized and renewables-based electricity generation mixes are associated with higher cost but also with greater social sustainability benefits. By combining a conceptual narrative of socially sustainable energy systems with system dynamics modelling, theoretical work on sustainable energy system development is bridged with the energy system modelling practice. The research design of this study may interest scholars working on the theoretical development of sustainable energy system principles and their application in modelling as well as energy system modellers.

1. Introduction

Today's global energy system is in crisis. Some parts of the world suffer from a lack of energy access, leading to insufficient provision to meet human needs [1]. At the same time, other regions experience excessive energy consumption. A long lists of other problems associated with the global energy system design includes unaffordable energy for consumers, pollution, climate change, economic and political inequalities [2,3].

1.1. Importance of energy system narratives and energy system goals

Dealing with energy problems is a complex task, which calls for novel methodological approaches and new ways of thinking. Today, a great amount of intellectual and political efforts are directed at solving the energy crisis and designing solutions for reaching a sustainable state of the energy system. However, these efforts often miss a fundamental component – questioning the current energy system narrative [4].

The concept of narrative is not explicitly addressed in energy system research. It is, for example, much more present in alternative-to-growth economies research field (e.g. degrowth, post-growth, sufficiency economy), where elaborated social narratives act as detailed scripts on how the economies of the future could look like [5]. Having similar types of narratives – detailed scripts of what an energy system in the future could look like – could help faster and more sustainable energy system transformations, broadening the perspectives of re-thinking and re-imagining the energy systems of the future. However, even if narrative as a term is not widely present in the energy discourse, there is still an implicit social narrative defining what an energy system is and how it should be organized.

Today, despite acknowledging the complexity of the energy system crisis, it is still common to think of the energy system as a techno-

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economic one, organized around cost-minimization principles. Within such a narrative, sustainability transitions would be primarily techno-optimist. This is reflected in energy research, which has been dominated by research questions related to technological advancements and cost-minimization objectives [6]. However, it is crucial that today all sustainability aspects of the energy system, including biophysical, economic and social components, are explicitly included in the dominating energy system narrative. As soon as they are included, solutions for addressing the multiple dimensions of the energy system crisis would become more diverse, thereby going beyond cost-minimization thinking.

Among all the sustainability components in the currently dominating energy system narrative, the social sustainability component is the weakest one and in the current energy systems literature, the social sustainability dimension of the energy system is largely missing. As a result, there is considerable potential for the social sciences to make a contribution to the sustainable energy system research agenda [7,8]. Calls for social science and interdisciplinary approaches in energy system research [8,9] can help fill the social sustainability gap in the energy system narrative. This study is one of the attempts to fill this gap. In this paper, a socially sustainable energy system (further – SSES) narrative is constructed and applied, and the process of its construction and application is discussed.

Any social narrative, including an energy system narrative, starts with defining the goals. In this case, it starts with defining energy system goals. Such goals set the general direction of energy system development that needs to be defined prior to designing any sustainable solutions. Sustainable energy principles that allow for achieving the goals of a SSES constitute the second component of the energy system narrative as it is defined in this study. Such principles are the underlying rules that help to guide technological choices for SSES design.

Discussion on what are the energy system goals is underrepresented in the public and research discourse. Most commonly, the context in which energy system goals are discussed and are named as such is the context of the Sustainable development Goals (SDGs) in particular SDG13 and SDG7. SDG13, climate action, is a key driver behind energy system development whereas SDG7 directly states the overall objectives of sustainable energy system development. SDG7 is widely used as a reference for sustainable energy system research and planning [6,10]. It mentions the targets and indicators for energy system development by 2030 (e.g. providing universal energy access, prioritizing energy efficiency, increasing use of renewable energy sources) [11] and provides a good starting point for designing a sustainable energy system narrative. However, SDG7 is not sufficient for formulating a SSES narrative. Being specific about aspects of a desirable energy system design, it does not give a holistic understanding of what a sustainable energy system is and does not provide any concrete vision of how desired energy system might look like. Therefore, SDG7 is not sufficient for formulating a SSES narrative. To complement the SDG7 and to fulfil the purpose of formulating SSES narrative, this study recruits the concept of energy sufficiency. Further in the paper, energy sufficiency is defined as a maximum desired amount of energy per capita to be produced and consumed and is discussed as the universal sustainable energy system goal.

1.2. Energy access provision

Securing universal access to high-quality energy, including electricity access, is among the top sustainable development priorities. This is explicitly addressed in SDG7 [11]. According to the IEA, access to electricity is defined as “a household having reliable and affordable access to both clean electricity, which is enough to supply a basic bundle of energy services initially, and then an increasing level of electricity over time to reach the regional average” [12]. Worldwide, more than 1 billion people are living today without access to electricity (Fig. 1). When it comes to the number of people lacking electricity access, the situation in the Global South [13], in particular in Sub-Saharan Africa (SSA), is the most critical (Fig. 1).

Active measures at the international level to provide electricity access have taken place over the last two decades [14] (Fig. 2). However, the fact that energy access provision has been implemented does not mean that energy access provision solutions have been chosen in accordance with sustainability principles. Based on Fig. 2., which depicts the energy resources used to provide electricity access in developing countries, it is evident that most electricity access since 2000 has been fulfilled using fossil fuels. Providing electricity from fossil fuels is questionable from an environmental sustainability point of view [15]. Yet some argue that the negative environmental effects associated with the use of fossil fuels can be counter-balanced by the social benefits of electricity provision [16].

Evaluating whether in the Global South the use of environmentally unsustainable solutions could indeed be justified by its social benefits, demands the development of a normative framework, providing criteria to classify different technological solutions as either having the potential to be socially sustainable or unsustainable. SSES narrative is aimed to be an example of such a normative framework.

1.3. Methodological contribution and research questions

The main methodological objective of the paper is to bridge social science advancement in sustainable energy research [7] with the practice of energy system modelling [17], to contribute to the methods of combining quantitative and qualitative approaches when designing sustainable energy systems [18].

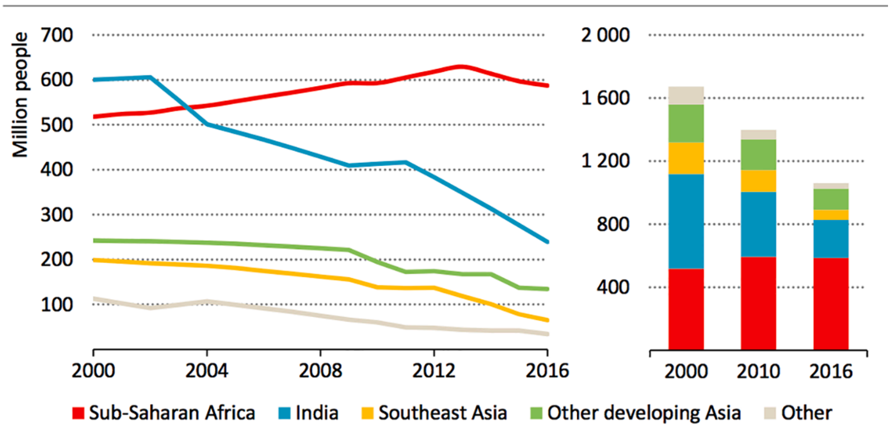


Fig. 1. Population without access to electricity by region (Source: IEA [12] World Energy Outlook-2017 Special Report: Energy Access Outlook. All rights reserved).

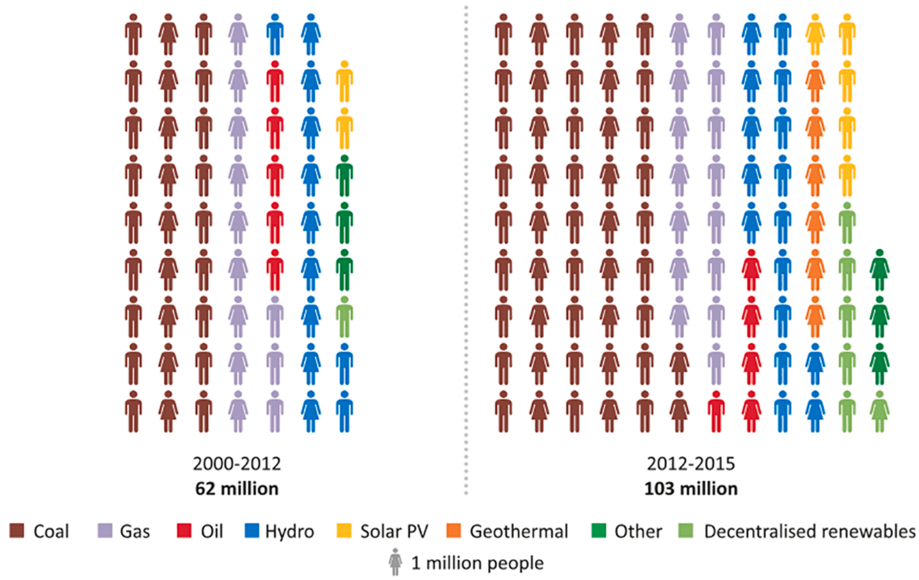


Fig. 2. The annual number of people gaining electricity access by fuel type in developing countries region (Source: IEA [12] World Energy Outlook-2017 Special Report: Energy Access Outlook. All rights reserved).

The theoretical part of this paper aims to contribute to the literature on social sustainability principles in energy system design by developing a framework for understanding how a SSES could be defined, and what the principles of a socially sustainable energy provision could be. Development of this framework, apart from applied, operational objectives aiming to incorporate energy justice framework into the principles of SSES design, pursues a purely theoretical objective aiming to identify connections between energy sufficiency and energy justice theory. This can contribute to the theoretical development of the energy justice field, where a gap in understanding between energy justice and energy sufficiency has been identified [19,20].

The modelling part of this paper provides a case of how theoretical SSES narrative can be integrated into the energy system modelling practice. This approach provides an instrumental value for energy policy-making and, particularly, for designing policies for energy access provision.

Energy justice theory [21,22] is the main conceptual instrument applied in the theoretical part of this study for formulating a socially sustainable energy narrative. It is used as the core operational framework for formulating the principles of socially sustainable energy provision. System dynamics [22] is the main method used in the modelling part of this paper.

The main research questions of this study are as follows:

(1) How SSES narrative can be defined and what are the key components of it?
(2) What are the systemic implications of incorporating SSES narratives into energy system modelling and planning?

To answer these research questions, this study presents a design of SSES narrative and applies it to the case of household electricity access provision in SSA until 2040.

This study consists of 7 parts. In part two of the paper, the main components of the theoretical framework of a SSES narrative are discussed. Part three presents the theoretical results of operationalizing the conceptual framework for constructing the narrative. Part four provides details of how modelling is connected to the theoretical work at the different stages of the modelling process. Part five gives an overview of the model structure, including its qualitative and quantitative modelling phases. Part six presents the results of the three different simulation scenarios and discusses them in the context of socially sustainable energy policy design. In part seven, the conclusion is provided.

2. Theoretical framework

In the theoretical part of this study, the energy system and energy system goals are discussed at a global scale, with the aim to understand the universal principles and underlying dynamics of energy system design as it transitions towards social sustainability. This section aims to establish a theoretical basis for determining the goals of a SSES.

2.1. Systems goal-setting. Defining energy system through the human needs' lens

This study departs from the premise that energy does not have an intrinsic value and plays an instrumental role in creating opportunities for meeting human needs [23]. The energy system, correspondingly, is a socio-technical structure designed to provide energy for meeting human needs. The way an energy system is defined determines its goals and the types of socio-technical structures that need to be designed to meet them. For example, desired and feasible technological solutions for the energy system aimed at providing energy services for industrial or military purposes would be different from the solutions oriented at meeting basic human needs. At the same time, an energy system that has as its main goal the meeting of human needs would not necessarily exclude energy use beyond this purpose. However, in the latter case, energy use that exceeds the direct and indirect amount of energy needed for meeting basic human needs would be considered a secondary priority.

Theoretical assumptions behind the arguments provided in this paper are based on capability theory assumptions [24-26].

2.2. Energy sufficiency

Energy sufficiency is discussed in this study in the context of a SSES narrative. As a term, it means the possibility of having enough affordable energy [27]. However, there is no universal definition of energy sufficiency, as well as no universal agreement on how much energy can be considered sufficient [28].

This paper discusses the energy sufficiency concept from both biophysical and social sustainability point of view. However, the main focus is on the social part of energy sufficiency, since the literature and available discussion on this topic is very limited.

The authors already explored biophysical aspects of energy sufficiency on a theoretical level, in the context of the Steady State of Energy concept [29]. Based on the results of that study, energy sufficiency was defined as a universal energy system goal compatible with biophysically sustainable energy system development in the long term.

When the energy sufficiency concept is applied to the Global South, it is most commonly used in the context of a minimum amount of energy services to be provided to satisfy basic human needs [19]. The context of reaching the goals of energy sufficiency in the Global South usually implies that it is desirable to have a continuous growth of energy supply and energy consumption per capita (see e.g. the energy access definition at International Energy Agency [12]).

In the Global North context, energy sufficiency is usually associated not only with a minimum but also a maximum amount of energy to be consumed. Since it is implied that the Global North already has a sufficient amount of energy per capita, for sustainability reasons there should be a cap imposed on individual energy consumption to avoid excessive energy use [30,31]. In this study, for both the Global North and the Global South, energy sufficiency is associated with the minimum and maximum limits of a desirable amount of energy consumption per capita.

This paper argues that energy sufficiency, with both minimum and maximum limits, is desirable from a biophysical as well as from a social sustainability perspective. While biophysical arguments supporting energy sufficiency are rather straightforward [32,33], social sustainability ones lack theoretical justification. The literature exploring this topic is very limited. One of the recent prominent attempts to provide argumentation for the inevitability of an "energy descent future" was made by Samuel Alexandra and Joshua Floyd [34]. There, the authors provide argumentation for biophysical and socio-technical limits for energy system growth (i.e. carbon budget, limited technical potential for renewable energy supply) and call for designing new socio-technical imaginaries of alternative-to-growth energy systems. According to the authors, the sooner humanity accepts the inevitability of a post-growth energy future, the higher chances for successful energy system transformation and for avoiding undesired socio-economic and political consequences globally. Another attempt to connect undesirable social dynamics with continuous energy system growth has been done by Illich [35]. In his work, Illich connects continuous growth in per capita energy consumption with the inevitable increase in power imbalances in society and the rise of inequality. He explains the undesired dynamics of energy system growth by contrasting a high energy society with a low energy society. In the former case, infrastructure is designed in ways encouraging excessive energy consumption and preventing people from access to essential services without consuming a certain amount of energy. Long commutes from home to work or urban planning which makes it impossible to buy food without using a car are examples of high energy society infrastructure. Such infrastructure design would necessarily lead to the emergence of disadvantaged groups of people, for whom access to essential services would be unaffordable due to high energy cost. In contrast, a low energy society that includes maximum limits when considering infrastructure and broader societal design aims to keep entry energy requirements for accessing basic social services low, thus minimizing barriers for access to social services for all social groups.

The argumentation provided by Illich was built on the societal organization and available technologies available in the 1970 s, and thus can be criticized. However, considering the limits to 100% renewable energy transition within the context of growth [36,37], a shift to fully renewables-based energy provision cannot be seen as the solution for preventing undesired biophysical and social dynamics. Therefore, Illich's arguments are still valid to explore, especially in the context of questioning the growth mindset dominating the current energy systems narrative. It is worth pointing out that this study does not argue that any increase in energy consumption and energy supply beyond a sufficiency level is undesirable. What this study argues is that having an energy sufficiency mindset as the energy system goal helps to shape a SSES narrative, leading to a more democratic and fair energy system design.

2.3. Energy justice theory

Energy justice theory provides an elaborated up-to-date framework that aims at providing analytical and conceptual tools for designing energy systems according to social justice principles [22,38].

A minimum amount of energy for satisfying basic human needs is connected to every human's entitlement to a minimum amount of energy. This statement is grounded in prohibitive and affirmative energy justice principles which derive from the assumption that everyone is entitled to basic goods to develop their human capacities [23]. Considering that basic goods cannot be produced without energy, everyone automatically becomes entitled to the amount of energy required for basic goods' production. This way, prohibitive and affirmative energy justice principles clarify the underlying aim of an energy system, where it has an instrumental value to help in meeting human needs, and justify why having the minimum limits of a sufficient amount of energy is essential. In this context, a sufficient amount of energy includes direct and indirect household energy consumption. The way energy sufficiency is discussed in this study emphasizes that meeting human needs is the main reason why an energy system is needed in society, where individuals and households naturally become the principal beneficiaries of the energy services.

The energy justice literature defines three pillars of energy justice: recognition, distributional and procedural justice [23,38,39]. Below, each of these pillars is discussed in more detail and in connection to energy sufficiency.

Recognition justice pillar's main role is defining who must be the priority beneficiaries to receive energy services [22]. In the context of this study, the recognition justice pillar defines priority beneficiaries to be provided with a sufficient amount of energy. Meeting human needs is the main reason why an energy system is needed in society and thus individuals and households naturally become the principal beneficiaries of the energy services. Direct and indirect household energy consumption is thus a primary priority for energy system development.

Additionally, recognition justice emphasizes the importance of providing energy services to the most disadvantaged actors [38,40]. Considering the lack of energy provision in the least developed world regions, individuals and households from the Global South would be at the top of the list of the sufficient energy provision beneficiaries. Consequently, from this pillar's perspective, energy access provision for the Global South should be considered a higher priority for global energy policy than energy transition is in the Global North. As for the households from the Global North (most of whom already have access to a sufficient amount of energy), as well as industrial and non-household energy consumers worldwide, they would be placed lower down in a hierarchy of energy service beneficiaries, especially those whose activity is not related to producing goods and services that help to satisfy basic human needs. It is worth mentioning that, in this study, the socially sustainable provisioning principles derived from the recognition justice pillar are based on the assumption of a regional divide between the Global North and the Global South, which does not take into account local contexts and inequalities existing within developed regions of the world [41,42]. For example, the households in the Global North that are not provided with a sufficient amount of energy will still be equally prioritized as the households in the Global South.

Distributional justice pillar is related to ensuring an equal distribution of cost and benefits in the energy system [22]. In the context of universal energy sufficiency for the Global North and the Global South, distributional energy justice would act as guidance to monitor the balances of resource and technological exchanges connected to energy access provision and energy transition policies. In particular, distributional justice would aim to prevent imbalances between the energy system cost and benefits associated with the choice of energy resources, technological solutions and financial mechanisms at local, regional and international levels.

Procedural justice pillar has to do with understanding how decisions about energy system design are made and how fair the procedures related to energy production and consumption are [22]. To ensure the highest inclusivity of decision-making, procedural justice, ideally, needs to be realized at a local scale. However, on a conceptual level, local level decision-making contradicts the idea of having a universal energy system goal, which can result only from a centralized decision-making process, provided that there is full decision-making autonomy at local levels. The idea of universal energy sufficiency implies that there is a universal normative amount of energy per capita decided upon in a top-down manner. From a distributional and recognition pillars perspective, there are no contradictions related to energy sufficiency. However, from a procedural justice perspective, defining a sufficient amount of energy is supposed to be the result of a democratic and participatory decision-making process, taking place locally [43]. This means that individuals and communities might potentially agree on very different amounts of energy that can be considered sufficient. This would apply to both minimum and maximum levels of sufficiency. According to the procedural justice principle, everyone should be able to decide locally how much energy is sufficient within biophysical limits. In this context, energy justice theory contradicts the principle of energy sufficiency as a universal energy system goal. The contradiction between energy sufficiency and the procedural energy justice pillar originates from a misalignment between the notion of universal basic human needs and procedural justice. The idea of universal energy sufficiency derives from the premise of universal basic human needs [44,45]. Therefore, solving the dilemma between universal energy sufficiency and the procedural energy justice pillar requires an elaborated discussion on the procedural aspects of decision-making related to satisfying universal basic human needs. Solving this dilemma, however, is beyond the boundaries of this study.

3. Operationalizing theory for SSES narrative

In this part, the concept of energy sufficiency and the energy justice pillars are operationalized for developing the second part of a SSES narrative – the energy provisioning principles. A hypothetical application of these principles is then used to choose between different technologies for energy access provision.

In Table 1, the three energy justice pillars (i.e. recognition, distributional, procedural) are connected to specific energy provision principles, which are derived from those pillars. These principles in turn are juxtaposed with the different types of energy provision technologies. To reach the goal of universal energy sufficiency, one needs to make sure that technological solutions associated with energy transitions are chosen and designed in line with social sustainability principles. The technologies presented in the table are on a highly aggregated level (i.e. small-scale fossil fuels, small-scale renewables, large-scale fossil fuels, large scale renewables). They do not specify particular types of energy resources or the technology used. The main aim of connecting socially sustainable principles of energy access provision with the energy provision technologies is to reveal how the principles could be used to demonstrate the types of energy provision that are most and least compatible with SSES design. A detailed discussion on the process of deriving energy provision principles from the energy justice pillars is provided below.

3.1. Operationalizing recognition justice pillar

This pillar prioritizes basic-needs-oriented energy provision for individuals and households in the context of reaching the energy sufficiency goal. Energy provision principles derived from the recognition justice pillar emphasize the importance of technological solutions that would be customized to the needs and living conditions of the energy service beneficiaries.

Within this mindset, technological solutions for lower energy demand would be prioritized over those that require fulfilling higher energy demand (Table 1: 1.1.). Energy provision within the energy sufficiency goal would have different implications than energy provision under growth-driven assumptions. In the latter case, it is often implied that an increase in energy access for households and decrease of energy poverty is derivative of industrial energy provision and economic growth and is driven by the following causal chain: energy access provision for industries – economic growth – household income increase – energy affordability for households – lack of energy poverty [46]. According to this logic, the preferable criteria for choosing energy

Table 1
Principles of socially sustainable energy provision based on the energy justice pillars.

Energy justice pillar	Energy provision principle	Small-scale Fossil Fuels	Small-scale Renewables	Large- scale Fossil fuels	Large- scale Renewables
1.Recognition justice pillar	1.1. Technological solution allows for low energy demand and absence of high energy consumers in the system	yes	yes	no	no
	1.2. Technology allows for prosuming	no	yes	no	no
	1.3. Technology can be associated with the intermittency of energy supply	yes/no	yes	no	yes/no
	1.4. Technology can be accessible on the community level for direct provision for households	yes	yes	no	no
	1.5. Technology can be accessible in remote rural areas with no access to centralized energy systems	yes	yes	no	no
2.Distributional justice pillar	2.1. Technology allows for minimizing dependencies between the Global North and the Global South	yes/no	yes/no	no	no
	2.2. Technology can contribute to community self-sufficiency and can create community co-benefits	yes/no	yes	no	no
	2.3. Technology depends on energy resource that is geographically widely available	no	yes	no	yes
3.Procedural justice pillar	3.1. Technology can be compatible with alternative-to-growth business models	yes	yes	no	no
	3.2. Technology allows for maximizing the use of locally available resources, technologies, expertise	no	yes	no	no
	3.3. Technology is associated with a low risk of creating power imbalances in the energy system	no	yes	no	no
	3.4. There is a low risk of stranded assets associated with the technology	yes	yes	no	yes/no
	3.5. Technology allows for relatively fast installation of generating capacities	yes	yes	no	yes/no

technologies would be rather large-scale energy technologies based on cost-minimization parameters, with no intermittencies in energy supply and possibilities to increase energy generation capacities in the future. In contrast, when an energy system prioritizes meeting basic human needs, small-scale technological solutions could be chosen (Table 1: 1.3; 1.4), where the flexibility of demand and an increase in generation capacities occurs without intermittency being a major concern. This is because the patterns of energy supply for satisfying basic needs is less demanding in terms of requiring an uninterrupted energy supply than energy-dependent production processes [47].

Recognition of households as potential energy prosumers (not only as energy consumers but also as energy producers) is another important component of this pillar (Table 1: 1.2). Prosuming implies the possibility for a household to produce energy autonomously. The most compatible prosuming technologies are, for example, solar PV and wind energy. Once the technological infrastructure for harvesting solar and wind energy are acquired, further energy generation becomes fully accessible and affordable for a household. In contrast, fossil-fuel-based energy generation technologies (e.g. a diesel generator) are not suitable for prosuming, because energy generation, in this case, would require ongoing fuel purchases, limiting the prosuming autonomy of a household. Typically, in a fossil-fuel-based energy system, an actor in the energy system has to accept either the role of energy producer or energy consumer [37]. Overall, energy prosuming would encourage local, community-based energy provision and local autonomy in decision-making related to energy system design, together with generating other co-benefits on a community level [37].

Additionally, technological solutions for energy provision need to take into account the energy needs of rural households, especially those living in remote areas (Table 1: 1.5). In the context of energy access provision in the Global South, this group of energy consumers is especially vulnerable [12].

3.2. Operationalizing distributional justice pillar

Aiming to prevent imbalance between energy system cost and benefits related to the choice of energy resources, technological solutions, and financial mechanisms on local, regional and international scales, the distributional justice pillar is primarily driven by the logic of fostering local/regional self-sufficiency. To discuss energy provision principles within this pillar, the terms energy affordability and energy availability are employed. These terms are widely used in the energy policy context [11] and this study re-interprets them. Here, energy is considered to be affordable if it is locally affordable and considered to be available if it is locally available (Table 1: 2.2). Local energy availability in turn would be defined not only by the availability of the energy resources but also by the availability of the means of energy production such as technologies, professional expertise and financial resources. The understanding of energy affordability is in line with the depiction of McCauley [48], who argues that affordability needs to account for a community's capability for acquiring the technologies and knowledge needed. Prioritizing regional self-sufficiency is also the way to avoid creating a technological, monetary, resource, and institutional dependencies between the Global North and the Global South (Table 1: 2.1). Understandably, absolute localization of energy access provision would be unrealistic, especially considering international knowledge and ecological flows embedded in technologies [49]. However, aiming to maximize local energy availability and affordability should be a priority (Table 1: 2.3).

When it comes to the choice of energy resources in the context of the distributional justice pillar, fossil fuel distribution is much more geographically concentrated than renewables. However, this is true for the physical resource part. As for the technologies, when considering know-how and the financial mechanisms related to different energy provision technologies, the difference between renewables' and fossil fuel distribution becomes more ambiguous. There is, in particular, a resource mining part related to the harvesting technologies for some of the renewables [36,50] that is often missing from the discussion on biophysical and social complexities associated with different renewable energy sources. This can be a source of new energy system injustices within energy futures where most of the energy provision is renewables-based [48,51]. For example, a local community might benefit from locally available and renewable geothermal energy. However, the high cost of exploration and extraction may result in the local community not being able to afford to harvest the geothermal resource for their own benefit. Large-scale development of the resource similarly may not benefit the local community if it is not equipped to receive electricity from the electric grid [52].

3.3. Operationalizing procedural justice pillar

This pillar deals with the procedures and overall principles of SSES design. The procedures associated with the procedural justice pillar are important for creating the conditions necessary for activating the recognition and distributional pillars. Avoiding the creation of power imbalances in the energy system, as well as enabling community-trust-building, are the main driving forces of the procedural justice pillar.

Procedural justice should be oriented at creating conditions for producing and consuming energy in ways that do not drive winner and loser dynamics between the actors in the energy system (Table 1: 3.3). Within this pillar, the term energy access is employed. Similarly to re-interpreting energy availability and energy affordability, here, energy access is re-interpreted. In this context, energy access relates not only to the physical energy services for consumption, but also to the means of energy production, including institutional, infrastructural, monetary, and technological aspects (Table 1: 3.2). In the context of the energy sufficiency goal and in line with prioritizing community access provision, it is important to have access to diverse business models and forms of organizing energy production (Table 1: 3.1). Ideally, these forms of organization need to be inclusive, helping to prevent power imbalances and serving a higher-level purpose of democratic community transformation [53]. Questioning the assumption of energy system growth would open up opportunities for new types of business models for energy production and not-for-profit organizations [54]. Such forms of energy provision would be in contrast to existing practices. With regards to current energy provision practices, especially in the Global South, nowadays it is common for these to involve for-profit business activities that can foster green growth not only in the Global South but also in the Global North [55,56]. Taking this into account, the social sustainability aspect of current energy provision practices, especially in the long run, is questionable.

When it comes to applying the principle of minimizing power imbalances for different types of energy resources, fossil fuels, compared to renewables, are more compatible in terms of creating winner-loser dynamics, because of resource distribution specificities, dependency on the stock and resource scarcity [16].

In terms of fostering community trust, from a procedural justice point of view, it is important to find the forms of energy provision that would encourage its cultivation. Based on social science research findings, a causal relationship exists between community trust and decentralized energy systems [57]. More insights and a deeper understanding of how energy system design is connected to the democratic processes of a society can be found in the energy democracy literature [58,59]. Decentralized energy access provision technologies are more compatible with the goals of trust-building. Centralized technologies, in contrast, by increasing "the spatial, social and political distances between actors", can undermine community trust [60].

Another driving principle for designing technologies for SSES design is avoiding the creation of technological inertia and technological lock-ins [61,62]. The winner versus loser principle can be applied not only to energy system actors but also to technological solutions for energy provision. A SSES would aim to minimize technological inertia in its energy provision solutions. Large-scale, centralized technological systems have higher technological inertia than decentralized, small-scale energy systems [63]. Levels of technological inertia associated with energy system development in different regions can influence patterns of energy system transformation. In the Global North, where there are already established energy systems with a high level of inertia, transformation to a more sustainable energy system would occur over a relatively long duration and at a higher cost. Stranded assets associated with existing fossil-fuel-based energy systems are an example of the costs and challenges associated with such a transformation [64]. Along with the stranded assets, there are also "vested interests", whereby powerful energy system actors are interested in maintaining the status quo of the energy system [65].

In terms of designing sustainable energy provision solutions for the Global South, where existing energy systems are not as developed as the ones in the Global North and have a much lower level of technological inertia, it is important to choose those energy provision technologies that would minimize the chances of having undesired energy system lock-ins in the long run (Table 1: 3.4).

Finally, it is important to minimize the time for setting up an energy provision system. Prioritizing meeting basic human needs as soon as possible drives the choice of faster ways of realizing energy provision (Table 1: 3.5). The limits for choosing the fastest solutions, however, should not jeopardize all other aspects of sustainability in the long term, including economic, environmental, political and social components.

It is important to mention that discussed principles of socially sustainable energy provision are the result of a generalized thought experiment rather than an exhaustive normative framework of socially sustainable principles of energy system design. These principles can be adjusted to specific contexts. A case of energy provision in SSA presented below is an illustrative example of how the designed SSES narrative can be applied for energy system modelling and planning.

4. Connecting theory and modelling

Connecting a SSES narrative with energy system modelling includes three main stages:

- building a model structure based on core theoretical principles;
- simulating electricity access provision scenarios with different levels of compatibility with socially sustainable energy provision principles;
- contrasting and analyzing simulation results, exploring the cost and benefits associated with different types of electricity access provision.

An important aspect of this modelling exercise is that obtaining precise numerical modelling results or replicating historical behaviour is not the principal goal. The role of the numbers presented is primarily to demonstrate the differences between basic and normative scenarios. Apart from discussing the actual simulation results, this study provides value by describing the modelling process, including setting the model's boundaries, conceptualization and structure-building phase, as well as the scenario simulation.

System dynamics [66] is used in this study as an energy systems modelling approach that includes both qualitative and quantitative stages. System dynamics is usually applied as a method for understanding how complex systems are organized and can be transformed by exploring underlying feedback mechanisms in their structures and identifying leverage points for policy interventions [67].

There are several main reasons for choosing system dynamics as a relevant modelling approach for the purposes of this study:

(1) System dynamics is suitable for designing models on highly aggregated scales, where the main research focus is understanding general structural and behaviour patterns [68].
(2) It has the tools suitable for both conceptual and quantitative analysis, which provides a good foundation for integrating theoretical concepts in the modelling exercise.
(3) The quantitative part of system dynamics modelling is relatively easy to use without advanced modelling skills, and the used software (Stella® Architect) has a user-friendly interface.

There are two main tools used in system dynamics modelling that are also utilized in this study: Causal Loop Diagrams (CLDs) (a conceptual tool) [69] and a simulation model (a quantitative tool) [70].

Table 2 presents how the main theoretical components of a SSES

Table 2
The connection between the modelling process and theoretical development.

Stage of the system dynamics modelling process	*Components of a SSES narrative*	*How the theory is represented in the model*
1. Formulating the model's goals	Energy sufficiency is a universal energy system goal on a global scale	On the level of the model's structure, a goal-seeking mechanism [70] is modelled with energy sufficiency as a goal, in contrast to a goal of a continuous energy system growth.
2. Defining the model's boundaries	Energy sufficiency is a universal energy system goal for the Global South and the Global North.	Geographically, the scale of the model is not global, but regional – in SSA. From a social justice point of view, meeting the goal of energy sufficiency in the Global South has the highest priority. For simplicity reasons, electricity for households direct use is the only energy service included in the model.
3. Conceptualizing the model's structure	According to the recognition justice pillar, households, including those in remote rural areas, are the highly prioritized groups of energy services beneficiaries. From the procedural and distributional justice perspectives, decentralized and renewables-based energy access provision is the most compatible with socially sustainable energy provision.	Electricity provision for urban and rural households in SSA is in the centre of the model's structure. Non-household electricity consumption is beyond the model's boundaries. On the electricity generation side, there are four general types of electricity generation technologies: centralized fossil-fuel-based, centralized renewables-based, decentralized fossil-fuel-based, decentralized renewables-based. Nuclear energy is not included in the model structure for simplicity reasons, because it meets very few requirements related to the socially sustainable ways of energy access provision.
4. Formulating assumptions for the model's simulation scenarios	A list of criteria has been designed for socially sustainable energy access provision based on energy justice principles (Table 1). Different energy technologies match with those criteria to a varying extent. The technologies that are the most compatible with the socially sustainable principles of energy access provision should be prioritized.	Basic and normative scenarios are simulated in the model. In the normative scenarios, those technologies that do not qualify for socially sustainable energy access provision are excluded from the simulation.

narrative can be translated into modelling language at various stages in the modelling process.

A model-building process is about finding the balance between a model's usefulness and its complexity. It was previously mentioned that the purpose of this modelling effort was not to fully capture electricity access provision in SSA but to build the structure that would include the main components of a SSES narrative.

5. Model description

The model demonstrates electricity provision for rural and urban populations in SSA from 2016 until 2040. In this section, only the principal components of the model structure are discussed. The main model inputs and equations are provided in the supplementary documentation in Annex A.[1]

5.1. Model's goals

As was mentioned in Table 2, a goal-seeking structure lies at the core of the model, where the aim is to generate a sufficient amount of electricity for rural and urban households. Goal-seeking behaviour belongs to one of the main so-called systems thinking archetypes and is considered one of the basic behaviour structures in system dynamics [70,71].

In Fig. 3, the major dynamics embedded into the model are illustrated with CLDs. From the system dynamics perspective, the driving dynamic mechanism of this model is a balancing loop, as shown in the figure. The balancing mechanism compares the sufficient amount of electricity that needs to be provided with already installed electricity generation capacity and gives the energy system a signal to increase electricity generation capacities until electricity generation reaches the level deemed to be sufficient.

In the model, two different goals of sufficient amounts of electricity are presented separately for urban and rural households because the different amount of electricity is required when providing a sufficient amount of energy services per capita. This difference is caused by varying energy demand to support infrastructure for energy service provision.

It is important to mention that the goal of the model, a sufficient amount of electricity per capita in SSA, does not change over time. However, the total amount of electricity to be produced and to be consumed dynamically increases due to population growth.

5.2. Model's structure: demand and supply

In Fig. 4, a CLD capturing the overall dynamics of the model is presented. The number of rural and urban households provided with a sufficient amount of electricity are the central variables in the model. The parameters of a sufficient amount of energy to be provided for rural and urban households are set at the level of 250 kWh per capita and 500 kWh per capita, respectively. This amount of electricity per capita is in line with the Tiers framework of the World Bank [72], specifically, within Tier 2, which reflects the amount of electricity necessary to satisfy basic human needs.

Both centralized and decentralized electricity generation capacities are present in the model excluding the electricity grid and energy distribution systems for simplicity reasons. This limitation is reflected in the assumption that rural households should be supplied only by decentralized electricity provision technologies.

The driving dynamic mechanisms embedded in the model on the structural level include only balancing loops (see the loops labelled B1, B2, B3, B4 in Fig. 4). The four parameters in bold are key parameters in the model. Tracking their change over time facilitates answers concerning whether the goals of sufficient electricity provision for rural and urban households in SSA are reached. As a result, there are no feedback loops in the model, which would drive an endogenous increase in electricity production and electricity consumption per capita. The only parameter in the model that drives electricity generation and electricity consumption increase is population growth. GDP growth is not included in the model's structure. The reason for this is that the model is capturing energy consumption for basic human needs. Considering this, GDP is not relevant for the level of the model simplification.

The supply side of electricity access provision for SSA is presented by centralized and decentralized electricity generation capacities. Table 3 presents the list of energy provision technologies included in the model. This list is not exhaustive and includes only the technologies most commonly present in the region.

The mechanism of electricity cost generation is modelled in a simplified way and includes only capacity installation costs for each energy technology. For every simulation year, the model chooses a certain technological mix. This selection is based on the cost-minimization principle. However, in contrast to the models primarily driven by cost-minimization, here the lowest cost is not applied as a primary criterion for defining a technological mix. For 2016, the initial year of a simulation timeline, investment cost (in USD/kWh) for each energy technology are pre-set based on the available international energy organizations' reports (see Annex A). After 2016, at every simulation time step, the costs are re-calculated based on the two main driving effects: a resource-scarcity effect and a learning effect, which dynamically interact with each other and affect the cost of technologies in opposite ways. The dynamic interaction of the cost-driving CLDs is portrayed in Fig. 5.

In the model, every energy technology is modelled the same way. The amount of electricity generated by different power capacities depends on the number of generation capacities installed as well as on their capacity factors. Explicit physical limits for the energy resources are modelled only for fossil fuels, in the form of the stocks of the corresponding resource reserves in the SSA region. Imports of fossil fuels to the region are not modelled, because the region is assumed to be self-sufficient in terms of available energy resources, which is important in terms of sustainability goals. For the renewable energies, physical limits for each energy resource are embedded in resource-cost curves (Annex A). These curves show the effect of energy resource limits on energy cost over time. Learning ratios for each energy technology are constant, but the resulting learning effect is endogenous and changes with time, depending on total installed capacity. The system dynamics structure of the learning effect is based on Pruyt et al. [73]. Fig. 6 depicts a structure for a centralized solar PV electricity generation, which is provided as an example of how electricity generation technologies are presented in the model.

The main structural elements of a system dynamics model are as follows: (a) stock variables, which are the square boxes presenting the values of the parameters accumulated over a certain time; (b) flow variables, which are inputs to the stock and outputs from the stocks and are portrayed as arrows with circles. Differences between inflows and outflows in each step create changes in the accumulated value of the stocks; (c) independent variables, which are circles connected to the stocks, inflows and outflows, changing their values or being changed by them.

5.3. Model's scenarios: Designing rules for alternative simulation runs

At the stage of scenario simulation, three different scenarios of the model are compared. Each of them results in a different technological mix of energy provision based on various allocation rules. The scenarios are as follows:

(1) Basic scenario;

[1] To receive a copy of the model or its full documentation, please contact the corresponding author.

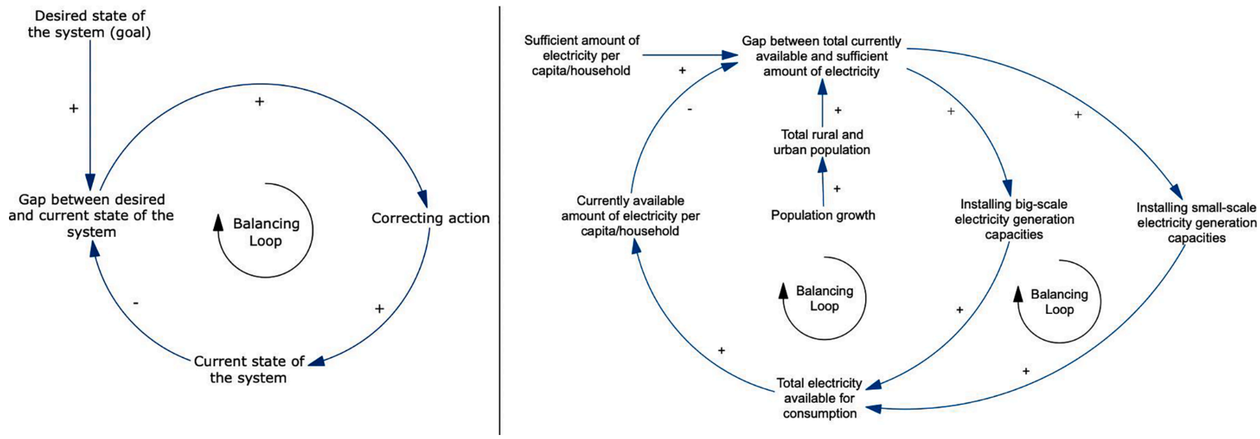


Fig. 3. CLD of a goal-seeking behaviour archetype in System Dynamics in its standard representation and in the way it is presented in the model.

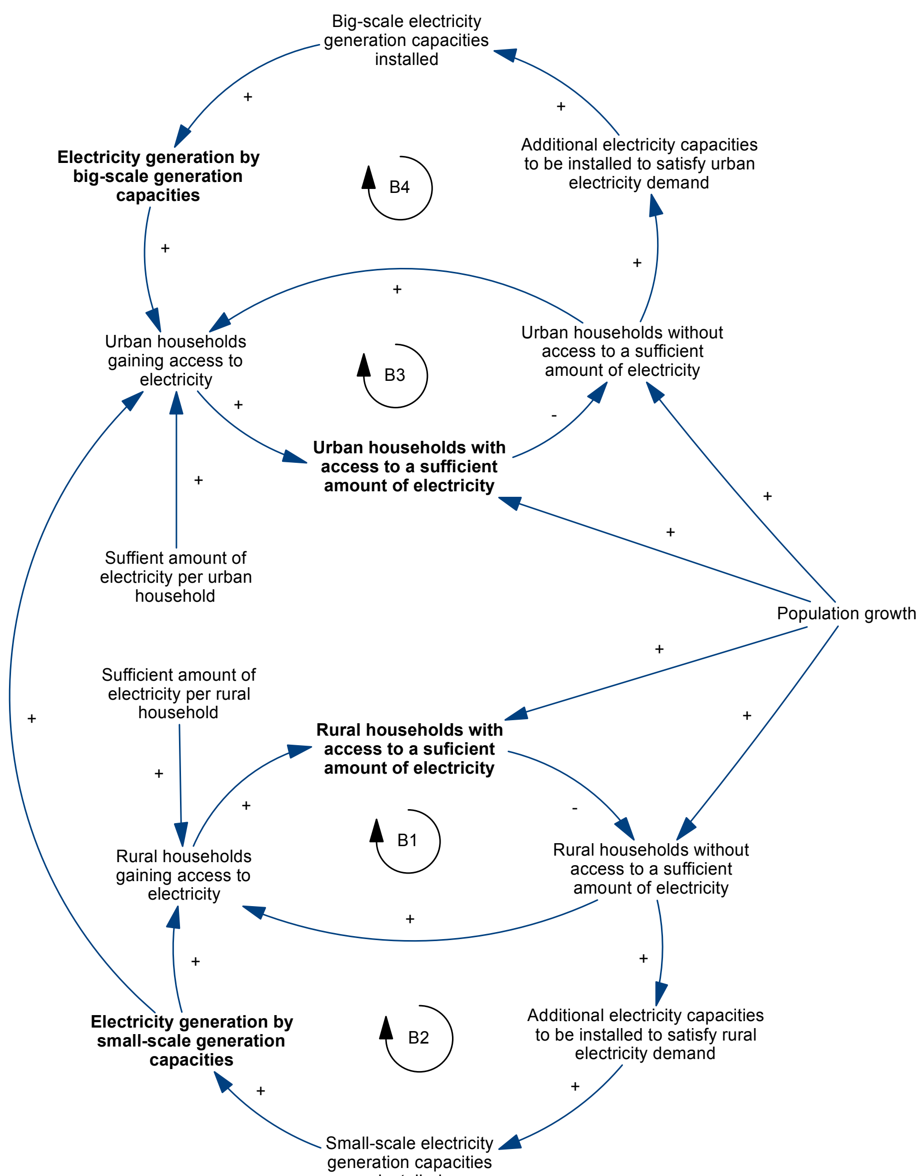


Fig. 4. Overview of the model structure in CLD.

Table 3
List of the electricity generation technologies present in the model.

Centralized electricity generation	Decentralized electricity generation
Coal	Small hydro
Gas	Stand-alone solar PV
Oil	Mini-grid solar PV
Hydro	Mini-grid wind
Centralized solar PV	Stand-alone diesel
Centralized concentrating solar	Mini-grid diesel
Centralized wind	
Centralized geothermal	
Bioenergy-based	

In this scenario, a choice of a technological mix for electricity generation is driven by the cost-minimization principle. All the centralized and decentralized fossil-fuel-based, as well as renewable energy technologies initially present in the model's structure, are included.

(2) Decentralized renewables & decentralized fossil fuels scenario;

In this scenario, decentralized renewables-based and fossil-fuel-based electricity generation technologies are included, while centralized renewables-based and centralized fossil-fuel-based technologies are excluded. The cost-minimization principle is a secondary technology selection criterion in this scenario.

(3) 100% decentralized renewables scenario;

In this scenario, only decentralized renewables-based electricity generation is possible. All other technologies are excluded from the potential technological mix. Within the decentralized renewables, the cost-minimization criterion is applied for defining a resulting technological mix.

The rationale behind having the normative scenarios (i.e. scenarios 2 and 3) is to design the rules for selecting electricity provision technologies based on socially sustainable energy provision principles(Table 1) in accordance with the SSES narrative. In these scenarios, technologies that are least compatible with those principles are excluded from the normative scenarios, even if they allow for the cheapest and fastest electricity provision. Based on this logic, large-scale, fossil-fuel-based technologies, as well as large-scale renewables-based technologies, are excluded from the normative scenarios. As for the decentralized

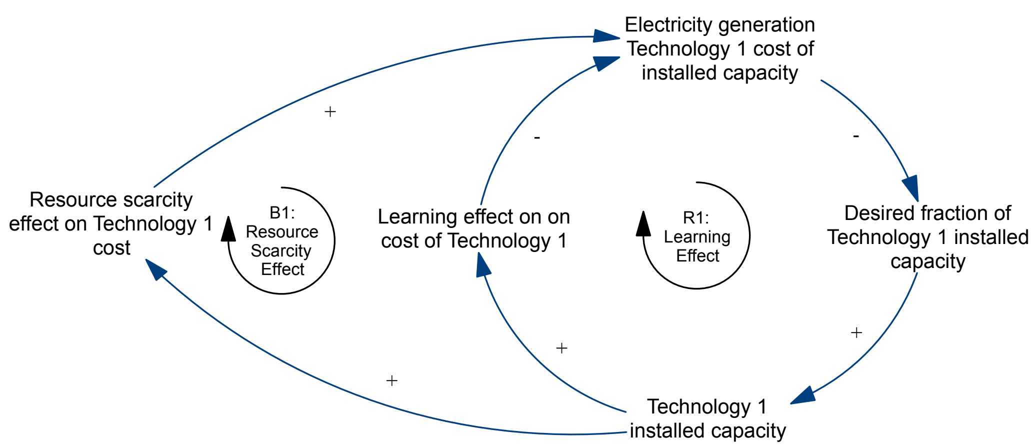


Fig. 5. CLD of the two energy cost-driving effects incorporated in the model's equations.

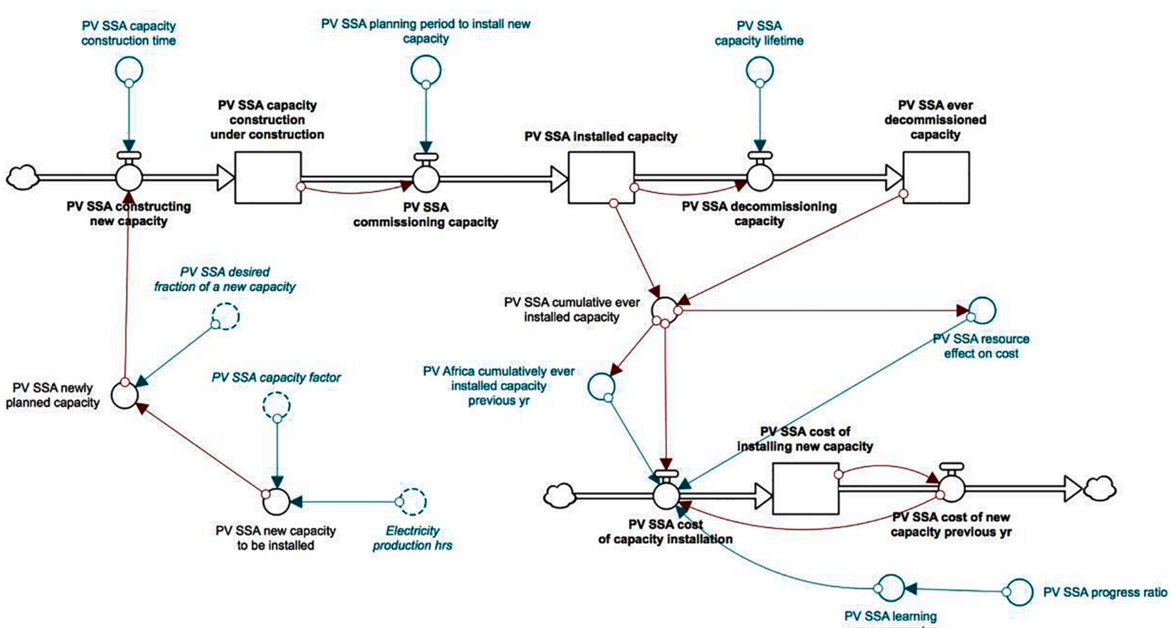


Fig. 6. Centralized solar PV power generation structure: a fragment of the model.

technologies, renewables-based solutions are more compatible with socially sustainable energy provision than fossil-fuel-based technologies. However, according to Table 1, decentralized fossil-fuel-based technologies are also compatible with most principles of socially sustainable provision.

For all three scenarios, the overall goal of the simulation is to provide urban and rural households with a sufficient amount of electricity during the simulation period from 2016 to 2040. A comparison between the three different provision scenarios depicts differences in electricity access provision, system-wide levelized cost, and the mix of electricity-generating technologies and energy resources.

6. Results and discussion

6.1. Modelling results

In this section, the main results of the scenarios' simulations are presented and discussed. Three main parameters are included in the summary table with the model simulation output (see Figs. 7, 8, 9):

(i) Percentage of the rural and urban population in SSA provided with a sufficient amount of electricity measured by bln people;
(ii) Average system-wide levelized cost of electricity generation in 2016–2040 measured by USD per kWh;
(iii) Technological mixes for electricity generation measured by the percentage of different technologies in the total energy mix.

Basic scenario

As mentioned earlier, due to the model's limitations, the comparative results of the different scenarios are more informative and relevant for this study than their absolute numerical outputs. In Table 4, the outputs of the three different scenarios are presented in a relative format, which allows for easier comparison of the scenario results based on the three main parameters detailed above.

6.1.1. Electricity access provision

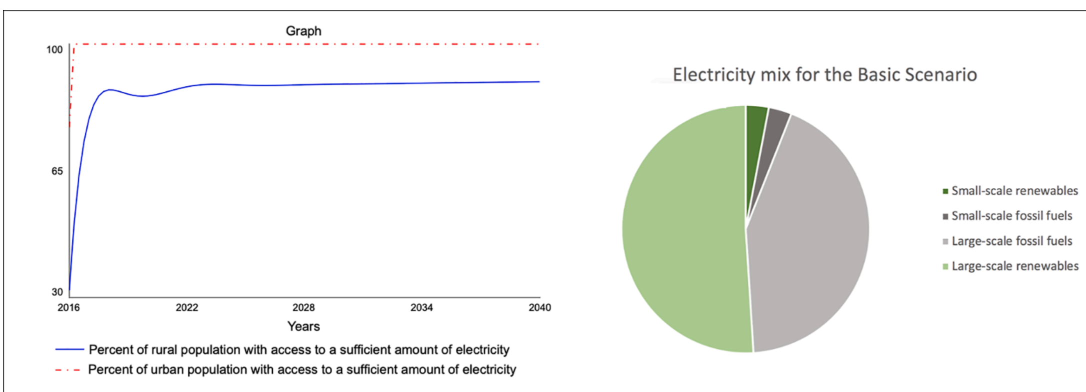
Among all three scenarios, scenario 1 allows for the highest percentage of electricity access for the urban population in SSA by 2040. Scenario 2 and 3 show a lower percentage of urban provision and a higher percentage of rural provision than scenario 1. However, none of the scenarios generates 100% sufficient electricity access for both the rural and urban populations. The reason for this is the effect of population growth which affects the goals of sufficient electricity provision, making total electricity demand a moving target that changes in every simulation step. If the model structure included a population growth forecast for planning installation capacities, the gap in provision would be filled and 100% sufficient electricity access would be reached.

Table 4 illustrates that a maximum level of electricity provision is reached during the first few years of the simulated duration in all three scenarios. The reason for this is the simplified model structure which assumes immediate information exchange between demand and supply; the absence of technological, economic, social and political obstacles for increasing electricity generation capacities; and the constant availability of financial resources for investing in new generating capacities. The only type of time delays present in the model is associated with the time needed to install additional electricity generation capacities. However, the model does not comprehend the full complexity and trade-offs associated with the use of different electricity generation capacities. All of the delays and obstacles present in the existing energy systems should be taken into account when designing sustainable energy systems [14]. Regarding the modelling results, even though the exact values of the numerical simulation are not the main focus, they inspire a further discussion on what can prevent or foster speedier electricity access provision in reality.

One more interesting aspect related to this part of the results is understanding how population growth is related to the overall electricity sufficiency vision at the core of the modelling exercise. Here, the question is: can the model still be considered compatible with the energy sufficiency narrative as opposed to the energy system growth one, considering that in the model total electricity supply and demand increase over time due to population growth? It is argued that the answer to this question is affirmative, with the model remaining compatible with the energy sufficiency narrative. Regardless of the presence of a population growth factor, a model can still be classified as one of sufficiency provided the following conditions are fulfilled: (a) the amount of sufficient energy per capita does not grow over time; (b) the way the energy system is organized prioritizes households as the main beneficiaries.

6.1.2. System-wide levelized cost

As the cost structure of electricity generation in the model is simplified (see 5.2. and Annex A), absolute values of cost are less important than comparative ones. According to the simulation results, scenario 1 is associated with the lowest system-wide levelized cost of



Percent of households provided with a sufficient amount of electricity in SSA by 2040:

100% urban households (1bln people);

90% rural households (1,03bln people).

Average system-wide levelized cost of electricity generation in 2016-2040: **0,45 USD/kWh**

Fig. 7. Model simulation output: basic scenario.

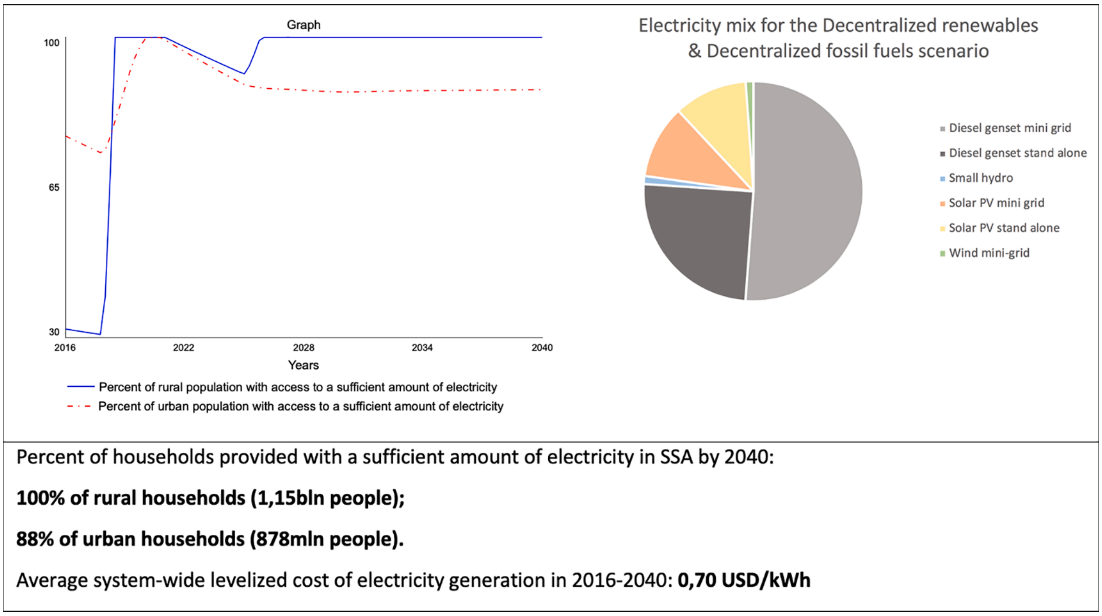


Fig. 8. Model simulation output: decentralized renewables & decentralized fossil fuels scenario.

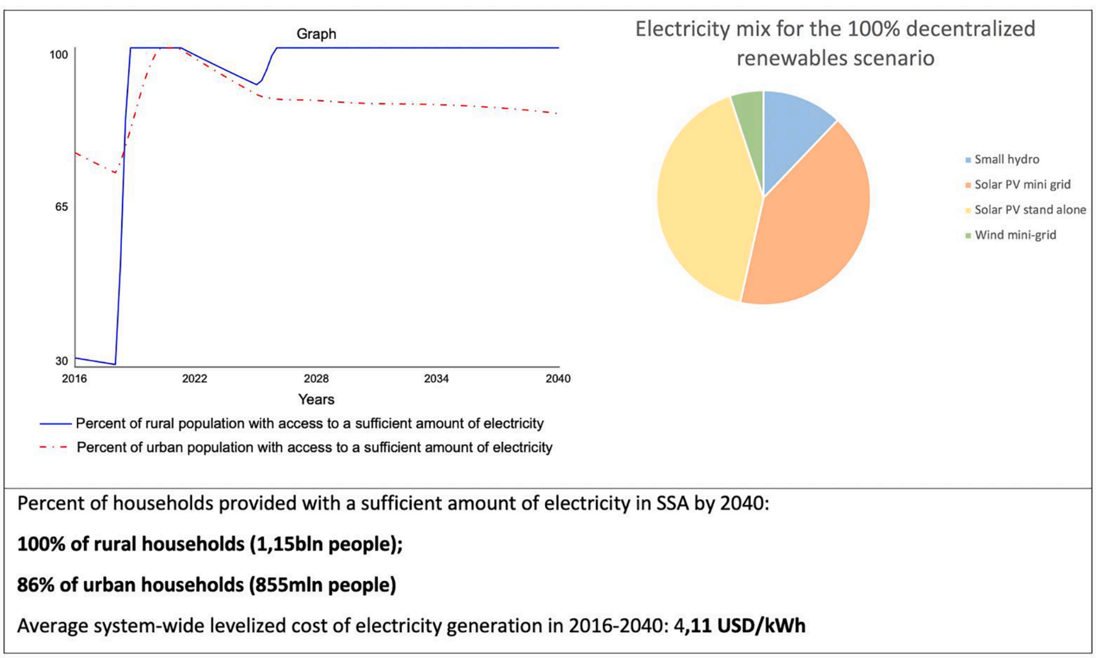


Fig. 9. Model simulation output: 100% decentralized renewables scenario.

electricity generation. The average cost of electricity generation in scenario 2 is 55% higher than in scenario 1. Scenario 3 is the most expensive one. In this scenario, system-wide levelized cost is nine times higher than in scenario 1 and six times higher than in scenario 2. Interestingly, even in scenario 1, where centralized fossil-fuel-based electricity generation is included, the share of renewables in a technological mix is larger than the share of fossil fuels. This means that even based on solely the cost-minimization principles of technological selection, fossil-fuel-based technologies are less competitive than renewables-based ones. This is an interesting finding in the context of energy access provision involving projects that have been to a large extent fossil-fuel-powered, as was mentioned in the Introduction (see Fig. 2). This simulation result questions how reasonable and desirable fossil-fuel-based electricity provision in the Global South is, not only from a social sustainability point of view but even from a pure cost-minimization perspective. Of course, independently from cost, renewables-based energy provision would be limited by local resource availability in the region which is present in the model only to a limited extent. Nevertheless, scenario 1 inspires a discussion on whether current technological choices of energy access provision are really driven by cost-minimization principles or are additional driving forces of continuous investment in fossil-fuel-based electricity provision rooted in path dependency [74].

6.1.3. Mix of electricity-generating technologies and energy resources

Technological mixes associated with the different scenarios of electricity access provision that are discussed and compared in this part correspond to the simulation results for 2040. They do not show how

Table 4
Comparative summary of the three scenarios' simulation results in 2040.

Scenario name	% of sufficient electricity provision among rural population	% of sufficient electricity provision among urban population	System-wide levelized cost (compared to basic scenario)	Large-scale electricity generation technologies mix	Small-scale electricity generation technologies mix
(1) Basic scenario	90%	100%	n/a	**Total large-scale fossil-fuel technologies in the mix (43%), which include the shares of:** Gas (40%); Coal(35%); Oil (25%) **Total large-scale renewable energy technologies in the mix (51%), which include the shares of:** CSP (46%); Solar PV (34%); Hydro (14%); Geothermal (6%).	**Total small-scale fossil-fuel technologies in the mix (3%), which include the shares of:** Diesel genset mini-grid (67%); Diesel genset stand-alone (33%). **Total small-scale renewable energy technologies in the mix (3%), which include the shares of:** Solar PV mini-grid (47%) ; Solar PV stand-alone (47%); Small hydro (6%)
(2) Decentralized renewables & decentralized fossil fuels scenario	+10% (higher than basic scenario)	−12% (lower than basic scenario)	+55% (higher than basic scenario)	n/a	**Fossil fuels (76%):** Diesel genset mini-grid (51%); Diesel genset stand-alone (25%). **Renewables (24%):** Solar PV mini-grid (11%); Solar PV stand-alone (11%); Wind mini-grid (1%); Small hydro (1%)
(3) 100% decentralized renewables Scenario	+10% (higher than basic scenario)	−14% (lower than basic scenario)	+815% (higher than basic scenario)	n/a	**Renewables (100%):** Solar PV mini-grid (41%); Solar PV stand-alone (41%); Small hydro (12%) Wind mini-grid (5%)

electricity generation mixes have changed dynamically over the entire simulation period.

In scenario 1, the shares of renewables and fossil fuels in 2040 are comparable, in both centralized and decentralized electricity mixes. Interestingly, in scenario 2, the share of fossil-fuel-based technologies in a decentralized technological mix is 76%, which is 30% higher than the total share of fossil fuels in the decentralized electricity generation mix of scenario 1. This result is caused by the fact that, in scenario 2, diesel electricity generation gains momentum at the beginning of the simulation and fills a large share of the gap in electricity supply. The rapid increase of diesel-based generation capacities at the early stage leads to a cost decrease in diesel generation, leading to other renewable energy technologies becoming economically uncompetitive until the end of the simulation period. In scenario 3, solar PV becomes a technological leader. In 2040, it provides 82% of total electricity generation.

In general, interpretation of the modelling results relating to the technological mixes is limited by the modelling assumptions linked to resource limits (see section 5.2.) that are only partially addressed in the model. This is a limitation to be taken into account, especially in the scenarios with large shares of biomass, hydro-power and solar PV in the electricity generation mixes. In the case of biomass and hydro-power, which are stock-based renewables, physical availability and resource limits matter. The production of solar PV is limited by non-renewable material resources [50,75]. The exclusion of these important dynamics results in lower levelized cost in the model's simulation output. Similarly, the high learning rates of diesel-based generation capacities in the model result in lower generating cost. The net impact of these results is not significant as the timeframe of the modelling exercise is relatively short. However, if the simulation duration increased, it would be important to take these limitations into account when analyzing the model's output.

6.2. Combined theoretical and modelling results

As results from this paper, SSES narrative consists of two main components: energy sufficiency as the universal energy system goal and the energy-justice-based principles of energy access provision. Derived from these principles, the guiding rules for developing a SSES can be summarized as follows:

(i) Energy provision solutions should be compatible with the idea of contributing to building a low rather than a high energy society (energy sufficiency goal).
(ii) Energy provision solutions should prioritize meeting the basic needs of individuals and households above any other types of energy use (recognition justice pillar).
(iii) Energy provision solutions should prevent creating power imbalances in the energy system at all levels (distributional and procedural justice pillars).

The model presented in this study incorporated the main components of a SSES narrative. On the level of the model's structure, this resulted in defining energy sufficiency as the energy system goal as well as rural and urban households in SSA as core beneficiaries of energy services.

Simulating three different scenarios aimed to test the theoretical principles of socially sustainable energy access provision (Table 3). Scenario 1 was not originally intended to be compatible with a SSES narrative. Its main role was to provide a baseline to compare the normative scenarios' simulation results. In contrast, scenarios 2 and 3 were initially designed to be in line with a SSES narrative. Simulation results demonstrated that scenario 2, which resulted in 76% fossil-fuel-based decentralized electricity provision in 2040, had a system-wide levelized cost of electricity that is six times lower than the 100%-renewables-based scenario 3. Judging by the number of socially sustainable energy provision principles (Table 1) presented in these two scenarios, scenario 3 could be considered to be more socially sustainable than scenario 2, if a multicriteria sustainability assessment was applied instead of pure cost-minimization. From a cost-benefit perspective, the benefits of cheaper electricity access provision in scenario 2 are counter-balanced by a higher social sustainability cost. Similarly, the higher social sustainability benefits of scenario 3 are counter-balanced by the higher monetary cost for electricity provision. Regarding the specific social sustainability criteria, differences between scenarios 2 and 3, the criteria that are not met by scenario 2 are related to fossil fuel use, including restricted access to electricity prosuming as well as potential dependencies on fossil resources that are not locally available. Even though the aggregation scale of this exercise does not facilitate a detailed discussion of social costs and trade-offs, the intention is to provide an example of how different types of technological mixes for electricity access provision can be compared and the trade-offs between economic and social costs and benefits can be considered. Overall, this modelling exercise shows that, when monetary cost-minimization logic is applied, then renewables-based energy provision solutions are likely to be underrepresented in the energy mix. This logic, however, may lead to higher environmental and social cost and hinder universal sustainable energy provision.

The biophysical aspect of sustainable energy access provision is included in this study only indirectly in relation to resource-cost curves. However, even with the limited presence of biophysical parameters within the scenario comparison criteria, fossil-fuel-based provision is less equipped to meet social sustainability criteria and thus less compatible with a SSES narrative.

Combining a SSES narrative with the modelling exercise provided an example of a model that could grasp the key components of socially sustainable energy access provision. On the one hand, this exercise provides insights into how theoretical work related to SSES can become more instrumental for energy policy analysis and development. On the other hand, it can further energy system modelling practice by giving an example of how theoretical assumptions can be incorporated into a model. The principles of socially sustainable energy access provision can be applied for multiple purposes in relation to SSES design and assessment at different scales.

Application and further development of a SSES narrative as well as connecting it to the energy system modelling would be especially important for designing energy access provision policies in the Global South, where energy systems are not as well developed as those in the Global North, and where it is crucial to provide energy access solutions that would not lead to any undesired dynamics in the energy system similar to those in the Global North or lead to new potential energy system injustices.

6.3. Limitations and further research

One of the biggest limitations concerning the applied value of a SSES narrative designed in this study is the fact that it is disconnected from a broader economic context. In further research, the results of this study could be connected to existing alternative-to-growth economic narratives and models, especially considering that energy systems there are rarely described in more detail than being renewables-based and decentralized [76]. Additionally, very few of those narratives go beyond the Global North scale, explicitly or implicitly, tending to assume that alternative-to-growth narratives are not applicable in the Global South. Therefore, the energy sufficiency concept, as a universal energy system goal and the universal principles of energy provision rooted in energy justice, can bring new perspectives and insights into sufficient economies' narratives and models [5,77], helping to inspire new research on understanding what economic sufficiency in the Global North could mean for the Global South and vice versa.

Further research is also needed on connecting energy justice theory with the concept of energy sufficiency as it is defined in this study. This can lead to new research questions in the energy justice field, particularly related to understanding the role of universal energy sufficiency in achieving social and environmental justice, globally and locally.

Concerning the modelling part of this study, the representation of the various costs and benefits of different energy provision scenarios can be enhanced by including the environmental cost associated with different energy provision technologies. The parameters that could be included in such analysis would likely include the environmental cost associated with building new energy generation capacities and decommissioning old capacities, and this could be estimated for each and every stage of energy production and consumption [15]. Additionally, electricity grid and energy distribution systems are not included in the presented model structure. Inclusion of the grid and distribution system in the further modelling exercises and applying to them socially sustainable provision principles can give a more detailed understanding of associated social, environmental and economic sustainability cost and benefits.

7. Conclusion

The main goal of this paper was to provide a methodological case of how qualitative and quantitative methods can be combined for providing better tools for sustainable energy system design. This study departed from the idea that the existing sustainable energy system narrative is missing a social sustainability component. Aiming to fill this gap, this research demonstrated an example of how to construct a socially sustainable energy system (SSES) narrative and how to use it in energy system modelling and analysis. SSES is defined through a combination of universal energy sufficiency and energy-justice-based principles for energy access provision.

Applying constructed SSES for modelling electricity sufficiency for SSA revealed the systemic implications of incorporating social sustainability principles into energy system modelling and planning. In the SSES narrative, social sustainability principles are prioritized over cost-minimization which leads to selecting technological mixes for energy access provision that are associated with higher monetary cost but at the same time higher social sustainability benefits. Therefore, when only the cost-minimization principle is prioritized in energy access provision projects, there is a high chance for the most socially sustainable technologies to be dismissed. The simulation model demonstrated in this study can serve as an example of how conceptual narrative and quantitative modelling can be combined for sustainable energy system planning. The demonstrated methodological case can be applied to different regional contexts. To obtain more realistic results, this will require the provision of specific details relevant to a selected region, which will allow better analysis of trade-offs between economic and social sustainability of energy provision projects. The latter is especially relevant in the context of developing countries.

A methodology outlined in this study can be instrumental for energy policy design and assessment as well as energy system research. One of the possible uses of the developed framework is applying it in multi-criteria decision analysis (MCDA) in the context of energy development, in addition to economic and environmental principles.

This study can be useful for energy system modellers, especially for those interested in the integration of specific theoretical assumptions in energy model structures. For researchers working on theory development for sustainable energy system design, this study can provide an example of how energy system narratives can be constructed and how certain conceptual principles can be tested with the help of qualitative and quantitative modelling tools.

Annex A. Model input

(i) *Initial cost of capacity installation:*

Name of technology	Cost (USD/GW)	References
Bioenergy	1250*10ˆ6	Source: IRENA [78]
Coal	3873*10ˆ6	Source: McKinsey [79]
Concentrated solar power	7500*10ˆ6	Source: IRENA [80]
Diesel genset stand alone	938*10ˆ6	Source: Worldbank [81]
Diesel genset mini-grid	721*10ˆ6	Source: [81]
Gas	1546*10ˆ6	Source: McKinsey [79]
Geothermal	4000*10ˆ6	Source: IRENA [78]
Centralized hydro	2800*10ˆ6	Source: IRENA [78]
Mini hydro	5000*10ˆ6	Source: Worldbank [81]
Oil	1546*10ˆ6	Source: McKinsey [79]
Solar PV centralized	2500*10ˆ6	Source: IRENA [78]
Solar PV mini grid	4300*10ˆ6	Source: Worldbank [81]
Decentralized Hydro	5000*10ˆ6	Source: Worldbank [81]
Wind centralized	2000*10ˆ6	Source: IRENA [78]
Wind decentralized	2500*10ˆ6	Source: Worldbank [81]

(ii) *Lifetime of electricity generation technologies:*

Name of technology	Technology lifetime in years	References
Diesel genset mini grid	15	Source: Worldbank [81]
Diesel genset stand alone	10	
Gas	30	
Geothermal	30	
Hydro	30	
Oil	30	
Solar PV centralized	25	
Solar PV mini grid	20	
Solar PV stand alone	15	
Wind power	25	

(iii) *Power generation capacity factors:*

Name of technology	Capacity factor	References
Bioenergy	0,8	Source: IRENA [78]
Coal	0,73	Source: EIA [82]
Concentrated solar	0,3	Source: EIA [82]
Gas	0,44	Source: EIA [82]
Diesel genset mini grid	0,44	Source: EIA [82]
Geothermal	0,8	Source: IRENA [78]
Hydro	0,49	Source: EIA [82]
Oil	0,54	Source: EIA [82]
Solar PV centralized	0,2	Source: IRENA [78]
Solar PV mini grid	0,2	Source: IRENA [78]
Solar PV stand alone	0,2	Source: IRENA [78]
Wind power	0,28	Source: EIA [82]

(iv) *Population data:*

Urban population without access to electricity in Sub Saharan Africa in 2016	122 mln people	IEA [12]
Rural population without access to electricity in Sub Saharan Africa in 2016	466 mln people	
Urban population with access to electricity in Sub Saharan Africa in 2016	409 mln people	
Rural population with access to electricity in Sub Saharan Africa in 2016	220 mln people	
Population growth coefficient in Sub Saharan Africa	UN forecast of population growth rate in Africa from 2,6% in 2016 to 1,8% in 2050Source:	Source: [83]
Sufficient amount of electricity in rural Sub Saharan Africa	250 KWh/people/year (based on Multi-tier framework)	Source: Worldbank [84]
Sufficient amount of electricity in urban Sub Saharan Africa	500 KWh/people/year (based on Multi-tier framework)	Source: Worldbank [84]

(v) *Cost of technologies:*

- Technological cost-resource curves are based on the xlsx approximation of the GCAM model learning curves. Source: GCAM v5.2 model documentation [85]
- Technology X learning curve parameter = -LN(Technology X Progress Ratio) : LN(2)
- Cost of installing Technology X capacity= (Technology X cost of new capacity previous year) * (Technology X cumulatively ever installed capacity : Technology X cumulatively ever installed capacity previous year) ^ (Technology X learning curve parameter) * Technology X cost-resource coefficient.

(vi) Technologies generation progress ratio:

Bioenergy power progress ratio	0,93	Source: [86]
Coal power progress ratio	0,99	
Concentrated solar power progress ratio	0,77	
Gas power progress ratio	0,86	
Geothermal power progress ratio	0,93	
Hydropower progress ratio	0,986	
Oil power progress ratio	0,86	
Solar PV progress ratio	0,77	
Windpower progress ratio	0,88	

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Declaration of Competing Interest

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

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