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How to Enhance Energy Services in Informal Settlements? Qualitative Comparison of Renewable Energy Solutions

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Abstract: More than half of the urban population of Sub-Saharan Africa lives in informal housing conditions. While urban areas are, in general, characterized by a high electrification rate, residents of informal settlements are still affected by energy poverty, the use of traditional energy sources and unreliable electricity supply. The aim of the study is to give an overview of different renewable-energy-based solutions which are able to improve local energy provision. These are Solar Home Systems, Mini-Grids, and Energy-Hubs. The technologies are compared to another option for improving energy supply, namely Grid Expansion. The analysis is based on 24 Key Performance Indicators, which can be classified into technical, economic, environmental, social, and political dimensions. The selection of indicators is based on the challenges prevalent in informal settlements that impede a comprehensive, sustainable energy supply. The literature-based indices are used to determine which of the four technologies is a suitable solution for minimizing the challenges prevailing in informal settlements. The resulting matrix provides a holistic comparison and serves as a decision aid in selecting the appropriate technology for future projects in informal settlements, depending on local conditions and the needs of the population. The results show that the Energy-Hub is a valid alternative for energy supply improvement in Informal Settlements.

Keywords: informal settlements; energy access; Sub-Saharan Africa; Energy-Hub; Mini-Grid

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Citation: Besner, R.; Mehta, K.; Zörner, W. How to Enhance Energy Services in Informal Settlements? Qualitative Comparison of Renewable Energy Solutions. *Energies* **2023**, *16*, 4687. https://doi.org/10.3390/en16124687

Academic Editors: Abdul-Ghani Olabi and Tek Tjing Lie

Received: 11 April 2023
Revised: 7 June 2023
Accepted: 9 June 2023
Published: 13 June 2023

1. Introduction

Informal Settlements (ISs) are a widespread phenomenon in cities in the global south. In Sub-Saharan Africa (SSA), about 56% of the urban population lives in ISs [1]. With an annual urban growth rate of 4% [2] paired with a lack of affordable, developed land, inadequate city planning, and inefficiently performing public governance [3,4], ISs will continue to exist and grow. In the absence of space for adequate housing, migrants settle in areas still available and previously avoided by citizens for environmental or health reasons. ISs have often been ignored by the country's administration in order to prevent creating the appearance of legitimacy for these regions [4,5]. Illegal residents lack political power and do not benefit from political measures [6]. Occurring challenges within the settlements are being neglected or addressed reactively with a focus on resolving short-term risks [7,8], leading to limited improvements in the quality of life of its population. The image of residents has improved over the last decades, and numerous slum upgrading programs have been launched [9,10]. However, the fast-changing environment, their complex, convoluted structure and the illegal status of residents complicate the subsequent introduction of sustainable, long-term programs or an improvement of the infrastructure [11,12]. ISs apply to areas built without legal housing permits and outside the authority and administration system [13,14]. Figure 1 represents the typical view of an IS.

Figure 1. An exemplary street in an informal neighborhood in Nairobi, Kenya (Source: Author).

Due to economic vulnerability and the location of settlements in areas with challenging environmental conditions, residents are particularly affected by the consequences of climate change. Although the trend in SSA has steadily improved since 2013, the COVID-19 pandemic led to a renewed increase in the share of the population without access to electricity, which can be estimated at 600 million for SSA in 2021 [15]. Despite the fact that its electrification rate is generally higher in urban than in rural regions, more than 20% of the urban population still lacks an electricity supply, and the majority belong to ISs [16].

1.1. Energy Situation in Informal Settlements

In ISs, the energy supply is often limited, unreliable, and expensive [12,17]. Many people living in these areas do not have access to legal grid electricity and furthermore rely on costly, traditional, and polluting energy sources such as kerosene, diesel, gas, and biomass. [11,18–20] Fossil fuels, such as (char-) coal or firewood, are often used for cooking, which accelerates environmental depletion and has a negative impact on health and the environment [21,22]. Some companies offer prepaid gas refills [23], but this form of energy is also fossil in nature. Lighting with candles or gasoline is still common, which can lead to fire outbreaks [24].

Access to electricity is usually measured by the ratio of to the grid-connected beings [25]. However, this yardstick does not reflect the complexity of reality, as the Multi-Tier Framework exemplarily confirms [26]. Aside from the fact that there are parts of the urban population that are not connected to the grid at all, other parts live unconnected but close to the grid or face an unreliable power supply. Dumitrescu et al. [27] introduced the end-user-market classification, which is being adapted within this context, given as an overview in Table 1 and subsequently described in greater detail.

Table 1. Options of unsatisfactory electricity supply based on Dumitrescu et al. [27].

Off-Grid	Close-to-the-Grid	Weak-on-Grid	Illegal Connection
Residents have no grid access.	Residents are in direct environment of transmission-lines, but not yet connected.	Residents are connected, but the electricity network is unreliable.	Supply is organized by intermediaries (e.g., cartels) illegally.

Off-grid: Energy supply companies often charge a high amount to connect new customers to the grid. In many cases, ISs residents cannot afford these high upfront costs [28,29]. The poor geographical location of ISs (e.g., flooding) makes sustainable installation difficult, may increase maintenance, and leads to higher supply costs [30]. Rising energy prices increase the barriers for dwellers to able to meet the monthly charges [18]. Their illegal status, lack of tenure, and high residential turnover prevent long-term contracts with the utility company. Untransparent communication, lacking capacities to improve the infrastructure, and absent community involvement in ongoing projects further impedes the mutual trust between the utility company and residents [31,32]. For lighting, if electricity is not available, often candles or kerosene are used, which are economically and environmentally unsustainable sources [32,33].

Close-to-the-grid: The nature of ISs is often characterized by extremely narrow, sometimes impassable roads. This makes it difficult for electricity supply companies to build or maintain grid infrastructure [12]. Often, due to the building density and lack of accessibility, only residents on the main road of the settlement are supplied with legal electricity [11]. In Mozambique, the electrification of buildings that are not accessible by road is prohibited because, in the event of an accident caused by electricity, rescue vehicles cannot reach the houses [34].

Weak-on-grid: Improving electrification coverage and radius does not automatically result in universal access. A large number of slum dwellers report blackouts lasting hours, days, or even weeks and frequent voltage fluctuations, which can damage electrical equipment [11,12]. Outdated transmission- and distribution infrastructures additionally lead to reliability problems due to above-average losses. Natural events (e.g., flooding) can further damage the infrastructure. Intentional interference (e.g., theft) or mismanagement by utility companies can also contribute to unreliable supply [27]. At the same time, Grid Expansion must respond to the additional demand of the surplus consumers, whereas responsible institutions are often unable to organize new supply sources [18].

Illegal connections: Illegal electricity connections, often provided by cartels [35], are the consequence of those challenges. These supply systems are widespread in ISs, especially due to the resellers' knowledge of the energy needs of the residents [36]. In the settlement of Mathare, Kenya, about 50% of electricity connections were informal between 2017 and 2019 [20,37]. Indirect connections can lead, due to a lack of electro-technical expertise, to several issues: Both health and safety are at risk from fire outbreaks or damaged electric appliances due to frequency oscillations and resulting blackouts. Furthermore, they endanger the reliability and security of the respective national power utility [19,36].

1.2. Potential Integration of Renewable Energy Systems to ISs

Clean, modern, renewable energy systems (RES) are not only mitigating climate change [38] but at the same time, are directly connected with benefits for the sector's well-being, health, economic development, and education [12,39–41]. The transition from carbon-based to RE-based forms of energy reduces emissions, therefore smog pollution, and risks of fire outbreaks, which both are prominent in ISs. With access to electricity, public institutions and social services have a higher functionality and can be utilized to a greater extent. With the accompanying higher availability and usability of smartphones, residents of ISs have better access to information, online services, education, and communication [25]. The implementation and use of RES can further lead to job creation and revenue gain [39], which can help to address the proportionally high unemployment rate in ISs, which is vital for an improvement of living standards [25,42].

If ISs are not included in future energy scenarios, risks slowing down the transition to RES-supply and an increase in poverty of already marginalized groups occur [43]. Jaglin [44] considers the energy supply in cities to be a central task in the future due to demographic growth, city expansion, increase in energy demand, and current unreliable power provision. To support people facing the challenge of lacking or unreliable electricity supply in ISs, there is a need to improve its match between consumption and generation.

1.3. Available Market Solutions

There are several ways to enhance the energy supply in ISs, which can address the above-mentioned energy challenges. The suitability of using different RES depends on a range of factors, such as the potential area of application and the local preconditions. The solutions considered in the framework of this article are Pico Solar and Solar Home Systems (SHS), Micro- and Mini-Grids, and a concept called Energy-Hubs. In the following, Pico Solar and SHS are merged into one category, hereinafter referred to as SHS. Micro- and Mini-Grids are also combined into one category, whereby within this article, the term refers to a classic Mini-Grid that supplies individual buildings, each with its own power connection. The Mini-Grid is defined as a 100% solar-powered island grid with the support of a battery energy storage system (BESS), while the use of diesel generators is not considered. The mentioned renewable energy-based solutions are being compared with the option of Grid-Extension, as displayed in Figure 2.

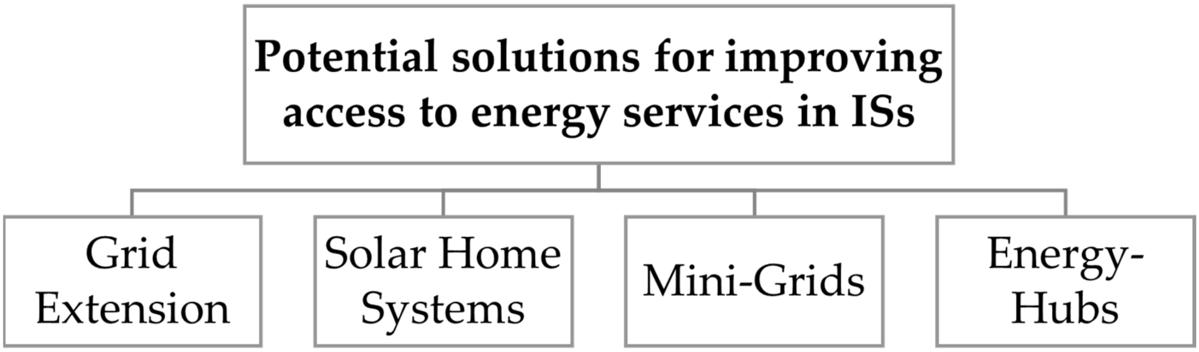

Figure 2. Overview of considered technologies for improvement of energy supply.

Grid-Extension means the extension and densification of the grid infrastructure. The Energy-Hub [45] includes all concepts that offer energy services for households and businesses at a central location, as implemented by, for example, a solar kiosk [46–48].

1.4. Aim of the Study

The presented article aims to provide an overview of different solutions for improving the energy infrastructure in ISs of SSA. It draws attention to the challenges that exist in ISs and assesses the potential solutions to mitigate these challenges when the technology is implemented. Different dimensions affected by the technologies will be considered, and characteristics of the technologies will be described according to the area they touch. The article assists in the selection of suitable technology for improving energy services in ISs. The evaluation is made depending on the characteristics of the technology, its potential to meet specific local conditions, and the needs of the local population.

2. Materials and Methods

The following section is divided into four parts. The first section describes the research methodology, which is based on the method of selecting the Key Performance Indicators (KPIs) and the subsequent assessment matrix.

Thereafter, the state of the art of relevant literature is presented, and finally, the gap in the research and the novelty of the paper are addressed.

2.1. Research Methodology

The research methodology of the presented work consists of several steps, which are displayed in Figure 3.

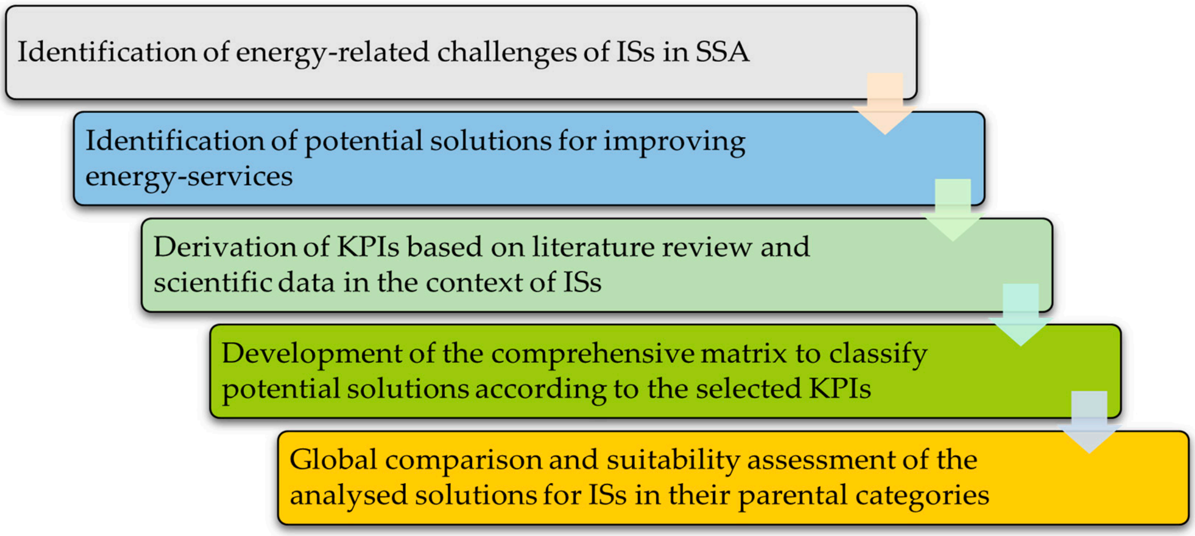

Figure 3. The overall methodology of this article.

As a first step, the energy-related challenges prevailing in ISs are elaborated primarily based on the literature in Section 1. The sources used are studies that are as recent as possible, not older than 10 years, in order to be able to depict the realities of life in ISs. As the key work served by Butera et al. [12], who analyzed the challenges of energy in ISs in cities of Africa and Latin America. Furthermore, keywords, such as electricity access, energy supply, grid extension, off-grid, and challenges in combination with Informal settlements, urban poor, or SSA were used to identify additional research work. The RE-based technological solutions, which are being compared with the option of Grid Extensions, are presented in Section 1.3. Due to the high solar irradiation values prevailing on the African continent and the combination of low operating, maintenance, and system costs, the choice of technologies is being rested on photovoltaics (PV). The selection of the KPIs, which are presented in Section 3, is primarily based on the literature and scientific data. The resulting matrix consists of the four technological options, which are evaluated against the pre-selected KPIs. The matrix and the associated cumulative knowledge are shown in Section 4, which represents the results of the study. In the discussion, the three potential systems based on RES (SHS, Mini-Grid, Energy-Hub) are being further evaluated, as shown in Figure 4. In the assessment, the solutions are ranked according to the data analyzed within every respective KPI.

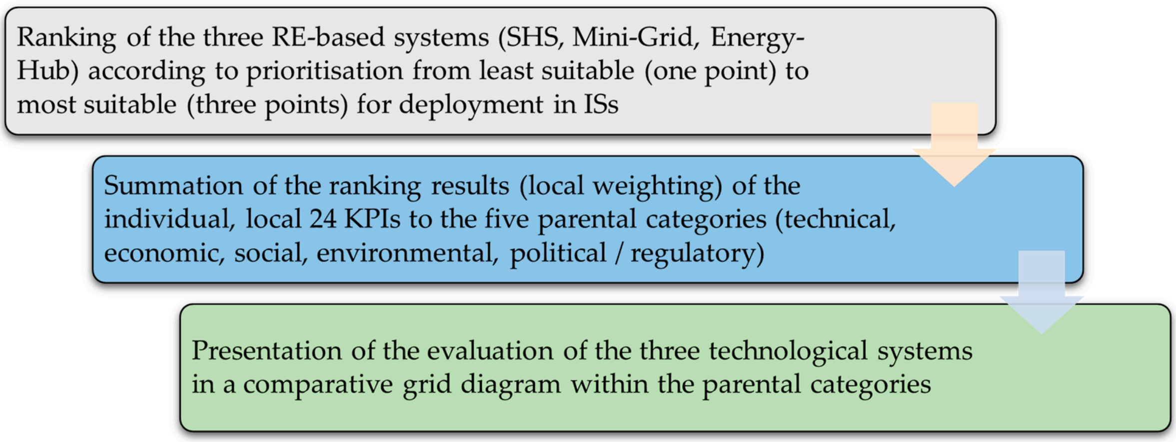

Figure 4. Methodology of the global comparison and suitability assessment.

The local ranking is carried out by assigning one point to the least and three points to the most suitable system. The detailed, local weighting of the systems based on each KPI is then summarized within each parent category. This is followed by an evaluation of the technologies within the parental category, thus achieving a summarized, condensed presentation of the elaborated results. An outlook concludes the work.

2.2. State of the Art

Chen [49] compared different electrification technologies, namely, Grid Extension, Mini-Grids and SHS according to their cost-effectiveness. Although he identified Grid Extension to be the most economical option, in countries lacking infrastructure and electrification, SHS and Mini-Grids can contribute greater to realizing universal access.

Blechinger et al. [50] developed a holistic manual displaying electrification scenarios via different technologies for 52 target countries. Considering Mini-Grids, Grid Extension, and SHS, they identified key obstacles and solutions for Off-grid electrification and gave recommendations for future implementation.

Ortega-Arriaga et al. [51] analyzed off- and on-grid solutions according to their economic and environmental impact. Key metrics for comparison were the levelized cost of electricity (LCOE), the life cycle costing for the economic dimension, and the life cycle assessment with a focus on Greenhouse Gas Potential for the environment.

A review of the sustainability of different off-grid solar systems, namely, Pico-solar and SHS for rural electrification, was implemented by Feron [52], where institutional, economic, environmental, and socio-cultural categories were analyzed. The aim was to identify barriers to reaching sustainable implementation. The main findings were a deficiency in regulations (institutional), lacking subsidization programs (economic) and a shortage of awareness and policies (environmental/socio-cultural).

Amupolo et al. [53] investigate different off-grid renewable energy technologies in terms of their techno-economic characteristics for use in an IS in Windhoek, Namibia. SHS with a central ground- or roof-mounted hybrid microgrid were compared. For different system combinations, the technologies PV, wind energy, diesel generator, and BESS were considered and sized with HOMER. The target values to be determined are the LCOE and the Net Present Cost of the three technologies. The best variants from a techno-economic point of view are the hybrid microgrids of PV, diesel generation, and BESS. The authors recommend including the option of Grid-Extension and pointing out the environmental issues associated with the use of diesel.

Conway et al. [5] explore two different model implementations of how access to basic services of electricity can be achieved in ISs in Zimbabwe and South Africa (SA) via the use of SHS. The Social Enterprise in SA acts as a solar utility and offers services for a fee. In Zimbabwe, group dynamics are strengthened to enhance the community's organizational capacity. The focus is on socio-economic impacts and explores the option of integrating both approaches into a hybrid model. The results show that subsidies can reduce investment costs and thus the financial hurdles. Synergies between locally formed groups (e.g., loan organizations) can contribute to the social structure of the community.

2.3. Gap in the Research

The contributions stated clearly show that there are already various studies that discuss the eligibility of the considered technologies depending on the characteristics of the application site [54–67]. However, the focus of these works is especially on the integration of such technologies in rural areas. Since urban areas are easier electrifiable by the expansion of the national grid and rural regions have, in general a lower electrification rate (on average, 25% are electrified, compared to 78% in cities) in SSA in 2019 [68]. This can be considered a gap in the research since the primary approach to electrification of urban regions is to pursue Grid Extension [69,70], rarely SHS or hybrid-micro grids [53].

While the assessment of various technologies has already been implemented, these are either limited to specific subject areas, such as economic characteristics, or limited to fewer technologies. The literature does not consider Energy-Hubs, and furthermore, direct comparison and classification of four different solutions have not yet been implemented for the introduction in ISs. Hence, there is an immediate need to perform the analysis to identify a suitable RE-based approach to enhance energy services for better living standards in ISs. The area of consideration is in the (peri-)urban region, specifically ISs, which are, as mentioned, not the scientific focus when discussing the improvement of energy access.

2.4. Novelty of the Study

This article aims at classifying possible technological while placing the Energy-Hub system within the existing market of electrification options. The novelty of this article is summarized in the following bullet points:

- The comparison of energy-improvement strategies focuses solely on the implementation in (peri-)urban areas, especially those of ISs;
- The selection of qualitative KPIs is realized for a comprehensive classification of different options for the improvement of energy services in ISs;
- In particular, the analysis does not only cover supply for the residential sector but includes the option to support Productive Use Chases (PUC) and energy services;
- A classification matrix is being developed, which helps identify the most suitable RES-based technology depending on the local conditions of a potential site by comparing the different RES-based solutions employing the selected KPIs;
- A subsequent evaluation of the four technologies in the technical, economic, social, environmental, and political/regulatory categories is implemented.

3. Derivation of Key Performance Indicators

KPIs are crucial for understanding and analyzing the situation of energy poverty in ISs. KPIs are quantitative or qualitative measures that are used to evaluate the performance of a project, program, or initiative. In the context of energy access, KPIs can be used to assess the impact of energy interventions. Thus, it is possible to identify the most appropriate technology for improving energy services in ISs, which can help to alleviate energy poverty and promote sustainable development. Based on the literature research and analysis of potential prevailing challenges in ISs, KPIs were selected in the following areas: Technical, Economic, Environmental, Social, and Political. Subsequently, the literature dealing with the selection of KPIs in the context of energy services is being presented:

Bhattacharyya [71] gives an overview of methods hitherto applied for the analysis and selection of off-grid systems for rural areas, e.g., the Multi-Criteria Sustainability Assessment. While the term sustainability usually refers to three dimensions, namely, economic, environmental, and social [72], many studies and applications are expanded to include further criteria [71]. Several review articles exist which use indicators to evaluate RES. Moner-Girona et al. [73] examine different countries in terms of their desirability for investment in decentralized electricity technologies by utilizing 52 indicators within the environmental, social, political, and financial areas. Feron [52] measured the sustainability of SHS and Pico-solar according to five pillars (institutional, economic, environmental, and socio-cultural), with each composed of up to five KPIs. The KPIs, which are used to benchmark the different technologies, should cover all areas that the technologies influence. This amounts to the holistic analysis with the technical, socio-economic, environmental, and institutional or policy perspective, as implemented by Ilskog [74]. Since the RES to be assessed should improve the living standards of the inhabitants, the aim is to evaluate the technologies in terms of whether they can mitigate and support solving several challenges that arise in ISs. The KPIs are selected based on local boundary conditions to cover major aspects of ISs and their challenges according to their sphere of influence. The resulting presentation of the aggregated KPIs, with a focus on the technical perspective, is shown in Figure 5.

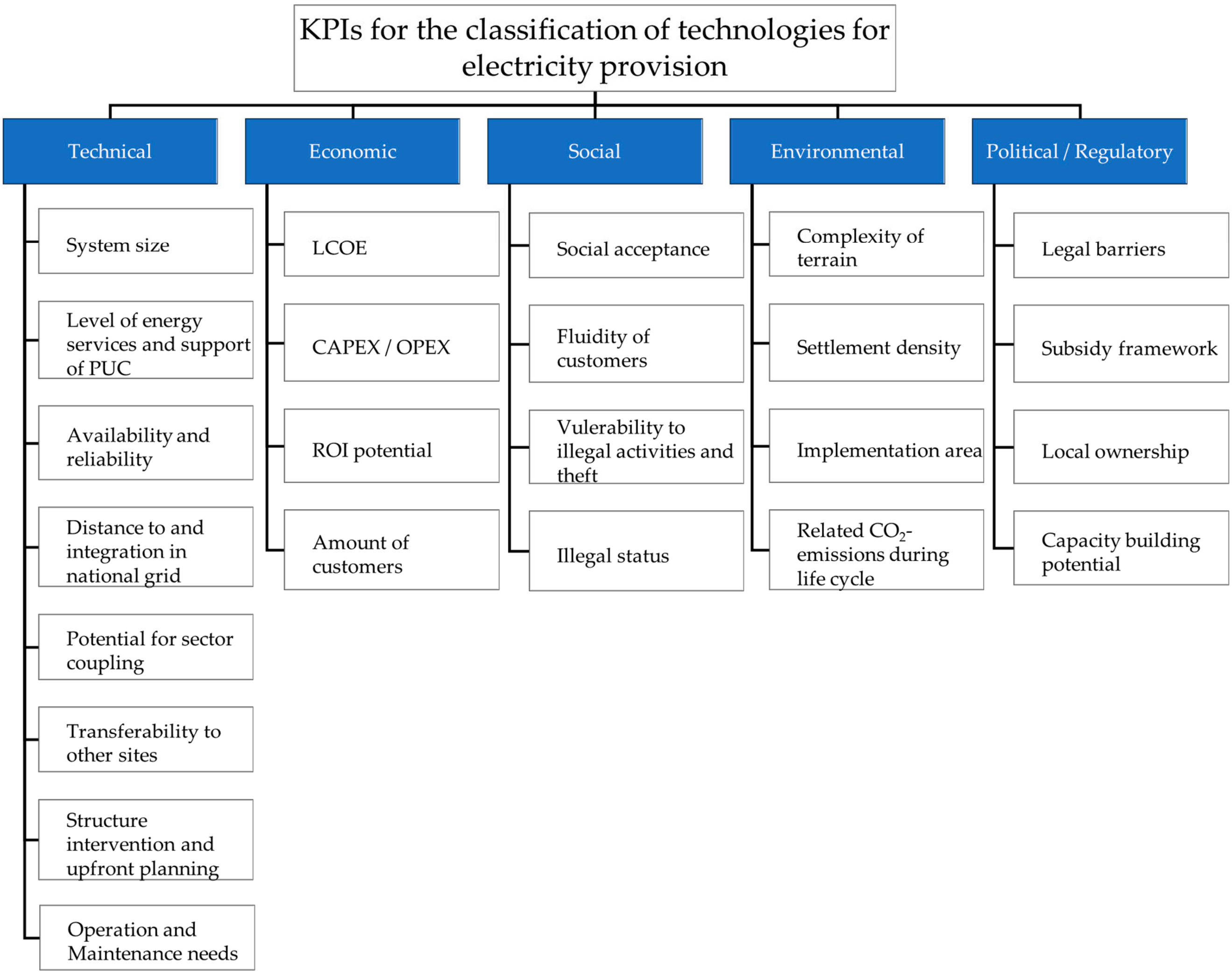

Figure 5. Selected KPIs, broken down by parent index.

The selected KPIs are not able to cover all areas that influence the use of the proposed technology. Accordingly, some KPIs are being neglected: health impact, job creation potential, justice, or poverty alleviation, as Nerini and Runsten [75,76] include.

4. Classification of Solutions Based on the Selected KPIs

The following section allows the holistic analysis of the potential technologies pre-selected in Section 1.3. All four technologies vary in their suitability depending on the area of application. The aim is to describe and evaluate the technologies individually based on the literature research for implementation in ISs. The results are comprehensively presented in the form of a matrix, displayed in Table 2. Following the logic of the matrix, a decision can be made on the most appropriate technology for use in ISs depending on the project focus and the local, prevailing energy-related challenges. According to the problems present in ISs, different KPIs can be focused on in the evaluation. A comprehensive analysis of the technologies based on different dimensions enables potential users of the matrix, e.g., project developers, to make better decisions during project implementation: If the economic factor is the main focus during implementation, an initial assessment can be made of which technology is suitable based on the in the matrix presented economic KPIs.

Table 2. The resulting matrix compares solutions for the improvement of energy services by means of preselected KPIs.

	KPIs	**SHS and Pico Solar**	**Mini-Grid**	**Energy-Hub**	**Grid Extension**
Technical	System size	Pico Solar < 10 Wp SHS < 150 Wp [77]	10 kW to >10 MW [77–79]	<35 kW: Size depends on residents' needs, offered services, and availability of space [80].	/
	Level of energy services and support of PUC	TIER 1–3 [5,76,81] No support for PUC	TIER 3–5 [82] PUC supports system profitability and sustainability.	TIER 1–4 PUC with limited energy demand is part of the system design.	TIER 5 [26] System should allow every range of electricity demand or service [6].
	Availability and reliability of services	Availability is limited to irradiation. Reliability dependent on usage and weather [76]. BESS drives costs upwards [60].	Highly reliable and available.	Services should be available during opening hours and expected to be highly reliable.	Depends on power utility; the goal is a fail-safe electricity supply; illegal connections often highly unreliable.
	Integrable in national grid	Operation parallel to the grid is possible.	If integration of RES in national grid is legal, connection is manageable. Feasible from a technical point of view, regulations need to be introduced from an economic point of view.		/
	Distance to national grid	Operation parallel to the grid or reselling with arrival of grid is possible.	Although concepts of grid integration exist, grid should be far away and not reach the site soon.	"close-to-the-grid" population can benefit due to reliable services. If E.H. is integrated in a grid, support of the reliability of the national grid is possible.	/
	Sector coupling potential (e.g., cooling, e-mobility)	Not suitable.	Integrable.	Limited integrable.	Integrable.
	Transferable to another site if the grid arrives	Highly transferable.	Not transferable.	Highly transferable.	/
	Settlement, Household or infrastructure upgrading required?	No Settlement-, but limited household-upgrading is necessary.	Yes, e.g., poles. If houses are made of certain materials, connections can be refused [70].	No upgrading is necessary. An open space is required.	Yes. If houses are made of certain materials, connections can be refused [70].
	Operation and Maintenance (OandM) needs	Low.	High: Higher voltage, hard- and software more complex, skills for OandM and monitoring needed [5].		Responsibility of energy provider: Embedded in national OandM scheme.
	Upfront planning requirements	Low.	Complex.	Medium.	Complex.

Table 2. *Cont.*

	KPIs	SHS and Pico Solar	Mini-Grid	Energy-Hub	Grid Extension
Economic	LCOE	Very wide range depending on local conditions and country: 0.25 and 1.4 USD2019$/kWh [51]. SHS tend to be more expensive than Mini-Grids [69,77].		Due to central- and lack of decentralized infrastructure cheaper than Mini-Grid.	Very wide range depending on tariff and country: <$0.1/kWh to >$8/kWh [51,83].
	CAPEX	High upfront cost for individual customer: ~300 USD/Kit [84].	Very high due to inclusion of BESS: USD 1420/kW to USD 22,689/kW [69].	Similar to Mini-Grid due to inclusion of BESS, but no distribution infrastructure.	High connection fees can occur [29].
	OPEX	26.5% maintenance of total costs [85].	35–40% of lifetime cost [69]. BESS drives OPEX upwards.		Electrification in ISs costs utilities disproportionate amount of money due to illegal activities [86,87].
	Revenue Potential/Return of investment	Upfront purchase or financed sale over 2–3 years [5]. Profitability given [88].	Profitability depending on the economic-, financial concept, the ownership model.	Profitability depends on the economic, financial concept, the ownership model and local acceptance.	Profitability in the area of ISs difficult. System and monetary losses due to illegal activities [86,87].
	Number of customers	Very limited.	Limited with determined, fixed customers.	Limited with partly determined commercial actors and walk-in customers.	If generation meets demand: unlimited.
Social	Social acceptance	Acceptance is earned if system quality is satisfactory, and awareness was created. Neighboring influence is factor [64].	With early engagement, interaction and awareness on operation and use: high acceptance [89].	As a temporal solution according to [76]. Depending on the design, the services offered and the collaboration with the community.	Preferred solution according to [76]. Often mistrust between dwellers and governmental/power utilities [32].
	Dynamic reaction to fluidity of customers	Flexible.	Limited.	Highly flexible.	Limited.
	Vulnerability to illegal activities and theft	Panel theft can occur [90], but overcome by appropriate installation design, social capacity building, and education [76].	By-passing is possible, Non-payment and theft should be included in the maintenance costs (OPEX) [69].	Theft-secure design necessary. Risks of crime when carrying borrowed appliances (BESS, lights) to the HH [76] Deposits for borrowed appliances are to be introduced [46].	Tampering is common via illegal connections and illegal sharing.
	Socioeconomic situation of customers and illegal status	Illegal status irrelevant if upfront costs of SHS can be balanced.	Provision of legal documentation for connection difficult [12].	PAYG, no long-term contracts necessary.	Provision of legal documentation for electricity connection difficult [69].

Table 2. *Cont.*

	KPIs	SHS and Pico Solar	Mini-Grid	Energy-Hub	Grid Extension
Environmental	Complexity of terrain	High complexity [50,77].	Low complexity [50,77].	High complexity, but one free space needs to be accessible.	Low complexity [34,50].
	Density of settlement	Suitable for dense settlements.	Complexity of implementation increases with the density.	One open space necessary, the density of the rest of the settlement is irrelevant.	Complexity of implementation increases with density.
	Spatial implementation area	In both regions, rural and urban areas, implementable.	In both rural and urban area implementable, but rural area is more common.	In both rural and urban areas implementable.	In urban regions, connections are more economical.
	CO_2 footprint	Solar off-grid: 50–160 g $CO_{2\text{-eq}}$/kWh [51,91].			~0 to >1000 g $CO_{2\text{-eq}}$kWh [51], depending on electricity mix.
Political/Regulatory	Legal Barriers	Low	High	High	Low
	Subsidy Framework	Grants and Subsidies are possible. FiTs do not apply due to self-consumption.	Grants and Subsidies possible.	Grants and Subsidies are possible. FiTs do not apply due to self-consumption.	Social tariffs for poor communities with low consumption.
	Local ownership	Individual ownership.	Community ownership is possible, but not universally implemented.	Community ownership likely.	No ownership.
	Capacity building potential	Possible within the SHS frame [92].	High	High	Low

The entries in Table 2, which could not be sufficiently explained in the matrix, will now be discussed in detail.

1. **Technical:**
    - System size: The system sizes are selected according to scientific sources [77–79] based on the local energy needs. One can visit the mentioned research to get a detailed understanding of the sizing approach. The maximum size of an Energy-Hub is set to 35 kW based on the maximum power of existing Energy-Hub concepts [80].
    - Level of energy services and support of PUC: As a point of reference for evaluating the systems, the Multi-Tier Framework (MTF) is being used. While SHS can achieve an MTF of 1–3 [5,76,81] with the possibilities of lighting, phone charging, and media use, such as a radio. Depending on local economic boundary conditions, a Mini-Grid can sustain an MTF level of 3 to 5 [82]. PUCs are often used to ensure the economic sustainability and profitability of the project. The Energy-Hub concept, on the other hand, can provide services to households at low MTF levels and only during the Hub's hours of operation. For the PUCs of the companies located in the Hub, a high energy level can be maintained, although very energy-intensive PUCs must be avoided due to the limited capacity of the Hub.
    - Availability and reliability of the services can basically be classified from low to high as follows: SHS, Grid Extension, Energy-Hub, and Mini-Grid. Although the national grid in Europe, for example, is extremely stable, blackouts and fluctuations can occur regularly in SSA's electricity supply, even in large cities. As described in the introductory section, ISs particularly suffer if their population is connected by an unreliable power supply.
    - Potential for sector coupling: While sector coupling is limitedly possible within the scope of an SHS due to its restricted capacity, the grid should be able to cover the integration of cooling, heating, or e-mobility if the generation is able to match the demand. The Energy-Hub should be planned based on local needs and is limited in dimensions due to the limited free space in ISs. If the need for electrified mobility is communicated in the course of sizing the Hub, it can support sector coupling within a limited range. The Mini-Grid, on the other hand, is often more flexible in its choice of location for energy production due to its planning over a larger area. This enables greater capacities and facilitates the realization of sector coupling.
    - Integration into or transferability to other sites if the national grid arrives: Whilst SHS can either be sold or continuously used in parallel when connected to the grid, the continued operation of a Mini-Grid is more difficult to reconcile with the arrival of the grid. This depends on the operating concept, financing strategy, and relationship with the grid operator. While "moving" a Mini-Grid is not possible, an Energy-Hub can be specially designed, e.g., containerized, to enable transferability to other sites.
    - Upfront requirements and settlement upgrading: SHS is installed and integrated into a building without the need for extensive planning. For Grid Extension and the use of Mini-Grids, on the other hand, a stable, secure neighborhood is needed, and agreements for decentral land use to install the generation source, including infrastructure, such as poles, must be obtained [5]. In some countries, areas need to be significantly redesigned for Grid Expansion—e.g., roads to be electrified, houses need to be made passable for emergency vehicles or houses are not allowed to be built with inflammable materials [34,70]. Land rights must also be obtained for the Energy-Hub, but this is limited to the open space where the system is located. No further settlement upgrading is necessary beyond this. In all cases, the operating and financing model must be established, and information on energy demand must be determined.

Operation and Maintenance (OandM) needs: SHS is being operated with low-voltage direct current and need regular monitoring and maintenance. Furthermore, the owners of the systems need training for correct operation [5,92]. Mini-Grids usually run on a higher voltage. Their hard- and software is complex to operate. Therefore, skilled personnel, who keep the system running, are essential. Knowledgeable local operators are also needed for the Energy-Hub. In the case of Grid Extension, the operator takes care of OandM; therefore, no local expertise is required.

2. **Economic:**
    - Costs: The economic analysis of the technologies in terms of LCOE, capital- (CAPEX) and operational (OPEX) costs, and the associated Return of Investment (ROI) is difficult to standardize across a region as large and diverse as SSA. Many factors, such as local market maturity, financial, and regulatory frameworks in each country, various system sizes and services offered and time and duration of installation, have different impacts on system costs and revenues. Especially policies that enable the implementation of feed-in-tariffs or tax cuts. Accordingly, only a ranking of the respective technologies and a range based on underlying literature values are presented. The "Mini-Grid space" [77] (p 20) compares the unsubsidized electricity retail costs of the options Grid Expansion, SHS, and Mini-Grids. Comparison criteria are building density, size and economic power of an area, proximity to the electricity grid, and terrain complexity. The electricity costs of SHS remain relatively constant and expensive to purchase per capita, regardless of the factors mentioned. They are characterized by high CAPEX and low OPEX [24]. The high upfront costs are a major barrier for financially restrained customers. The development of flexible financing systems, e.g., through the introduction of "pay as you go" (PAYG) or the leasing of SHS [92], is becoming more popular, but this is not yet widespread in a standardized way. Due to the dense settlement combined with a large community and the short distance to the legal power grid, the option of Grid Extension is most favorable for ISs from an economic point of view. Only with increasing rurality, i.e., in communities of medium density and higher distance to the grid and free area and high potential of RES generation, Mini-Grids become more economical than the option for Grid Extension. From an economic perspective, Mini-Grids are correspondingly less suitable for deployment in ISs. The cost of Energy-Hubs tends to be slightly lower compared to Mini-Grids because the items for distributed infrastructure and individual power connections are omitted.
    - Number of customers: Whereas the costs and ownership for SHS are usually concentrated on one household, for a Mini-Grid or an Energy-Hub, these are being passed onto many customers. While the Mini-Grid has a static number, the Energy-Hub has a mixture of static (businesses within the Hub offering services) and fluctuant (community using energy services) customers.
3. **Environmental:**
    - Complexity of terrain and density of settlement: As Peterschmidt et al. [77] (p. 20) show in their illustration of the "Mini-Grid space", the potential terrain for (Mini-) Grid deployment must not be too complex, and the building structure not too densely built. There must be sufficient space for infrastructure, such as transmission and distribution cables. In contrast, all that is needed for the Energy-Hub is a free area, whereby the complexity of the terrain and the density of the buildings are irrelevant. For the Energy-Hub, the number of potential customers increases with the density of the settlement.
    - Spatial application area: Due to the high CAPEX of Mini-Grids and the long time to break even, and the lower priority and capacity for Grid Expansion for rural populations, the focus for the implementation of Mini-Grids is in remote, rural areas. Coupled with the ability to integrate the system into the national grid, the

Energy-Hub can be deployed in both urban and rural areas. As the distances between housing and Hub are greater in rural areas, an implementation of the system in urban areas is more advantageous due to a higher potential number of customers.

CO_2 footprint: Since the SHS, Mini Grids, and Energy-Hub solutions are all photovoltaic-based systems and differ in their balance of system, the carbon footprint is considered comparable per kWh. If a BESS or a diesel generator is additionally used, the environmental impact values will increase depending on various parameters, e.g., the BESS technology and capacity or the duration of use of the generator. Antonanzas-Torres [91] identified the range of 100–160 g CO_{2eq}/kWh for a 100% PV-Mini-Grid. In comparison, the emissions of the national power grid are higher, depending on the share of renewable energy in the generation. For example, the energy generation for Nigeria's power grid has about 370 g $CO_{2\text{-}eq}$/kWh and South Africa's 690 g $CO_{2\text{-}eq}$/kWh on average during 2022 [93].

4. **Social:**
   - Social acceptance: Social acceptance depends strongly on experience. Acceptance is "earned" if the quality of the system is satisfactory and sufficient awareness of the benefits of the system is created among residents. Neighborhood influence and affordability is an important factors for acceptance [64]. According to Runsten [76], local charging stations, which can be categorized as Energy-Hubs, do not enjoy a high level of acceptance. An increase can be achieved by analyzing the energy-related needs of the population and designing the Hub accordingly.
   - Vulnerability to illegal activities: Decentralized solutions face a higher risk of falling victim to crime. It is easy to manipulate the infrastructure of the national grid or Mini-Grids towards illegal connections. A centralized system, such as the Energy-Hub, can be more easily protected against crime through a customized design or the selection of a suitable location within a secure compound. The safety of SHS is the responsibility of the facility owners. While panel theft may occur [90], security can be increased with appropriate installation design and social capacity building [76].
   - Illegal status of customers: While official identity documents must be available for legal supply through the national grid or Mini-Grids, services in an Energy-Hub can be paid for in advance or tied to the service (PAYG) without contracts or identification required. SHS could also theoretically be purchased once, finances permitting, without relevance to the status of the purchaser.
   - Fluidity of customers: The owner of an SHS product is an operator and can resell independently. The fluidity of customers is limited for Mini-Grids and Grid Extension due to fixed connections. With the laying of the power line, an investment is being made in a new customer.

Although operators are compensated by high connection costs, a high turnover means significant additional efforts. Due to the service-based concept, such as the status of the customers, a high fluctuation among the customers of the Energy-Hub is irrelevant.

4. **Political/Regulatory:**
   - Legal barriers: The Grid Extension option is not affected by legal but rather by political barriers, as already mentioned. The necessity of restructuring the settlement can be cited as a legal barrier (see "Technical: Upfront requirements"). Legal obstacles mainly affect RES. The duration and costs of receiving permission to build a Mini-Grid differ from country to country in SSA [94]. There are often no regulations for integration of the Mini-Grid for the case when the grid arrives [95]. This makes the deployment of Mini-Grids in ISs difficult, as their inhabitants often either live close to the grid or even have unreliable or illegal electricity connections. In Mozambique, the operation, including selling of electricity parallel to the existing national grid, is not legal [34], which hinders the implementation of RES-based solutions in ISs further. Due to their individual application without

the need for feed-in tariffs and their clearly regulated ownership, SHS encounters lower legal barriers.

- Subsidy framework: Since affordability is the key requirement in ISs, several authors call for tax incentives, such as reduced VATs and import duties for, e.g., solar panels, which encourages their use [96]. The prevailing energy poverty can be addressed by introducing social tariffs. This is applicable to each of the four technologies.
- Local ownership: Local ownership for SHS is ensured, while no ownership is possible with the option of Grid Expansion. Various models exist for Mini-Grids, and the involvement of the local community is increasingly cited as a criterion for sustainable, successful implementation [96,97]. For the success of the Energy-Hub, on the other hand, local ownership is defined as a conceptual component.
- Capacity building potential: The potential for local development by providing education, training, and knowledge exchange is possible to be implemented with all presented technologies. Local expertise in retail, OandM is essential for maintaining customer satisfaction and high product quality [92]. With its low complexity for installation, operation, and maintenance, SHS technology is particularly suitable for capacity building. Part of the Energy-Hub system is to provide education, which could serve as an initial training ground and dissemination of local expertise.

5. Discussion and Outlook

In the case of an area to be electrified, a decision must be made on the technology to be utilized. This selection depends on the local conditions and the regulatory, institutional, and economic framework. The substantial analysis of the different technologies in this article supports the selection specifically for the implementation of RES in ISs.

Electrification by grid connection of certain areas is often implemented in a systematic order. BloombergNEF [69] developed such a prioritization by first defining area segments based on their population density and average daily income. They then rank the areas according to the order in which they are expected to gain access to the national electricity grid. While urban regions with incomes from $1.9 per day are said to be electrified the fastest, urban areas inhabited by low-income residents, which include slums and ISs, are in second place. Although Grid Expansion would be the most cost-effective option, the many challenges in ISs, ranging from political, and regulatory to socio-cultural, bring other solutions to the foreground.

5.1. Global Assessment of the Potential Solutions

Whereas the previous section dealt with the description of the technologies presented, this section focuses on a concluding evaluation of the options mentioned. The assessment is conducted for the RES-based SHS, Mini-Grids, and Energy-Hub solutions, as these three options are available to private investors for implementation in ISs. The option of Grid Extension is exclusively in the control of the national energy suppliers. The evaluation consists of three levels, namely, “low, not beneficial” (one point), “medium, neutral” (two points), and “high, very beneficial” (three points), as presented in Section 2.1, Figure 4. The evaluation was performed by the author and based on the information elaborated in Table 2. If the assessment of the KPI “Sector coupling potential” is taken as an example, it becomes clear that SHS is the least favorable with “Not suitable”, the Energy-Hub takes second place with “Limited suitable”, and the Mini-Grid is the highest scoring with “Integrable”. If no clear ranking can be made based on the data given in Table 2, the system technologies in the respective category receive the same rating. Table 3 shows the results of the evaluation of the mentioned solutions across the KPIs.

Table 3. Assessment of the solutions and their performance of the parental dimension with one being not beneficial (low) and three being very beneficial (high).

	KPIs	SHS	Mini-Grid	Energy-Hub
Technical	System size	Not applicable		
	Level of energy services and support of PUC	1	3	2
	Availability and reliability of services	1	3	3
	Integrable in national grid	3	3	3
	Distance to national grid	3	2	3
	Sector coupling potential	1	3	2
	Transferable to another site if grid arrives	3	1	3
	Settlement, Household, or Infrastructure upgrading required?	3	1	3
	Operation and Maintenance needs	3	1	1
	Upfront planning requirements	3	1	2
Economic	LCOE	1	2	2
	CAPEX	1	1	2
	OPEX	2	1	1
	Return of investment	3	2	2
	Number of customers	1	1	2
Social	Social acceptance	3	3	2
	Dynamic reaction to fluidity of customers	2	1	3
	Vulnerability to illegal activities and theft	2	1	3
	Socioeconomic situation of customers and illegal status	3	1	3
Environmental	Complexity of terrain	3	1	2
	Density of settlement	3	1	2
	Spatial implementation area	Not applicable		
	CO_2 footprint	3	3	3
Political/ Regulatory	Legal barriers	3	1	1
	Subsidy framework	Not applicable		
	Local ownership	2	3	3
	Capacity building potential	2	3	3

In order to achieve a comprehensive evaluation of the systems, the local weighting, which is carried out with the help of the individual KPIs, is combined with a global weighting. The scores presented in Table 3 are subsequently summed up within their parental category (technical, economic, environmental, social, and political/regulatory). The resulting score for each technology, i.e., its performance in the respective parental category, is thereafter ranked. Figure 6 shows the resulting global weighting of the parental category.

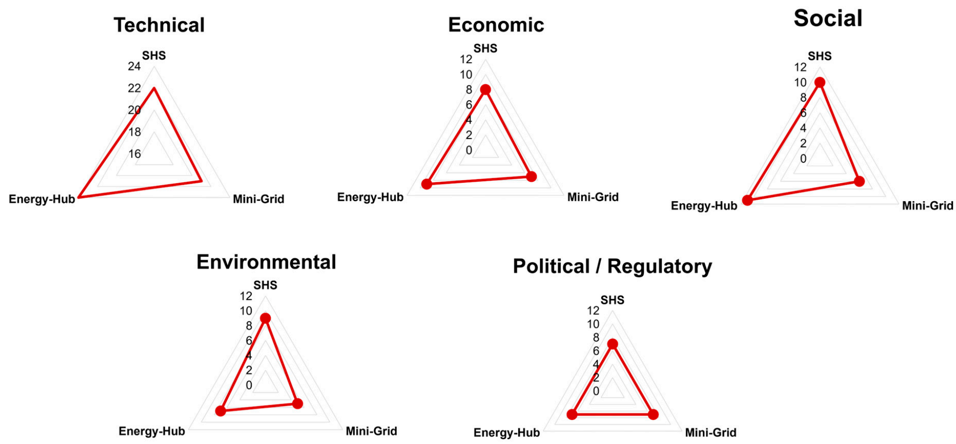

Figure 6. The resulting global weighting of the parental category.

Applying SHS as a private solution allows greater freedom and independence from the possible unreliable power supply and gives the security of ownership. SHS can support households, but higher-capacity solutions are rather suitable for small businesses. SHS can be deployed in a wide range of settings since solely a rooftop is necessary, and without BESS, the impact on the environment is comparatively low. However, the use of SHS is often not affordable for residents. SHS shows a medium score in four out of five criteria in the final evaluation, reflecting the eligibility of SHS only under certain conditions.

Mini-Grids are not particularly suitable for ISs, as they share the weaknesses of the Grid Extension and have fewer strengths. This is reflected in the results of Figure 6, where Mini-Grids score lowest in all but the political category. Apart from the high reliability, their RES-based operation, and the associated climate change mitigation contribution, Mini-Grids are more expensive in CAPEX and OPEX, and more complex to plan, operate, and maintain than the national grid. The density of the settlement, the complexity of the terrain, and the vulnerability of the infrastructure to theft and illegal activities in ISs decrease the attractiveness of Mini-Grids in comparison to other solutions.

The decentralized Energy-Hub is another solution for such dense areas because of its scalable and modular approach, which allows adaptability to local demands. The Energy-Hub, and SHS, is not a competitor to grid connections or Mini-Grids since it cannot achieve universal access for every household. It is a small-scale, sustainable solution that can provide flexible, independent use of energy services as needed when settlement upgrading is not planned in an ISs. The additional expense due to frequent resident fluctuation is eliminated when using the Energy-Hub. The smaller capacity of the Hub allows for a limited but more flexible number of customers than Mini-Grids. Additionally, a protected Energy-Hub can minimize illegal activities and crimes, such as theft. The challenge of the Energy-Hub is to add value and willingness to pay for services in a system with an unreliable energy supply and consumption-independent payment in the case of illegal connections. Ownership, such as having one's own electricity connection, is more attractive than borrowing a battery system or lights. Accordingly, energy services that cannot be provided by an unreliable grid supply should be offered. Looking at the matrix in Table 3, it is becoming apparent that compared to the other technologies, the Energy-Hub overall has an advantage in responding to the challenges in ISs. Figure 6 reflects the results, with the Energy-Hub scoring highest in three of five categories.

The many challenges call for a more comprehensive approach that needs to support the local economy. Efforts to advance ISs electrification should be embedded in a system of assistance for its population. The government needs to provide an enabling environment, including a sound regulatory framework and subsidies to assist low-income households.

Utilities must be willing to engage in activities that are outside of their standard role, notably in designing and implementing approaches and business models keyed to informal realities [31].

5.2. Limitations of the Study

This article does not claim to be exhaustive and cannot cover all articles published on the topic analyzed. Only a limited number of KPIs could be considered. The ranking of the technical solutions is based on the author's assessment of the literature review. For this article, a relative ranking was chosen. The work is based on the literature and stays in the theoretical area of research. The accuracy of the local weighting of the individual KPIs is limited in that it is based on the respective literature, which deals with many different ISs. The authors focused on ISs in Kenya as a research subject. The challenges mentioned can occur in the respective ISs, but do not have to in their entirety. A direct transferability to all ISs in the whole of SSA is thus not given. The underlying work describes a general tendency of the suitability of the respective technologies. In individual cases, the suitability of the respective technologies must be checked when potentially implementing a system. With as much involvement of the local community as possible, interviews with stakeholders such as small entrepreneurs, residents, illegal energy providers, or authority figures within the neighborhood of the ISs can reveal which solutions are suitable.

6. Conclusions

This article analyses and compares different RES-based solutions, namely, Mini-Grids, SHS, and the Energy-Hub with the option of Grid Extension. The aim of the article is to discuss which of the four systems can best contribute to improving the electricity supply in ISs in SSA. The technologies are evaluated comprehensively on the basis of 24 KPIs in the areas of technology, economy, environment, society, and politics. Subsequently, a comprehensive assessment of the potential solutions is being implemented.

In the course of the analysis, it becomes clear that diverse solutions are needed in complex, rapidly merging, dynamic ISs, since network expansion, as is usual in urban areas, is not always feasible in informal regions. Although SHS can usefully support individual households, this technology is unlikely to support the local economy due to its low energy provision. While the dense structures in ISs as and the high costs, can be an obstacle to the implementation of a Mini-Grid, the Energy-Hub is a valid alternative for the fast-changing environments in ISs. Further research needs to be implemented in-depth: The construction and installation of the Energy-Hub are to be implemented at a potential location and extensive, long-term monitoring is to take place. Particular attention should be paid to economic profitability and the adoption of the most suitable operational strategy. Since projects and efforts to improve infrastructure in ISs have already failed, a study to specifically identify the causes of failure is recommended.

Author Contributions: Conceptualization, R.B. and K.M.; methodology, R.B. and K.M.; writing—original draft preparation, R.B.; writing—review and editing, K.M.; visualization, R.B.; supervision, W.Z.; project administration, W.Z.; funding acquisition, W.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Federal Ministry of Education and Research (BMBF) of the Federal Republic of Germany within the funding program "Promoting research on resilience-building and structure-building in African cities and urban areas" under the project "SEED" (Project 01DG21015A). The authors acknowledge support by the German Research Foundation and the Open Access Publication Fund of Technische Hochschule Ingolstadt.

Data Availability Statement: Not applicable.

Acknowledgments: The authors acknowledge the library of Technische Hochschule Ingolstadt to provide needful resources and support.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Odarno, L. Closing Sub-Saharan Africa's Electricity Access Gap: Why Cities Must Be Part of the Solution. Available online: https://www.wri.org/insights/closing-sub-saharan-africas-electricity-access-gap-why-cities-must-be-part-solution (accessed on 12 March 2023).
2. The World Bank Group. Urban Population Growth (Annual %)—Sub-Saharan Africa. Available online: https://data.worldbank.org/indicator/SP.URB.GROW?name_desc=false&locations=ZG (accessed on 23 February 2023).
3. UNECE. *Search for Sustainable Solutions for Informal Settlements in the ECE Region: Challenges and Policy Responses*; UNECE: Geneva, Switzerland, 2008.
4. Jimenez-Huerta, E.R. Informal Settlements. In *The Wiley Blackwell Encyclopedia of Urban and Regional Studies*; Orum, A.M., Ed.; Wiley: Hoboken, NJ, USA, 2019; pp. 1–4. ISBN 9781118568453.
5. Conway, D.; Robinson, B.; Mudimu, P.; Chitekwe, T.; Koranteng, K.; Swilling, M. Exploring hybrid models for universal access to basic solar energy services in informal settlements: Case studies from South Africa and Zimbabwe. *Energy Res. Soc. Sci.* **2019**, *56*, 101202. [CrossRef]
6. Gaunt, T.; Salida, M.; Macfarlane, R.; Maboda, S.; Reddy, Y.; Borchers, M. Informal Electrification in South Africa. *Sustain. Energy Afr.* **2012**, *8*, 2020.
7. Nassar, D.M.; Elsayed, H.G. From Informal Settlements to sustainable communities. *Alex. Eng. J.* **2018**, *57*, 2367–2376. [CrossRef]
8. Satterthwaite, D.; Archer, D.; Colenbrander, S.; Dodman, D.; Hardoy, J.; Mitlin, D.; Patel, S. Building Resilience to Climate Change in Informal Settlements. *One Earth* **2020**, *2*, 143–156. [CrossRef]

9. Muungano Alliance. *Situational Analysis: Mukuru Kwa Njenga, Kwa Reuben & Viwandani*; Mukuru: Nairobi, Kenya, 2017.
10. Muraguri, L. Kenyan Government Initiatives in Slum Upgrading. *East Afr. Rev.* **2011**, *44*, 119–127. [CrossRef]
11. Cheseto, M.N. Challenges in Planning for Electricity Infrastructure in Informal Settlements: Case of Kosovo Village, Mathare Valley—Nairobi. Master's Thesis, University of Nairobi, Nairobi, Kenya, 2013. Available online: http://erepository.uonbi.ac.ke/bitstream/handle/11295/56433/Cheseto%2CMoses%20N_Challenges%20in%20planning%20for%20electricity%20infrastructure%20in%20informal%20settlements.pdf?sequence=3&isAllowed=y (accessed on 11 December 2022).
12. Butera, F.M.; Adhikari, R.S.; Caputo, P.; Facchini, A. The challenge of energy in informal settlements. A review of the literature for Latin America and Africa. In *Analysis of Energy Consumption and Energy Efficiency in Informal Settlements of Developing Countries*; Working Paper Series (in Press); Enel Foundation: Roma, Italy, 2015; pp. 1–32. Available online: https://www.enelx.com/content/dam/enel-found/topic-download/The%20challenge%20of%20Energy%20in%20Informal%20settlements.pdf (accessed on 23 May 2022).
13. Silva, E. Sustainable Development. Slums, Informal Settlements, and the Role of Land Policy. 2018. Available online: https://www.lincolninst.edu/publications/articles/sustainable-development (accessed on 26 August 2021).
14. OECD. Informal Settlements Definition. Available online: https://stats.oecd.org/glossary/detail.asp?ID=1351 (accessed on 26 August 2021).
15. IEA. The Pandemic Continues to Slow Progress towards Universal Energy Access. Available online: https://www.iea.org/commentaries/the-pandemic-continues-to-slow-progress-towards-universal-energy-access (accessed on 23 August 2022).
16. World Bank Group. Access to Electricity, Urban (% of Urban Population) | Data. Available online: https://data.worldbank.org/indicator/EG.ELC.ACCS.UR.ZS (accessed on 10 August 2022).
17. González-Eguino, M. Energy Poverty: An Overview. *Renew. Sustain. Energy Rev.* **2015**, *47*, 377–385. [CrossRef]
18. Takase, M.; Kipkoech, R.; Essandoh, P.K. A comprehensive review of energy scenario and sustainable energy in Kenya. *Fuel Commun.* **2021**, *7*, 100015. [CrossRef]
19. Karekezi, S.; Kimani, J.; Onguru, O. Energy access among the urban poor in Kenya. *Energy Sustain. Dev.* **2008**, *12*, 38–48. [CrossRef]
20. Njoroge, P.; Ambole, A.; Githira, D.; Outa, G. Steering Energy Transitions through Landscape Governance: Case of Mathare Informal Settlement, Nairobi, Kenya. *Land* **2020**, *9*, 206. [CrossRef]
21. Barbieri, J.; Riva, F.; Colombo, E. Cooking in refugee camps and informal settlements: A review of available technologies and impacts on the socio-economic and environmental perspective. *Sustain. Energy Technol. Assess.* **2017**, *22*, 194–207. [CrossRef]
22. Amesa, R.O. An Analysis of Determinants of Adoption of Clean Energy Cooking Technologies and Energy Sources in Kibera, Nairobi County—Kenya. Ph.D. Thesis, University of Nairobi, Nairobi, Kenya, 2019. Available online: http://erepository.uonbi.ac.ke/bitstream/handle/11295/109443/Amesa_An%20Analysis%20of%20Determinants%20of%20Adoption%20of%20Clean%20Energy%20Cooking%20Technologies%20and%20Energy%20Sources%20in%20Kibera%2C%20Nairobi%20County%20-%20Kenya.pdf?sequence=1 (accessed on 14 March 2023).
23. M-GAS LIMITED. Introducing M-Gas—Furahia Upishi Wako. Available online: https://mgas.ke/ (accessed on 14 March 2023).
24. Kamau, A.L.W. The Challenges in Preventing and Fighting Structural Fires in Nairobi's Informal Settlements. Master's Thesis, University of Nairobi, Nairobi, Kenya, 2007. Available online: http://erepository.uonbi.ac.ke:8080/handle/123456789/6270 (accessed on 14 March 2023).
25. Cotton, M.; Kirshner, J.; Salite, D. The Politics of Electricity Access and Environmental Security in Mozambique. In *Energy and Environmental Security in Developing Countries*; Asif, M., Ed.; Springer International Publishing: Cham, Switzerland, 2021; pp. 279–302. ISBN 978-3-030-63653-1.
26. Bhatia, M.; Angelou, N. *Beyond Connections: Energy Access Redefined*; ESMAP Technical Report 008/15; World Bank: Washington, DC, USA, 2015; Available online: https://openknowledge.worldbank.org/handle/10986/24368 (accessed on 13 September 2022).
27. Dumitrescu, R.; Groh, S.; Philipp, D.; von Hirschhausen, C. Swarm Electrification: From Solar Home Systems to the National Grid and Back Again? In *Sustainable Energy Solutions for Remote Areas in the Tropics*, 1st ed.; Gandhi, O., Srinivasan, D., Eds.; Springer: Cham, Switzerland, 2020; pp. 63–80. ISBN 978-3-030-41951-6.
28. GNESD. *Country Report (Kenya): Energy Poverty in Developing Countries' Urban Poor Communities: Assessments and Recommendations. Urban and Peri-Urban Energy Access III*; Report Prepared for the Global Network on Energy for Sustainable Development by The Energy, Environment and Development Network for Africa (AFREPREN/FWD); African Energy Policy Research Network (AFREPREN/FWD): Nairobi, Kenya, 2014.
29. Blimpo, M.; McRae, S.; Steinbuks, J. *Why Are Connection Charges So High? An Analysis of the Electricity Sector in Sub-Saharan Africa*; World Bank: Washington, DC, USA, 2018.
30. Singh, R.; Wang, X.; Ackom, E.; Reyes, J. *Energy Access Realities in Urban Poor Communities of Developing Countries: Assessments and Recommendations*; Report Prepared for the Global Network on Energy for Sustainable Development (GNESD) by the Energy and Resources Institute (TERI) and the GNESD Secretariat. Summary for Policy-Makers; GNESD-SPM-UPEAI II-01/2015; Global Network on Energy for Sustainable Development (GNESD); UNEP DTU Partnership: Copenhagen, Denmark, 2015; ISBN 978-87-93130-21-0.
31. Rutu, D.; Smyser, C.; Koehrer, F. *Where and How Slum Electrification Succeeds: A Proposal for Replication*; Live Wire 2019/100; World Bank: Washington, DC, USA, 2019; Available online: https://openknowledge.worldbank.org/handle/10986/31896 (accessed on 12 September 2022).

32. Broto, V.C.; Stevens, L.; Ackom, E.; Tomei, J.; Parikh, P.; Bisaga, I.; To, L.S.; Kirshner, J.; Mulugetta, Y. A research agenda for a people-centred approach to energy access in the urbanizing global south. *Nat. Energy* **2017**, *2*, 776–779. [CrossRef]
33. van der Kroon, B.; Brouwer, R.; van Beukering, P.J. The energy ladder: Theoretical myth or empirical truth? Results from a meta-analysis. *Renew. Sustain. Energy Rev.* **2013**, *20*, 504–513. [CrossRef]
34. Melo, J., Jr. *Os Desafios e Oportunidades de Acesso a Energia em Assentamentos Informais: Perspectivas do Município de Maputo [PowerPoint Slides]*; Universidade Eduardo Mondlane: Maputo, Mozambique, 2022.
35. Muchiri, E. The Dark Slum. *Muungano wa Wanavijiji*. 24 March 2016. Available online: https://www.muungano.net/browseblogs/2016/03/24/the-dark-slum (accessed on 10 December 2021).
36. Christley, E.; Ljungberg, H.; Ackom, E.; Fuso Nerini, F. Sustainable energy for slums? Using the Sustainable Development Goals to guide energy access efforts in a Kenyan informal settlement. *Energy Res. Soc. Sci.* **2021**, *79*, 102176. [CrossRef]
37. Kovacic, Z.; Musango, J.K.; Ambole, L.A.; Buyana, K.; Smit, S.; Anditi, C.; Mwau, B.; Ogot, M.; Lwasa, S.; Brent, A.C.; et al. Interrogating differences: A comparative analysis of Africa's informal settlements. *World Dev.* **2019**, *122*, 614–627. [CrossRef]
38. Sverdlik, A.; Mitlin, D.; Dodman, D. Realising the Multiple Benefits of Climate Resilience and Inclusive Development in Informal Settlements, New York. 2019. Available online: https://www.citiesalliance.org/resources/publications/cities-alliance-knowledge/realising-multiple-benefits-climate-resilience-and (accessed on 19 November 2021).
39. Akella, A.K.; Saini, R.P.; Sharma, M.P. Social, economical and environmental impacts of renewable energy systems. *Renew. Energy* **2009**, *34*, 390–396. [CrossRef]
40. Castán Broto, V.; Salazar, D.; Adams, K. Communities and urban energy landscapes in Maputo, Mozambique. *People Place Policy Onlines* **2014**, *8*, 192–207. [CrossRef]
41. IRENA. *Off-Grid Renewable Energy Solutions to Expand Electricity Access: An Opportunity Not to Be Missed*; IRENA: Abu Dhabi, United Arab Emirates, 2019. Available online: https://www.irena.org/publications/2019/Jan/Off-grid-renewable-energy-solutions-to-expand-electricity-to-access-An-opportunity-not-to-be-missed (accessed on 25 January 2022).
42. Muungano Alliance. Youth Priorities: Mathare, Mukuru, Kibera, Nairobi, Kenya. 2022. Available online: https://www.muungano.net/publicationslibrary/2022/8/11/youth-priorities-9-demands-1-appeal (accessed on 3 December 2022).
43. Janda, K.; Fennell, P.; Johnson, C.; Tomei, J.; Lemaire, X. Towards inclusive urban building energy models: Incorporating slum-dwellers and informal settlements (IN-UBEMs). In Proceedings of the European Council for an Energy-Efficient Economy Summer Study, Belambra Presqu'île de Giens, France, 3–8 June 2019.
44. Jaglin, S. Off-Grid Electricity in Sub-Saharan Africa: From Rural Experiments to Urban Hybridisations. halshs-02078148. 2019. Available online: https://shs.hal.science/halshs-02078148 (accessed on 2 March 2023).
45. Technische Hochschule Ingolstadt. SEED Initiative—Sustainable Energy Education Districts. Available online: https://www.seed-initiative.org/ (accessed on 13 March 2023).
46. Knobloch, C.; Hartl, J. The Energy Kiosk Model. Current Challenges and Future Strategies. Issue 01. 2014. Available online: https://2020.endeva.org/publication/the-energy-kiosk-model-current-challenges-and-future-strategies (accessed on 31 August 2021).
47. Resch, M.; Breyer, C.; Harborth, N.; Gaudchau, E.; Schnorr, F.; Wolff, M.; Bartschat, A. *Solarkiosk–Abschlussbericht RLI*; RLI gGmbH: Brussels, Belgium, 2012. [CrossRef]
48. Tavernier, L.; Rakotoniaina, S. *Review of Energy Kiosk Development Projects*; Field Actions Science Report; Special Issue 15; Institut Veolia: Aubervilliers, France, 2016; pp. 66–67. Available online: https://journals.openedition.org/factsreports/4165 (accessed on 27 March 2023).
49. Chen, M. Optimal Electrification Planning in Sub-Saharan African Countries. Master's Thesis, The University of Texas at Austin, Austin, TX, USA, 2021. Available online: https://hdl.handle.net/2152/114794 (accessed on 14 March 2023).
50. Blechinger, P.; Köhler, M.; Juette, C.; Berendes, S.; Nettersheim, C. *Off-Grid Renewable Energy for Climate Action—Pathways for Change*; Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ): Bonn, Germany, 2019.
51. Ortega-Arriaga, P.; Babacan, O.; Nelson, J.; Gambhir, A. Grid versus off-grid electricity access options: A review on the economic and environmental impacts. *Renew. Sustain. Energy Rev.* **2021**, *143*, 110864. [CrossRef]
52. Feron, S. Sustainability of Off-Grid Photovoltaic Systems for Rural Electrification in Developing Countries: A Review. *Sustainability* **2016**, *8*, 1326. [CrossRef]
53. Amupolo, A.; Nambundunga, S.; Chowdhury, D.S.P.; Grün, G. Techno-Economic Feasibility of Off-Grid Renewable Energy Electrification Schemes: A Case Study of an Informal Settlement in Namibia. *Energies* **2022**, *15*, 4235. [CrossRef]
54. Bertheau, P.; Oyewo, A.; Cader, C.; Breyer, C.; Blechinger, P. Visualizing National Electrification Scenarios for Sub-Saharan African Countries. *Energies* **2017**, *10*, 1899. [CrossRef]
55. Bhattacharyya, S.C.; Palit, D. The Nexus of Grids, Mini-Grids & Off-Grid Options for Expanding Electricity Access. 2019. Oxford Policy Management. Available online: https://www.researchgate.net/publication/339076931_The_nexus_of_grids_mini-grids_off-grid_options_for_expanding_electricity_access (accessed on 20 September 2022).
56. Rabah, K.V. Integrated solar energy systems for rural electrification in Kenya. *Renew. Energy* **2005**, *30*, 23–42. [CrossRef]
57. Ngowi, J.M.; Bångens, L.; Ahlgren, E.O. Benefits and challenges to productive use of off-grid rural electrification: The case of mini-hydropower in Bulongwa-Tanzania. *Energy Sustain. Dev.* **2019**, *53*, 97–103. [CrossRef]
58. Bahaj, A.; Blunden, L.; Kanani, C.; James, P.; Kiva, I.; Matthews, Z.; Price, H.; Essendi, H.; Falkingham, J.; George, G. The Impact of an Electrical Mini-grid on the Development of a Rural Community in Kenya. *Energies* **2019**, *12*, 778. [CrossRef]

59. Kaygusuz, K. Energy services and energy poverty for sustainable rural development. *Renew. Sustain. Energy Rev.* **2011**, *15*, 936–947. [CrossRef]
60. Den Heeten, T.; Narayan, N.; Diehl, J.-C.; Verschelling, J.; Silvester, S.; Popovic-Gerber, J.; Bauer, P.; Zeman, M. Understanding the present and the future electricity needs: Consequences for design of future Solar Home Systems for off-grid rural electrification. In Proceedings of the 2017 International Conference on the Domestic Use of Energy (DUE), Cape Town, South Africa, 4–5 April 2017; pp. 8–15. ISBN 978-0-9946759-2-7.
61. Okoye, C.O.; Oranekwu-Okoye, B.C. Economic feasibility of solar PV system for rural electrification in Sub-Sahara Africa. *Renew. Sustain. Energy Rev.* **2018**, *82*, 2537–2547. [CrossRef]
62. Payen, L.; Galichon, I. Energy Access in Rural Togo: The Relevance Of The Energy Kiosk Solution, Paris. 2017. Available online: https://www.enea-consulting.com/en/publication/energy-kiosk-a-solution-for-rural-electrification-in-togo/ (accessed on 3 September 2021).
63. Rabetanetiarimanana, J.C.I.; Radanielina, M.H.; Rakotondramiarana, H.T. PV-Hybrid Off-Grid and Mini-Grid Systems for Rural Electrification in Sub-Saharan Africa. *Smart Grid Renew. Energy* **2018**, *9*, 171–185. [CrossRef]
64. Opiyo, N.N. Impacts of neighbourhood influence on social acceptance of small solar home systems in rural western Kenya. *Energy Res. Soc. Sci.* **2019**, *52*, 91–98. [CrossRef]
65. Mandelli, S.; Barbieri, J.; Mereu, R.; Colombo, E. Off-grid systems for rural electrification in developing countries: Definitions, classification and a comprehensive literature review. *Renew. Sustain. Energy Rev.* **2016**, *58*, 1621–1646. [CrossRef]
66. Peters, J.; Sievert, M. Impacts of rural electrification revisited—The African context. *J. Dev. Eff.* **2016**, *8*, 327–345. [CrossRef]
67. Grimm, M.; Munyehirwe, A.; Peters, J.; Sievert, M. A First Step up the Energy Ladder? Low Cost Solar Kits and Household's Welfare in Rural Rwanda. *World Bank Econ. Rev.* **2016**, *31*, 631–649. [CrossRef]
68. World Bank Group. Access to Electricity (% of Population)—Sub-Saharan Africa | Data. Available online: https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS?locations=ZG (accessed on 19 April 2023).
69. BloombergNEF. State of the Global Mini-Grids Market Report 2020. 2020. Available online: https://www.seforall.org/system/files/2020-06/MGP-2020-SEforALL.pdf (accessed on 16 August 2022).
70. Bos, K.; Chaplin, D.; Mamun, A. Benefits and challenges of expanding grid electricity in Africa: A review of rigorous evidence on household impacts in developing countries. *Energy Sustain. Dev.* **2018**, *44*, 64–77. [CrossRef]
71. Bhattacharyya, S.C. Review of alternative methodologies for analysing off-grid electricity supply. *Renew. Sustain. Energy Rev.* **2012**, *16*, 677–694. [CrossRef]
72. Purvis, B.; Mao, Y.; Robinson, D. Three pillars of sustainability: In search of conceptual origins. *Sustain. Sci.* **2019**, *14*, 681–695. [CrossRef]
73. Moner-Girona, M.; Bender, A.; Becker, W.; Bódis, K.; Szabó, S.; Kararach, A.G.; Anadon, L.D. A multidimensional high-resolution assessment approach to boost decentralised energy investments in Sub-Saharan Africa. *Renew. Sustain. Energy Rev.* **2021**, *148*, 111282. [CrossRef]
74. Ilskog, E. Indicators for assessment of rural electrification—An approach for the comparison of apples and pears. *Energy Policy* **2008**, *36*, 2665–2673. [CrossRef]
75. Fuso Nerini, F.; Howells, M.; Bazilian, M.; Gomez, M.F. Rural electrification options in the Brazilian Amazon. *Energy Sustain. Dev.* **2014**, *20*, 36–48. [CrossRef]
76. Runsten, S. Energy Provision and Informality in South African Informal Urban Settlements: A Multi-Criteria Sustainability Assessment of Energy Access Alternatives. Bachelor's Thesis, KTH, School of Industrial Engineering and Management (ITM), Energy Technology, Energy Systems Analysis, Stockholm, Sweden, 2015.
77. Franz, M.; Peterschmidt, N.; Rohrer, M.; Kondev, B. Mini-Grid Policy Toolkit: Policy and Business Frameworks for Successful Mini-Grid Roll-Outs, Eschborn. 2014. Available online: https://www.ren21.net/2014-mini-grid-policy-toolkit/ (accessed on 8 August 2022).
78. Bhattacharyya, S.C. Mini-Grids for the Base of the Pyramid Market: A Critical Review. *Energies* **2018**, *11*, 813. [CrossRef]
79. IRENA. *Innovation Landscape Brief: Renewable Mini-Grids*; IRENA: Abu Dhabi, United Arab Emirates, 2019. Available online: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Feb/IRENA_Innovation_Landscape_2019_report.pdf (accessed on 17 September 2021).
80. OMC Power Private Limited 603. Micropower Plant. Available online: https://www.omcpower.com/page/whatwedo (accessed on 31 March 2023).
81. Narayan, N.; Chamseddine, A.; Vega-Garita, V.; Qin, Z.; Popovic-Gerber, J.; Bauer, P.; Zeman, M. Exploring the boundaries of Solar Home Systems (SHS) for off-grid electrification: Optimal SHS sizing for the multi-tier framework for household electricity access. *Appl. Energy* **2019**, *240*, 907–917. [CrossRef]
82. Mukoro, V.; Sharmina, M.; Gallego-Schmid, A. A review of business models for access to affordable and clean energy in Africa: Do they deliver social, economic, and environmental value? *Energy Res. Soc. Sci.* **2022**, *88*, 102530. [CrossRef]
83. Bhattacharyya, S.C.; Palit, D. A critical review of literature on the nexus between central grid and off-grid solutions for expanding access to electricity in Sub-Saharan Africa and South Asia. *Renew. Sustain. Energy Rev.* **2021**, *141*, 110792. [CrossRef]
84. González-García, A.; Ciller, P.; Lee, S.; Palacios, R.; de Cuadra García, F.; Pérez-Arriaga, J.I. A Rising Role for Decentralized Solar Minigrids in Integrated Rural Electrification Planning? Large-Scale, Least-Cost, and Customer-Wise Design of Grid and Off-Grid Supply Systems in Uganda. *Energies* **2022**, *15*, 4517. [CrossRef]

85. Carrasco, L.M.; Narvarte, L.; Lorenzo, E. Operational costs of A 13,000 solar home systems rural electrification programme. *Renew. Sustain. Energy Rev.* **2013**, *20*, 1–7. [CrossRef]
86. Mgwali, T. City Power pounces on illegal connections in informal settlement near Ruimsig. *Roodepoort Record*. 6 June 2022. Available online: https://roodepoortrecord.co.za/2022/06/06/city-power-pounces-on-illegal-connections-or-city-power-pounces-on-illegal-connections-in-informal-settlement-near-ruimsig/ (accessed on 4 April 2023).
87. Omondi, A. Kenya Power Targets to Recover KSh 2b from Illegal Connections in Slum Areas. *TUKO.co.ke*. 5 November 2021. Available online: https://www.tuko.co.ke/411711-kenya-power-targets-recover-ksh-2b-illegal-connections-slum-areas.html (accessed on 4 April 2023).
88. Sarker, S.A.; Wang, S.; Adnan, K.M.M.; Anser, M.K.; Ayoub, Z.; Ho, T.H.; Tama, R.A.Z.; Trunina, A.; Hoque, M.M. Economic Viability and Socio-Environmental Impacts of Solar Home Systems for Off-Grid Rural Electrification in Bangladesh. *Energies* **2020**, *13*, 679. [CrossRef]
89. Antonanzas-Torres, F.; Antonanzas, J.; Blanco-Fernandez, J. State-of-the-Art of Mini Grids for Rural Electrification in West Africa. *Energies* **2021**, *14*, 990. [CrossRef]
90. Azimoh, C.L.; Wallin, F.; Klintenberg, P.; Karlsson, B. An assessment of unforeseen losses resulting from inappropriate use of solar home systems in South Africa. *Appl. Energy* **2014**, *136*, 336–346. [CrossRef]
91. Antonanzas-Torres, F.; Antonanzas, J.; Blanco-Fernandez, J. Environmental life cycle impact of off-grid rural electrification with mini grids in West Africa. *Sustain. Energy Technol. Assess.* **2021**, *47*, 101471. [CrossRef]
92. Kizilcec, V.; Parikh, P. Solar Home Systems: A comprehensive literature review for Sub-Saharan Africa. *Energy Sustain. Dev.* **2020**, *58*, 78–89. [CrossRef]
93. Electricity Maps ApS. Live 24/7 CO_2 Emissions of Electricity Consumption. Available online: https://app.electricitymaps.com/map?lang=de (accessed on 17 March 2023).
94. Eales, A.; Unyolo, B. Renewable Energy Mini-Grids in Malawi: Status, Barriers and Opportunities, Glasgow. 2018. Available online: https://strathprints.strath.ac.uk/64868/ (accessed on 2 April 2023).
95. Numata, M.; Sugiyama, M.; Mogi, G. Barrier Analysis for the Deployment of Renewable-Based Mini-Grids in Myanmar Using the Analytic Hierarchy Process (AHP). *Energies* **2020**, *13*, 1400. [CrossRef]
96. Come Zebra, E.I.; van der Windt, H.J.; Nhumaio, G.; Faaij, A.P. A review of hybrid renewable energy systems in mini-grids for off-grid electrification in developing countries. *Renew. Sustain. Energy Rev.* **2021**, *144*, 111036. [CrossRef]
97. Gill-Wiehl, A.; Miles, S.; Wu, J.; Kammen, D.M. Beyond customer acquisition: A comprehensive review of community participation in mini grid projects. *Renew. Sustain. Energy Rev.* **2022**, *153*, 111778. [CrossRef]