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A review of hybrid renewable energy systems in mini-grids for off-grid electrification in developing countries

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ABSTRACT

Rural communities in developing countries lack access to affordable, reliable, and sustainable forms of energy, which are essential factors for improving living conditions. These communities rely on diesel and kerosene, which are highly polluting compared to renewable energy technologies, to satisfy their energy needs. In this study, hybrid renewable energy systems (HRESs) have been analyzed, which are designed to overcome the fluctuating nature of renewables, for off-grid electrification. The results of this study—which covers many countries and examples—show that the successful integration of HRES is influenced by factors such as government support—and community organization — which is essential to keep these systems operating over the project lifetime. The levelized cost of energy (LCOE) of different mini-grids was compared and analyzed. The results reveal that by comparing the LCOE range of diesel (between USD 0.92/kWh and USD 1.30/kWh), solar photovoltaic (USD 0.40/kWh and USD 0.61/kWh), and hybrid solar photovoltaic/diesel (USD 0.54/kWh to USD 0.77/kWh), diesel is the most expensive technology. Additionally, the study addressed barriers that can hinder the implementation of mini-grids, such as lack of supportive policies and high capital cost. However, governments' incentives are instrumental in lowering capital costs. These results are of particular importance for developing countries, where electricity supply via HRES is often quicker and cheaper than grid extension. The insights from this paper are a good starting point for in-depth research on optimal local design and ownership models, which can help accelerate the implementation, and lower the costs of sustainable electricity supply in remote areas.

1. Introduction and problem statement

It is estimated that 13% of the world's population, especially in the sub-Saharan Africa and South Asia regions, lives without access to electricity [1]. This is due to various factors, such as the lack of financial capability to extend the grid, population density and dispersion characterized by low electrical energy consumption that makes grid-extension infeasible, and other social and cultural aspects.

In these regions, people depend on fossil fuels (diesel and kerosene) to meet their energy needs, due to their easy acquisition and installation, though these fuels have some disadvantages associated with the instability of fuel prices, distances to transport the fuel, high operation and maintenance (O&M) costs, and negative environmental impacts [2,3].

Renewable energy technologies have been recognized by many nations as a solution to overcome the drawbacks of fossil fuels. However, unlike dispatchable resources, renewable energy sources (mainly solar and wind) are intermittent and variable and cannot respond to increasing demand, making it difficult to secure system reliability [4,5]. Additionally, they require high capital investment compared to conventional sources.

Hybrid renewable energy systems (HRESs), typically consisting of renewable energy as the primary sources plus batteries and/or diesel generators as a backup, have been applied to overcome the fluctuating nature of renewables because HRESs can ensure the availability of power when one of the generation sources experiences intermittence. These systems may also lower the costs, and optimize the size of the system components, thereby reducing operation costs and ensuring access to affordable, reliable, and sustainable forms of energy [6,7].

The literature covers three ways of providing electricity for remote areas, namely, grid-extension, mini-grids, and decentralized standalone systems. A comparison of these forms reveals that the grid-extension

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Abbreviations:

AC/DC	Alternating current (AC) and direct current (DC)
AEPC	Alternative Energy Promotion Center
ARE	Alliance for Rural Electrification (ARE)
CO_2	Carbon dioxide
CREDA	Chhattisgarh Renewable Energy Development Agency
CH_4	Methane
DG	Diesel Genset
EEP	Energy and Environment Partnership
EWURA	Energy and Water Utilities Regulatory Authority
FUNAE	Energy fund
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH
GHG	Greenhouse gas
HOMER	Hybrid optimization model for electric renewables
HYBRIDS	Hybrid power system simulation model
HRESs	Hybrid renewable energy systems
IPCC	Intergovernmental panel on climate change
iHOGA	Improved Hybrid Optimization by Genetic Algorithm
kW	Kilowatt
kWh	Kilowatt-hour
LCOE	Levelized cost of energy
LOEE	Loss of energy expected
LOEP	Loss of energy probability
LOLE	Loss of load expected
LOLP	Loss of load probability
MNRE	Ministry of New and Renewable Energy
MCDM	Multi-criteria decision-making
MW	Megawatt
NPC	Net present cost
NGOs	Non-governmental organizations
O&M	Operation and maintenance
PESTEL	Political, economic, social, technological, environmental, and legal
PV	Photovoltaic
REA	Rural electrification agency
RETScreen	Clean energy management software
SHS	Solar Home Systems
SPUG	Small Power Utility Group
SPPs	Small Power Producers
TRNSYS	Transient energy system simulation
UNEP	United Nations Environment Program
USAID	United States Agency for International Development
WBREDA	West Bengal Renewable Energy Development Agency
W_p	Watt peak
VAT	Value-added tax
VEC	Village Energy Committee
VECS	Village Electricity Consumer Societies

option is not a viable solution for rural areas due to the high cost of extending the grid for very low population density and dispersed houses, while standalone solutions are limited to one household/institution. Mini-grids are considered an optimal solution [7,8] for rural electrification compared to the other two options. According to the International Renewable Energy Agency (IRENA) [7,8], mini-grids range from 1 kW to 10 MW and also include micro-grids.

Recently, HRESs have attracted significant attention from researchers due to their reliability and cost-effectiveness in providing electricity for rural and remote communities. There have been several studies addressing the techno-economic performance [8–13] for the adequate utilization of the resources, as well as the size optimization of the hybrid system [14–17].

Additionally, international organizations and donors have also commissioned studies addressing the implementation of mini-grids. The Energy and Environment Partnership (EEP) [18] released a report providing the opportunities and challenges for mini-grids deployment in Africa as well as recommendations for developers. The World Bank, through the Energy Sector Management Assistance Program (ESMAP) [19,20], released studies on the technical and economic assessment of power generation technologies, including mini-grids. The reports provided indicators on the current stage of mini-grid development worldwide, and on mini-grids costs for 2005 and projections for 2010 and 2015. The IRENA [21–27] provided the costs of renewable energy technologies in general, indicating that these costs were declining and will continue to fall up to 2035 and beyond. On the other hand, the Alliance for Rural Electrification (ARE) provided reports on technical configurations of hybrid systems, including the business models [28,29].

These studies provide insights into the techno-economic and implementation aspects of HRESs. However, they do not offer clear evidence of the extent to which these systems have successfully integrated into different communities.

Even though it is not widely addressed in this review, the "user-perceived value" of HRESs is also an important aspect to consider, because the viability throughout the life cycle depends on users' satisfaction. However, little attention has hitherto been given to this aspect. Two publications have been found [30,31] providing methods to better understand the relationship between the needs and the perceived value of the user for rural electrification.

Additionally, scant focus has been given to general reviews of HRESs [32] and social and governance issues [25]. A gap also exists in the literature concerning the costs of mini-grids—few reports present mini-grids and hybrid mini-grid costs precisely—and planning issues that involve the decision-making approach.

The above finding related to the planning issues concurs with the study by the United States Agency for International Development (USAID) [33] suggesting the establishment of a comprehensive rural electrification plan that integrates mini-grid approach, and Zerriffi [34] that considers the use of multi-criteria decision-making (MCDM) methods as an important aspect for the energy planning process and selection of right technologies for the specific local settings.

This study primarily focuses on HRESs, sometimes hybridized with diesel generators as a backup, in the context of mini-grids. It aims to fill the gap by reviewing the existing literature on HRESs by concentrating mainly on experiences of mini-grids implementation in developing countries, the techno-economic performance of mini-grids and hybrid mini-grids, and the primary aspects that can hinder or stimulate the integration of these systems. In particular, it focuses on the policy and regulatory landscape, economic aspects, social, technological, environmental, and legal factors. The main research questions addressed in this study are based on these topics, and are outlined below:

Q1: What has been done so far for mini-grids' integration in developing countries (lessons learned)? Which countries have a good experience?

Q2: Are mini-grids technically and economically viable for rural electrifications? Based on the techno-economic performance, which hybrid combinations are more feasible, and why are others less viable?

Q3: Which are the main aspects that can hinder or stimulate the successful implementation of mini-grids in developing countries?

To answer the research questions, this paper is organized as follows: Section 2 presents the methodology of the study. Section 3 outlines the current stage of development of mini-grids and country experiences. Section 4 discusses the techno-economic performance and reliability of off-grid hybrid systems and undertakes a comparative analysis with grid-connected systems. It includes the discussions on the levelized cost of energy (LCOE) for different mini-grids and hybrid mini-grids and also the main hybrid configurations presented in the literature. Section 5 identifies the main opportunities and barriers to the deployment of these systems, followed by the synthesis in section 6. Finally, section 7 provides the main conclusions and recommendations.

The present study may be of particular importance to developing countries, considering that they are on their early stage of HRES integration. Understanding the main aspects behind the success or failure of these systems is extremely important. Thus, specific opportunities and barriers that strongly influence the integration of HRES in developing countries is the primary objective of this review. They have been clustered based on the political/policy, economic, social, technological, environmental, and legal (PESTEL) analytical framework. Moreover, the study may also be applied for future research in this field.

2. Methodology and approach

This study reviews the existing literature on HRESs with a specific focus on the experiences, the techno-economic performance, and the main aspects that can hinder or stimulate the integration of these systems in developing countries.

The selected articles were extracted from the following scientific journals: Renewable and Sustainable Energy Reviews (43 articles), Renewable Energy (7), Energy (6), Applied Energy (4), Energy Procedia (4), Solar Energy (4), and other journals with the number of articles ranging from 3 to 1. The review also considered publications from international organizations and donors with relevant experience in HRESs distributed as follows: IRENA (14) including its database, World Bank (11), Intergovernmental Panel on Climate Change (IPCC) (6), ARE (5), Renewable Energy Policy Network for the 21st Century (3), USAID, United Nations Environment Programme (UNEP), International Energy Agency, Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH (GIZ), Energy and Environment Partnership (EEP), Department for International Development, African Development Bank, United Nations Industrial Development Organization, among others.

In general, the review found that scientific journals mostly addressed the techno-economic feasibility of hybrid systems, while the information on the implementation of mini-grids, including some case studies, was found primarily in the reports from international organizations and donors.

In this study, the PESTEL tool has been used as an inspiration to cluster the main opportunities and barriers toward mini-grids' integration in developing countries.

The PESTEL is a tool that can be applied for planning or decision-making for an entire project/initiative [35]. PESTEL helps balance the political (government's interventions, including policy framework), economic, social, technological, environmental, and legal aspects. However, none of the studies reviewed used the PESTEL macro-environment analyses specifically for HRESs, although many studies mentioned PESTEL elements; for example, Carvallo et al. [36] identified the policy framework, economic, social, technical, and environmental aspects as important for the sustainability of mini-grids, and Zalengera et al. [37] employed the PESTLE framework to analyze the challenges hindering the development of renewable energy in Malawi.

However, a full PESTEL analysis is not performed in the present study. Regarding the policy/political context, the study was focused on how the policy mechanisms and administrative aspects affect the successful implementation of HRES. In terms of the economic context, it has focused on how financial mechanisms influence the deployment of HRES without going into other aspects of the macro-economic environment. As part of the social context, an analysis of the social acceptance of the systems was made. For technological dimensions of HRES, the emphasis is on the local skills and local capacity to ensure long-term operation of the systems and the technology knowledge and transfer. In terms of the environmental context, the local environmental impact of the technologies is discussed, while the legal context focused on the incentives for mini-grids' implementation.

In addition to the literature review, semi-structured qualitative interviews with experts in off-grid electrification were conducted in Mozambique, allowing to identify specific socio-economic barriers.

3. Overview of mini-grid developments

3.1. Current stage of development

The off-grid electrification provided by diesel generators was one of the first and most applicable solutions for the electrification of rural villages. Later, due to the slow and unpredictable expansion in the main grid, especially in remote/rural areas, a large number of decentralized solar home systems (SHS), few solar mini-grids, and mini-hydro systems emerged. Diesel-based systems are currently being progressively replaced or hybridized by renewable energy.

In this section, some examples of well documented mini-grid developments are presented. Mini-grids' achievements in terms of installed capacity have been summarized in Appendix A, and examples of mini-grids based on different technologies deployed in many countries are illustrated in Appendix B.

A recent report from IRENA [38] indicates an installed capacity of 12,000 MW of mini-grids worldwide. However, it is unclear whether this represents only the renewable-based mini-grids or also includes diesel mini-grids. It is estimated that between 2008 and 2016, the number of people connected to renewable mini-grids, particularly small hydro and solar photovoltaic (PV), increased significantly from 0.2 million to 1.3 million across Africa, from approximately 3 million to 8.8 million across Asia [39,40]. Additionally, the World Bank, through the ESMAP [19], released a technical report in 2019, estimating that at least 19,000 mini-grids, mostly based on diesel, hydropower, and solar PV, had been installed in 134 countries worldwide.

Developing Asian countries have been relatively successful in deploying mini-grids for rural electrification owing to their efforts in establishing rural electrification programs, with policies and incentives to stimulate private sector participation and community organizations to ensure long-term operation. China, India, Nepal, Sri Lanka, the Philippines, Indonesia, Cambodia, Afghanistan, Myanmar, and Bangladesh are among the countries where a significant number of people have benefited from mini-grids. In Africa, the penetration of mini-grid systems remains low for some countries such as Malawi and Mozambique. It is observed that countries with low penetration neither have a law nor a regulatory framework for mini-grids [19,41–44].

Sri Lanka, Nepal, Tanzania, and parts of India have witnessed notable developments in hydropower mini-grids, while Mali, Indonesia, Cambodia, and the Philippines predominantly have diesel mini-grids, indicating the potential for hybridization. Solar PV is dominant in Bangladesh and India [41–43]. African countries like Tanzania, Mali, and Morocco are considered leaders in electrification through mini-grids. However, the largest hybrid solar PV/diesel generator are located in Koro (384 kW) and Bankass (384 kW) in Mali and Tsumkwe (202 kW) in Namibia [45,46].

In countries such as India, Nepal, Sri Lanka, Myanmar, and Indonesia, community members play an important role in ensuring the commercial viability of mini-grids by collecting the revenue, which is used to ensure the financial sustainability of the systems. In Sri Lanka, the private sector has been encouraged through a bonus payment for each mini-grid created and takes care of its operation for six months. On the other hand, in Bangladesh, Indonesia, Sri Lanka, India, Nepal, and Tanzania, the government provided incentives that helped lower the generation costs. The summary of the experiences of various countries on mini-grid deployment is presented below, while Table 1 presents an overview of the main aspects behind the successful experiences.

In **China**, the rural electrification with renewable energy has witnessed different phases, from small hydro to solar PV home systems and

Table 1
Summary of some successful experiences in the development of mini-grids, These countries are considered successful examples based on factors such as their efforts to establish rural electrification programs, accompanied by clear policies and incentives to boost the participation of the private sector and the community organization (ownership models) to ensure the financial sustainability and long-term operation of the systems.

Country	Most dominant technology/ resource	Government support mechanisms for mini-grids deployment	Sustainable operation boosted by:	Community role	Private sector role
India	Solar, biomass, and hydro	Policy (Regulatory framework for mini-grids); Fiscal incentives (subsidies).	Clear definition of roles and responsibilities among the stakeholders; Revenue covers the O&M costs; Bonus payment for O&M services provided.	Communities involved in decision-making. Communities are responsible for O&M and setting tariffs in consultation with WBREDA.	Private developers install and manage the systems the mini-grids.
Sri Lanka	Hydro	Fiscal incentives (subsidies) through VECS.	Bonus payment to encourage the private sector and NGOs for each mini-grid created and operational after six months; Payment for the community members' functions in the project.	Community-based cooperatives own and operate the mini-grids.	The private sector covers the O&M costs.
Nepal	Hydro	Fiscal incentives (subsidies) through AEPC to scale up investments in mini-grids.	Communities receive a bonus payment for revenue collection.	Trained communities own and operate the mini-grids, and are responsible for revenue collections.	The private sector provides technical support.
Indonesia	Hydro, and solar to a lesser extent	Fiscal incentives (subsidies, grants, exemption and reduction in import taxes); The government provides funds for the private sector to build mini-grids.	Revenue collected is used to ensure the commercial viability of the mini-grids.	The mini-grids are owned, operated and maintained by the local communities.	The private sector builds the mini-grids in collaboration with communities assisted by NGOs.
Tanzania	Hydro	Policy (regulatory framework for mini-grids); Fiscal incentives (exemptions from VAT and import duty) to reduce the upfront costs. The EWURA introduced SPPs framework to support private sector integration for mini-grids deployment.	Technical support provided by the country's REA.	N/A	Private sector install the mini-grids.

then to hybrid systems. The small hydro mini-grids were initially built and operated in off-grid mode and then fed into the main grid as the central grid was extended [47]. Currently, the country has pursued the development of mini-grids, with the central government supporting the capital costs, while the private entities play an active role in building the small hydropower and solar PV mini-grids [36]. The Township Electrification Program is one of the robust decentralized generation program, launched by the central government in 2001, under which, 377 communities were connected through small scale hydropower and 688 communities through solar PV and hybrid solar PV/wind mini-grids in three years. In 2013, the country had 60,000 diesel and hydro mini-grid, mostly connected to the main grid. Three lessons learned from China's success are extensive local coordination, incorporation of electrification in national development plans, and selection of appropriated technologies [41,43,44].

India has been adopting several policies and programs for the implementation of mini-grids. Various states have implemented mini-grids based on Solar PV, small hydro, and biomass technologies, supported by the government's capital subsidies [43]. Mini-grid development has been conducted by the Ministry of New and Renewable Energy (MNRE) as a policymaker and implemented at the state-level by agencies that have been responsible for the deployment of renewable energy mini-grid.

West Bengal Renewable Energy Development Agency (WBREDA) and the Chhattisgarh Renewable Energy Development Agency (CREDA) implemented the most successful mini-grids models, where the community was designated for mini-grid development. In these cases, the Village Energy Committee (VEC) is incorporated into the decision-making process.

In the case of WBREDA, local communities are engaged from planning to implementation and have been trained for daily operation, while private developers install and manage the systems. The communities have the responsibility of setting tariffs in consultation with WBREDA, collect the revenues, and passing them on to WBREDA. The capital costs are covered by WBREDA and MNRE in equal proportion, while consumer tariffs cover the operations and maintenance costs. On the other hand, CREDA operates and manages the mini-grids and also selects a village operator to take care of the systems, which include the monthly cleaning, switching the systems on and off, and reporting any technical failure. This operator is paid a fixed monthly amount for the services, while an official monitors the installations and replaces the damaged equipment [36,48,49]. The Chhattisgarh state and the MNRE support the capital and O&M costs, which results in low fees [50]. In 2016, the state government of Uttar Pradesh established a strong policy that provided specific guidance for mini-grids development in India [39]. In the period between 2016 and 2017, about 206 mini-grid systems were installed. The Indian state of Uttar Pradesh has made significant strides in the rural electrification process, with about 1850 solar and biomass mini-grids in operation and a capacity installed of approximately 3 MW [39,51,52].

The government of the **Philippines** introduced the private sector participation scheme based on the privatization of power generation that prompted the private sector to lead the mini-grids. The diesel generator was the first form of mini-grids in the country and has been used for electrifying most small island communities. In 1988, the government of the Philippines created a group denominated Small Island and Isolated Grids to establish the maximum electricity tariff for communities served by mini-grids, basically powered by diesel generators. Later, this group was substituted by Small Power Utility Group (SPUG) created to generate electricity for off-grid islands, and subsidize fossil fuel electricity supplied to cooperatives and local government units. The SPUG was operating more than 300 power plants in 2012 with a total capacity of 283 MW [29,53,54]. The Philippines installed approximately 375 MW of diesel-based mini-grids by 2014, under the SPUG's Missionary Electrification Plan, which comprised a strategy for hybridization part of diesel-based mini-grids with solar PV [41,55]. As of 2017, there were 108 diesel mini-grids in different islands of the country [43].

Among the South Asian countries, **Sri Lanka** can be distinguished as the country with a high electrification rate, owing to the government's initiative to create grid electricity infrastructure and develop the vast hydropower resource. The country has successfully implemented micro/mini-hydropower. One of the powerful approaches for the successful operation of the mini-grids is the local community organization in Village Electricity Consumer Societies (VECS) that owns and operates the mini-grids. The VECS is assisted by the private sector and other authors such as non-governmental organizations (NGOs). The private sector and NGOs are encouraged through a bonus payment for each mini-grid they help create and which operates even after six months. Meanwhile, the government, as a provider of subsidies, keeps control over technical specifications. Sri Lanka had 268 isolated community-owned micro-hydropower projects by 2011, with capacities ranging from 3 kW to 50 kW, financed by the government and the World Bank. The private sector had developed 102 small power plants based on small hydropower (92), wind (3), biomass rice (1), waste heat (1), sustainably grown biomass (1), and solar PV (4), all connected to the national grid through the Ceylon Electricity Board. As the grid expanded to isolated villages, the households closer to the grid abandoned the VECS and turned into customers of the Ceylon Electricity Board due to its subsidized tariffs and more hours of supply. Therefore, more than 100 projects were abandoned, and only three mini-grids became small power producers (SPP's) that sell their electricity to the utility company [36,54,56–58].

Similar to Sri Lanka, hydropower mini-grids dominate in **Nepal** owing to the country's abundant hydro resources. The government of Nepal created the Alternative Energy Promotion Center (AEPC) to scale up investment in mini-grids, through community mini-grids and SHS, and grid-extension through the national utility. The AEPC launched a subsidy program to promote rural electrification through mini-grids in 2012, and hydropower mini-grids have become an important part of its rural electrification strategy. The AEPC initially provided subsidies for community and cooperative owned mini-grids (small hydropower with a capacity ranging from 10 kW to 1 MW), and later, privately owned projects became eligible. The program has been successfully implemented and has resulted in more than 2000 mini-grids based on hydropower between 1996 and 2015. Communities have played an important role in ensuring the long-term operation of mini-grids. They are trained to operate and maintain the systems and are paid to collect the revenue, which helps maintain the commercial viability of the mini-grids, while private entities provide technical assistance such as installation and repair. The standalone micro-hydropower are interconnected with each other to ensure the stability of electricity supplied to the grid [36,44,56]. In 2017, an estimated 2600 mini-grids were installed in the country, with 9% of the rural population electrified by micro and pico-hydro systems [59].

Bangladesh introduced fiscal incentives, including reduced import taxes, as well as partial subsidies and loans on renewable energy products to encourage private sector investment and ensure the affordability of the systems that lead to consistent yearly increases in the access rate [60,61]. The Infrastructure Development Company Limited, a government-owned institution, subsidizes the mini-grids through capital grants (up to 50% of project costs) to solar-powered mini-grids and concessional loans (up to 30% of project costs) to mini-grid developers for projects located in rural areas [62]. Mini-grids in Bangladesh are built, owned, operated, and maintained by the private developers. They are mainly systems composed of solar PV with batteries and diesel generators as a backup with capacities varying from 100 kW to 250 kW [62,63]. There is no national tariff policy in the country. All mini-grids charge a similar tariff [62].

The government of **Indonesia** installed many mini-grids based on diesel, hydro, solar PV, and bioenergy technology systems. The country has deployed more than 1300 mini-grids since 1990, of which 1033 mini-grids have been supported by the government. Since 2011, the country has developed 900 mini-grids (with 36 MW installed capacity), some of which are connected to the national grid under the government-specified tariffs. Currently, the country has many islands powered by mini-grids, ranging between 5 kW and 40 kW, based on diesel, small hydro, and solar PV systems. The income collected from these mini-grids is used to ensure the commercial viability of the projects and improve the village social conditions [39,53,54,56,63]. Mini-grids have been supported through subsidies and grants. Similar to Bangladesh, the country has introduced fiscal incentives, including import exemptions, to encourage investments in renewable energy [39]. The private sector receives funds from the government to build the mini-grids in close collaboration with the local community and supported by NGOs, while the ownership and O&M are the responsibility of the communities. Similar to Sri Lanka, with the arrival of the main grid, communities left their mini-grids (about 150) and turned into customers to Perusahaan Listrik Negara, the national grid. The off-grid mini-grid that survives are those that charged lower retail tariffs than the national grid. Nine of the abandoned mini-grids successfully made the transition to grid-connected, under the government tariff scheme, when the main grid arrived in the village [56].

In **Myanmar,** a trilateral agreement model has been adopted that establishes the rights and responsibilities of the village, private sector, and government agency to give grants to mini-grids. The country has various diesel mini-grids in operation stage that can be hybridized with renewables to lower the generation costs and reduce the greenhouse gas (GHG) emissions resulting from fossil fuels. Myanmar also has 12 solar PV mini-grids systems scattered in different villages across the country. Local private entrepreneurs own and operate the mini-grids and other mini-grids are operated by communities selected by a village's electrification committee where the leader of each 10-household block collects the revenue (monthly). Partial subsidies have been adopted in the country to decrease the capital cost of mini-grids [64,65].

Similar to Sri Lanka, **Vietnam** has achieved universal access to electricity, with an access rate above 99%, due to government commitment and the country's willingness to allow many approaches to evolve [59,63]. Vietnam went through various stages for rural electrification development. The most remarkable was the first stage (1994–97), when little attention was given to the term "sustainability" compared to the subsequent stages. In the early stage, the country's main goal was to increase access to electricity by empowering local authorities and communities to build their own systems. However, despite the low quality, the country's electrification rate jumped up from 14% to 61% in just three years. The public utility had a limited role. There were 169 operational off-grid projects in 2011 with a total capacity of 132 MW, including mini-grids. The government or international organizations sponsored most of the projects. Currently, there are many private mini-grids in operation, which include hybrid systems, small hydropower, and solar PV mini-grids, accounting for a substantial part of grid infrastructure [66,67].

In 2004, the government of **Cambodia** created the Rural electrification fund responsible for providing subsidies (grants and low-interest loans, and tariff subsidies) and technical assistance for mini-grids. Meanwhile, the government also offers financial support to encourage private sector in the building and maintenance of the mini-grids. Unlike Nepal and Sri Lanka, in Cambodia, small hydropower is scarce, and most predominant mini-grids are based on diesel generators built and operated by local entrepreneurs. Since the 1990s, the local entrepreneurs have been active in build and operated diesel mini-grids in areas not served by the national grid. Upon the arrival of the main grid in these rural areas, the national utility company, Electricité du Cambodge, attempted to connect hundreds of privately-owned diesel mini-grids, providing more hours of service [39]**.** Similar to Vietnam, the first stage of mini-grid development was marked by the poor quality of supply. At that time, the government was concerned about increasing access to electricity rather than guaranteeing the quality of supply. Today, mini-grids are off-grid or grid-tied, serving about 120,000 customers. With the arrival of the main grid, 250 off-grid mini-grids turned into small power distributors that acquire electricity from the utility company and resell it to the customers, which raised the number of customers from about 100,000 to 1million in 2005 and 2015, respectively. They switched from diesel electricity, which supplied only a few hours during the nights, to 24 h power supply from the national grid increasing the reliability of power supply [56,58,63,68,69].

In **Rwanda**, mini-grid development started years ago with the implementation of solar PV/diesel hybrid in 50 remote health centers, financed by international development partners [41]. In 2015, the Rwanda Utility Regulatory Agency issued a dedicated mini-grid regulatory framework, with specific rules applied for generation capacities below 50 kW exempted from licensing requirements and between 50 kW and 100 kW are qualified for simplified licensing. Private owned and operated mini-grids require grant support between 40% and 70% and capital expenditure subsidies for capacities up to 100 kW. In case the main grid reaches the village supplied by the mini-grid, the operator of the mini-grid can transfer or sell the assets to the utility company, or sell the electricity based on a fixed tariff as a small power producer [39,59,63,70]. The country's installed capacity was 112 kW, of which 61 kW solar PV mini-grids and 11 kW of hydro are operated by private entrepreneurs, while the remaining hydro of 40 kW is operated by community, to be connected to the national grid shortly [71].

Similar to many developing countries, in **Mozambique,** rural electrification started with the extensive use of diesel generators to supply electricity to remote communities. Later, in 1997, the government created the Energy Fund (FUNAE) responsible for off-grid solutions, including mini-grids for remote areas. By 2015, FUNAE had installed 69 diesel mini-grids operated by local communities, although most of them were not operational due to lack of funds for maintenance [72]. Moreover, FUNAE helped expand a large number of decentralized standalone solar PV systems in the country. Mozambique had 12 mini-grids implemented with a capacity installed of approximately 3 MW by 2017, which included 6 solar PV mini-grids ranging from 0.01 MW to 0.55 MW, 5 micro-hydropower implemented by FUNAE and GIZ, and 1 biomass cogeneration of 1.5 MW capacity developed and owned by a sugar factory (Maragra) for their consumption. In addition, 10 solar PV mini-grids have been implemented by 2019, with a total capacity of approximately 0.3 MW increasing the capacity installed to 3.3 MW. However, uncertainty about who will manage the off-grid projects in the future remains. Currently, FUNAE owns and operates the existing off-grid mini-grids, while for small capacities below 10 kW, FUNAE identifies a local management committee in the local communities for the systems' O&M [73–76].

Tanzania has been a regional leader in mini-grid deployment. The country issued a mini-grid regulatory framework and also provided exemptions from value-added tax (VAT) and import duty as an incentive to reduce the upfront costs [77]. In addition, the Energy and Water Utilities Regulatory Authority (EWURA) introduced the SPPs framework to encourage the involvement of the private sector in the development of both off-grid and grid-tied mini-grids. This framework boosted the number of mini-grids, and by 2016, the country had 109 mini-grids, of which 93 were isolated, and the remaining 16 were connected to the main grid. Due to the vast hydro resources, micro/mini-hydropower accounts for the majority of the existing mini-grids with solar contributing only 0.2 MW (13 projects) [39,59,78]. In Tanzania, the private sector installs the mini-grids while the Rural Electrification Agency (REA) provides technical support [43,70]. Faith-based organizations have implemented some hydro mini-grids installed in rural hospitals and schools with assistance from donors and NGOs [79]. The country has installed many hybrid systems ranging from 1 to 10 kW [70].

Like many African countries, **Nigeria** recently started to develop mini-grid projects. In 2017, the government, through the Nigerian Electricity Regulatory Commission, adopted the regulations with comprehensive guidelines to support mini-grids for grid-connected and off-grid systems, to regulate tariffs for grids with distribution capacity of more than 100 kW. Mini-grid developers for isolated mini-grids with generation capacities ranging from 100 kW to 1 MW may ask for a permit, while for capacities up to 100 kW, the registration with Nigerian Electricity Regulatory Commission is enough. Currently, the country has 30 operational mini-grids (mostly based on solar PV-Battery, solar PV-Diesel, and only one based on biogas) with 1 MW of installed capacity, providing electricity to 6000 clients. The REA of Nigeria provides capital cost subsidies, which contributed significantly to the development of mini-grids by ensuring access to financing sources and lowering the tariffs. Some of the mini-grids have hybrid ownership model. The federal government provides the funding while the local communities provide the land and ensure security for the site [39,43,56,70].

Mali is one of the successful countries in the implementation of diesel mini-grids in sub-Saharan Africa, with more than 200 diesel-based systems. In 2003, to boost the private sector participation in the hybridization of diesel mini-grids, the government of Mali established a rural electrification fund for mini-grids' development, covering capital costs, as well as supporting pilot projects and feasibility studies. To offset generation from diesel generators, the Malian Agency for the Development of Domestic Energy and Rural Electrification supports the hybridization with solar PV and batteries by providing financial support and eliminating the VAT on imported and purchased renewable energy equipment. The number of operational mini-grids jumped from none in 2000 to over 160 in 2015. The developers added solar PV to 30 diesel generators during this period. The two largest hybrid solar PV/diesel were implemented in 2013 in Koro and Bankass, each with 384 kW of solar PV and 675 kVA of diesel generator. In 2011, a 216 kWp hybrid solar PV/diesel was installed in Ouéléssébougou village, which was upgraded to 334 kWp in 2015 [43,44,58–60,70].

Similar to other developing countries, in **Kenya,** diesel generators were the primary type of electricity supply. Later, micro/mini-hydropower, solar PV, and wind were introduced in the country by NGOs, faith-based organizations, and research institutions. The government of Kenya set a pilot program to hybridize diesel systems with renewable energy. Consequently, the country had 21 mini-grids, in operation, with approximately 19.16 MW of total capacity installed in 2014, a majority (18.1 MW) from fossil fuels, and the rest from hybrid diesel/solar or diesel/wind. The mini-grids are developed by the country's REA. The Kenya Power and Lighting Company operate and maintain the systems, while NGOs support the community-based mini-grids, and the private sector operates under a variety of business models. To ensure the operation of the mini-grids, the government signed an agreement with the Kenya Power and Lighting Company that retains all revenues generated from the mini-grid for the system's O&M, while the government covers the losses, resulting in increased viability of the systems [41,43,80–83].

Like Kenya, the government of **Senegal** has set up its REA, namely, the Senegalese Agency for Rural Electricity, to attract private investments. Senegal has been actively implementing hybrid mini-grids [29,70]. The country applies the hybrid utility-private ownership model for mini-grids. The government owns the mini-grids and the private sector operates and maintains it, while a local leader in the community is responsible for the revenue collection. The country's REA had implemented 400 mini-grids by 2017, with support from multilateral and development finance institutions [29,84,85].

This section reviewed experiences with mini-grids deployment in different regions. Despite efforts to expand energy services to rural communities, there are still many challenges to reaching the desired result. It has been found that successful implementation of mini-grids was influenced by many factors, in particular regulatory frameworks with clear guidelines such as adopted in India, Rwanda, and Tanzania, community organization and involvement to ensure the long-term operation of these systems, for example, in India and Nepal, and fiscal incentives (exemption and reduction in import taxes) to encourage the private sector to build and operate the mini-grids, such as adopted in Bangladesh and Tanzania. However, the literature also reported challenges such as the lack of specific plans or regulations on what will happen to the mini-grids upon the main grid's arrival in the villages supplied by these systems. For example, in Indonesia and Sri Lanka, the communities abandoned the mini-grids and became customers to the main grid, and the systems were left behind. In contrast, Indonesia established specific rules to connect the mini-grids to the main grid, such as government-specified feed-in tariffs. Thus the off-grid mini-grids successfully transited to grid-connected, which avoided abandoning of the projects.

3.2. Operation/ownership models

Depending on the country or local conditions, utilities, private entrepreneurs, and communities can own, install, manage, operate, and maintain mini-grid systems. The literature has hitherto identified four main types of ownership/operation models, namely, community, private, utility, and hybrid-based models, each with their advantages and disadvantages.

The **community-based model** has a positive impact on the community itself. In this model, communities are mobilized as active stakeholders, providing system maintenance, revenue collection, and management services, in most of the cases with the external support from NGOs. Nevertheless, they need to be formulated and trained to operate and maintain the mini-grid systems. These communities are organized as cooperatives. In the **utility-based model,** an experienced state-owned or private utility owns and operates the mini-grids, mostly subsidized by the government (although, governed by political agendas). **In the private sector-based model,** a private entity owns and manages the mini-grid. Unlike the utility model, private entities do not operate the main grid. However, they provide electricity more efficiently than the community model due to their experience in O&M services. Finally, **the hybrid-based model** may involve different entities owning and operating various parts of the systems, which may be suitable, but also tricky, due to the combination of different technical aspects [29,39,43,86]. The hybrid operation model can be a combination of community-private such as in India, Myanmar, Sierra Leone, Uganda, and Cape Verde or utility-private such as in Senegal. Table 2 presents an overview of the most dominant ownership models in some developing countries. As is evident, they have adopted either one or two types of operating models [29,39,43,45,70,87–91].

Table 2
Dominant ownership/operation models in some developing countries.

Country	Community-based	Utility-based	Private-based	Hybrid-based
India	✓		✓	✓
Pakistan	✓			
Philippines			✓	
Sri Lanka	✓		✓	✓
Lao PDR		✓		
Thailand		✓		
Bangladesh			✓	
Indonesia	✓			
Myanmar	✓		✓	✓
Cambodia			✓	
Nepal	✓			
Tanzania			✓	
Nigeria			✓	
Sierra Leone	✓		✓	✓
Malawi	✓			
Uganda				✓
Namibia		✓		
Kenya		✓		
Tunisia		✓		
Mali			✓	
Rwanda	✓		✓	
Morocco	✓			
Senegal		✓	✓	✓
Cape Verde	✓		✓	✓

4. Techno-economic performance of hybrid mini-grids

4.1. Technical configurations of HRESs

Hybrid systems comprise distributed generator resources (renewables or conventional), energy storage (batteries, loads, and energy control), bus bars, and distribution networks. They can have the benefits of both dispatchable and non-dispatchable power sources, as presented in Table 3. A simple description of the main components of hybrid systems is presented in this section.

The renewable energy technologies that have been used in hybrid systems are solar PV, small or micro-hydro, wind, and biomass. In most of these cases, they are hybridized with conventional diesel generators to increase the reliability and lower the costs of the systems.

Batteries are the most commonly used storage devices, significantly more than super-capacitors and flywheel storages [92]. They store electricity, and are activated when the generation of the renewable energy system is not sufficient to satisfy the load demand. Batteries represent an important element in the cost of electricity during the lifetime of the project due to the need for their regular replacement, usually after every 6 or 8 years [70]. The battery lifetime depends on the manner they are operated and on external conditions, such as ambient temperature and dirt. However, the battery storage market has witnessed significant advancements in the last few years, having shifted from sodium-sulfur to lead-acid batteries due to their reliability and low costs [4,93]. Lead Acid batteries are more used in HRESs. However, they have short lifetime (depending on the management) and low depth of discharge compared to other batteries, such as the expensive lithium-ion battery, which provides better performance, long operating lifetime, and high depth of discharge. Nevertheless, despite the current high initial cost, the lithium-ion is a promising technology, as the cost is likely to drop compared to mature lead-acid batteries [94–98].

The bus bar and local distribution network are also important elements of hybrid systems. Hybrid power generation systems can be classified—according to the voltage they are coupled to—as direct current (DC), alternating current (AC), and mixed (DC and AC) bus. The selection of AC/DC depends on the technologies to be coupled as well as the use of the batteries in the system. . DC loads need inverters to connect to the AC bus. This topology is applicable for small and large scale generators, however, it requires synchronization of the inverter with grid voltage in phase and frequency through the use of grid-synchronization methods such as phase locked loop to avoid the damage of the system due to the flow of large currents [99–101]. Solar PV and batteries usually run on a DC bus bar, which comprises DC loads and resources, providing basic energy services (mostly used in small loads, typically, basic lighting and mobile phone charging).

In contrast, the AC bus bar has been used in most electrical power systems because of its simplicity and flexibility compared to DC in electricity transmission. Diesel generators, wind, and small hydro produces AC power (Fig. 1), and need an AC/DC converter [29,38,64,102–105]. However, wind turbines can produce both AC and DC—small wind turbines produce DC and large wind turbines produce AC. Although diesel generators usually operate in AC, they may also operate in DC (which is not common due to lower efficiency compared to AC), while the batteries receive the load in DC and discharge it in DC. Hybrid AC/DC micro-grids have superior performance over other types of hybrid systems and combine the main advantages of AC and DC micro-grids.

Inverters balance the energy flow between AC and DC. As PV power output is DC and mini-grids operate in AC, an inverter is needed to convert the DC electricity produced into AC electricity to satisfy the AC

Table 3
Description of the main components of HRESs.

Type	Component	Description	Ref.
Non-dispatchable resources	Solar	Solar PV is suitable for many locations. It generates electricity in the form of DC (low voltage) and can be used for DC and AC loads.	[8,29,64,106–109]
	Wind	Wind resources vary from place to place, which makes these resources very site-specific. The resources must be investigated for a certain period (one year or more) before the installation of the system. It produces AC power.	
	Small Hydro	Small hydro is the most cost-attractive technology compared to others. However, it is necessary to have a river with an enough flow rate and volume conditions. For the places where hydro resources are available, it can be used efficiently without combining with other resources, ensuring a continuous supply of energy. It produces AC power.	
Dispatchable resources	Diesel Generator	Diesel generators supply AC power and are important to ensure the power supply when the power output from other technologies is insufficient to meet the demand. However, their use should be minimized as the fuel is expensive.	
	Biomass	The technical and economic viability of biomass is still uncertain. Biomass highly influences the costs of the hybrid system.	
Storage	Battery	Batteries represent a key element of the cost of electricity over the project lifetime due to the need for regular replacement. Charge and discharge of the battery are dependent on the condition of generated power.	[29,110,111]
	Loads	The loads that are to be integrated into hybrid AC/DC are categorized as electrical and thermal loads.	[92]
Balance-of-plant items	Converters	Converters transform power from one form to another. They convert electrical power from AC to DC in a process called rectifier and DC to AC in a process called inverter. There are also DC to DC or AC to AC converters where power is converted from one voltage and/or frequency level to another.	[10,112]
	Inverters	Inverters convert DC to AC before supplying the AC load.	
Bus bars and local distribution networks	AC/DC	The choice of AC or DC has an impact on the system, and in most cases, is dependent on the selected technologies to be used in the system and energy management strategy.	[10,111,113]
	Distribution networks	Consists of distribution lines, transformers, and infrastructures.	[70]

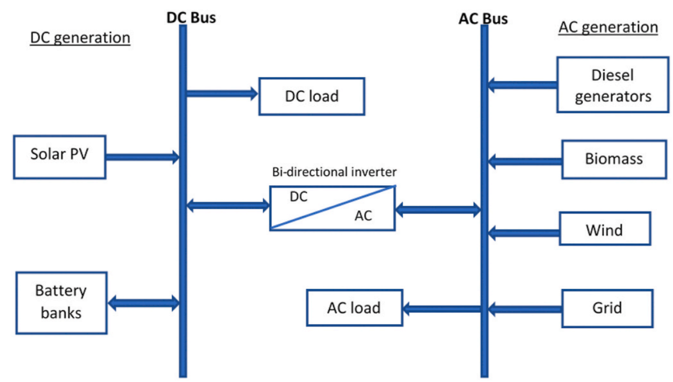

Fig. 1. Typical schematic of HRESs.

load demand, while converters are used to convert power from one form to another.

4.2. LCOE for different mini-grids and hybrid mini-grids

This section analyzes the techno-economic viability of different HRESs presented in the literature, using the LCOE. The LCOE helps in assessing the economic viability and comparing the cost competitiveness of different technologies applied in mini-grid systems such as diesel, solar PV, wind, biomass, and hydro. It considers various parameters such as the initial cost of investment, O&M costs, incentives, resource availability, and fuel costs as inputs, and is calculated using the following equation [103,114,115].

$$LCOE = \frac{Sum\ of\ costs\ over\ lifetime}{Sum\ of\ electrical\ energy\ production\ over\ lifetime} = \frac{\sum_{t=1}^{n}\frac{I_t+M_t+F_t}{(1+r)^t}}{\sum_{t=1}^{n}\frac{E_t}{(1+r)^t}}$$

where I_t denotes the capital expenditure in year *t*, M_t represents the O&M expenditure in year *t*, F_t is the fuel expenditure in year *t*, E_t denotes the electrical expenditures in year *t*, *r* is the discount rate, and *n* is the lifetime of the project.

Various factors affect the LCOE, such as economies of scale that contribute to decreasing the costs of the system due to high automation in production. Another issue is that LCOE does not consider the daily variation in demand and supply, taxes and subsidies, and externalities such as the environmental impacts of the project, all of which significantly affect the viability of the different generation technologies [116,117].

Solar PV, wind, hydro, and biomass are the most common generation technologies employed in HRESs, frequently hybridized with diesel generators as a backup. However, renewable energy costs, particularly solar and wind costs, have declined over the last years due to advancements in technology, which include improvements in the manufacturing solar PV and in wind turbine design, and growth in the economies of scale [21–27].

Fig. 2 presents the estimated variations in LCOE between 2015 and 2035 based on data extracted from IRENA [22], which indicates that the LCOE for mini-grids, in general, would continue to fall up to 2035. In 2015, the LCOE for mini-grids ranged from USD 0.47/kWh to USD 0.92/kWh, while projections for 2035 show that it would vary between

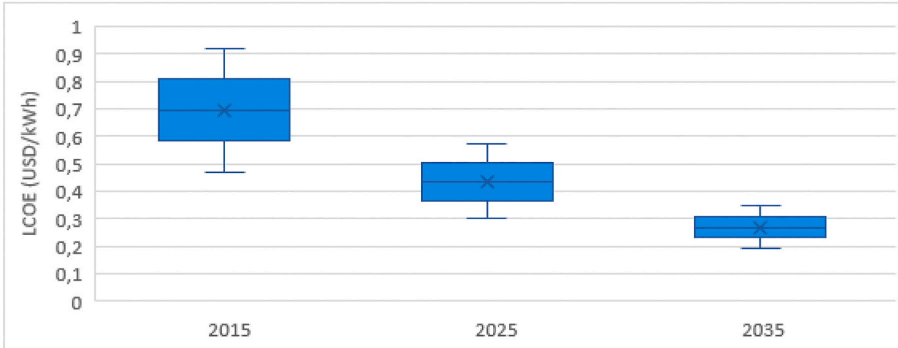

Fig. 2. LCOE for mini-grids in general (2015–2035). Based on IRENA [22].

USD 0.19/kWh and USD 0.35/kWh.

Based on data obtained from the IRENA [22], Fig. 3 illustrates the fall in LCOE for small scale solar PV, small wind, and biomass mini-grids. The LCOE for Solar PV is expected to fall, ranging between USD 0.04/kWh and USD 0.05/kWh in 2035, USD 0.09/kWh and USD 0.14/kWh in 2025, compared to USD 0.15/kWh and USD 0.25/kWh of 2015**,** while that of small wind is estimated to drastically decline up to 2023, beyond which it is likely to fall by 1% annually. The LCOE for mini-hydro is expected to remain stable (~0.27). As the cost of renewable technologies fall and fuel prices rise, mini-grids are becoming economically more attractive.

The techno-economic performance of HRESs was presented in the literature using economic indicators such as LCOE, renewable fraction, net present cost (NPC), investment cost, and operation cost. However, few publications have addressed the costs of renewable energy mini-grids to date.

Studies commissioned by international organizations such as IRENA, World Bank, and UNEP estimated the LCOE for different renewable energy mini-grids, including hybridization with diesel and diesel-only systems.

The Frankfurt School of Business [118] analyzed the economic and financial viability of the diesel-only system and hybridizing diesel with solar PV across seven sites located in Indonesia, the Philippines, Colombia, Dominican Republic, Saint Vincent and the Grenadines, Kenya, and The Gambia. The study found that the LCOE of mini-grids that are 100% powered by diesel and solar PV ranges from USD 0.34/kWh to USD 0.47/kWh and from USD 0.16/kWh to USD 0.22/kWh, respectively, which means that solar PV is significantly less expensive than diesel. However, the study was limited to solar PV technology. It would have been more illustrative if the author (s) had considered hybridizing diesel with other renewable technologies beyond solar, considering that the selected places are located in countries with different energy characteristics. For example, Indonesia is dominated by micro/mini hydropower.

Similarly, according to Safdar [43], the LCOE of a mini-grid powered 100% by solar PV varies between USD 0.47/kWh and USD 0.71/kWh, which is economically more attractive than a 100% diesel generator ranging between USD 0.35/kWh and USD 0.80/kWh, considering world fuel prices. However, diesel costs may differ from country to country, based on factors such as specific incentives provided by governments. The LCOE of a diesel generator varies between USD 0.23/kWh to USD 0.49/kWh for fuel prices in the Indonesian context [119], while it is estimated to range between USD 0.35/kWh to USD 0.50/kWh if the world fuel prices are considered [120].

The State of Electricity Access Report [63] estimated that on average, mini-grids powered by diesel generators could cost USD 0.43/kWh, which is less economically viable than mini-grids powered by renewable energy (expected to cost USD 0.33/kWh). While Comello et al. [121] assessed the LCOE of diesel mini-grid, solar/battery, and hybrid solar/diesel were found to have LCOEs of USD 0.57/kWh, USD 0.38/kWh, and USD 0.55/kWh, respectively. The results indicate that 100% diesel mini-grids are economically less attractive than hybrid solar/diesel, implying that hybridization of diesel with renewables has the potential to lower the generation costs and reduce fuel consumption in diesel-based mini-grids.

IRENA [115] assessed the technical and economic aspects of biomass power generation technologies and found that for a biomass gasifier, the LCOE ranges between USD 0.11/kWh to USD 0.28/kWh. However, when biomass feedstock for gasifiers is used for power generation in mini-grids, it results in high operational costs [122].

The World Bank (2005) [123] compared the LCOE of different mini-grids at specific size capacity in 2005, with projections for 2010 and 2015. The study estimated that for 25 kW solar PV mini-grid, the LCOE ranged between USD 0.43/kWh and USD 0.63/kWh; for 100 kW

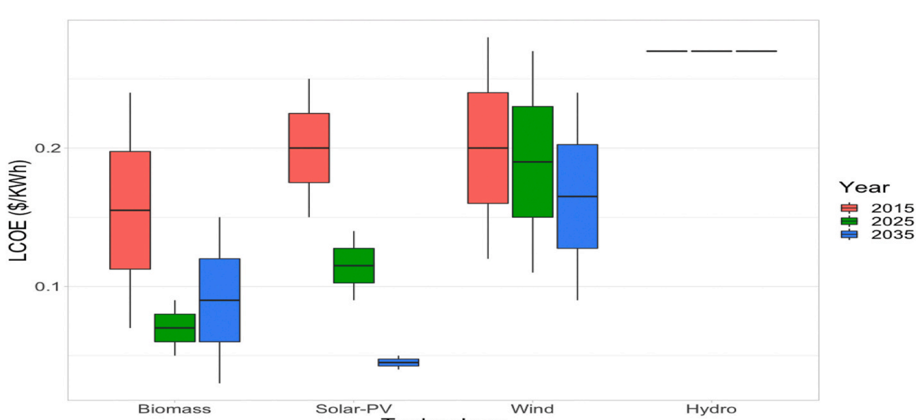

Fig. 3. LCOE for different mini-grids (2015–2035). Based on IRENA [22].

wind mini-grids, the LCOE ranged between USD 0.17/kWh and USD 0.23/kWh; for 1 kW diesel, the LCOE ranged between USD 0.47/kWh and USD 0.58/kWh; and for 100 kW biomass gasifier, the LCOE ranged between USD 0.08/kWh and USD 0.1/kWh. On the other hand, Ruud [124] estimated that for 30 kW solar PV mini-grid, the LCOE ranged from USD 0.40/kWh to USD 0.61/kWh, while a feasibility study released by Ondraczek [125] in Kenya indicated that for a 10 MWp solar PV power plant, the LCOE is estimated to be about USD 0.21/kWh. Deichmann et al. [126] found that, in Africa, the average LCOE of mini-grids based on wind ranges between USD 0.14/kWh and USD 0.29/kWh, which is favorable for mini-grid applications based on the local resource availability.

The data presented in Fig. 4 are based on the projections provided by the World Bank [103] for 2015, and studies released by IRENA [104], Ruud [124], and Advisory Services on Climate, Energy and Development Issues (ASCENDIS) [127] in 2013 and 2017, respectively, for capacities ranging from 20 kW to 100 kW. They provide a comparison among different mini-grids and hybrid mini-grids of different scales.

It is evident from Fig. 4 that, in general, small hydro and wind mini-grids may represent the least-cost options compared to diesel and solar mini-grids. However, they are very site-specific (highly dependent on the availability of resources). Diesel mini-grid shows the highest LCOE compared to other generation sources and are highly dependent on fuel price fluctuations. Another important finding was that hybrid solar PV/diesel and solar PV/wind have the potential to lower the costs of generation based only on diesel or solar PV, respectively.

Various studies have also been conducted to analyze the techno-economic performance of hybrid micro/mini-grids, in different locations, using cost and system optimizing tools such as hybrid optimization model for electric renewables (HOMER). Ramli et al. [13] and Hiendro et al. [128] used HOMER software to analyze the techno-economic viability of hybrid solar PV/wind systems using with the same sizes of solar (1 kW) and wind (1 kW), for two different sites located in Saudi Arabia and Indonesia. Their analysis shows that, despite the similarities, the systems presented different LCOE. This finding reveals that the costs of the systems are dependent on the region or country and technology, considering the renewable energy local resource, capital, replacement, and O&M costs. Ahmad et al. [8] applied the HOMER software to investigate the potential generation of hybrid solar PV/Wind/biomass for a village in Pakistan. The authors found that this combination required high capital investment and that biomass highly influenced the costs of the hybrid system.

Table 4 presents a comparison of different LCOE for hybrid renewable system configurations as well as the impact of using diesel generators to lower the costs. They have been selected from the reviewed literature to offer different insights on the importance of technology selection, taking into account the country conditions. Hybrid systems implemented within the same country conditions have been considered for comparison. For example, a study compared four hybrid systems installed within the same country conditions in Bellavista (Ecuador). The results reveal that hybrid small hydro/diesel is the most cost-effective compared to hybrid solar PV/diesel, wind/diesel, and solar PV/wind/diesel, while for the same size capacity, solar PV/diesel and wind/diesel show almost similar LCOE values of USD 0.46/kWh and USD 0.45/kWh, respectively. On the other hand, the same configurations (hybrid solar PV/diesel/wind/battery) implemented in different country conditions and size capacities in Thlatlaganya (South Africa) and Kadayam (India) show different LCOE of USD 0.41/kWh and USD 0.76/kWh, respectively.

According to Table 4, hydro is the most cost-effective solution compared to other sources due to lower generation costs. They entail a high capital cost that includes planning, licensing, plant construction, and other social and environmental costs, although O&M costs are low [129]. A study released by the ARE [29] compared the LCOE of 100% diesel-based mini-grid with different hybrid configurations in a village located in Ecuador (island of Bellavista) and found that hybrid small hydro/diesel is the most cost-effective solution compared to diesel mini-grid (Table 4). However, hybrid combinations with hydropower are very limited (Table 7).

From Table 4, it is evident that hybrid mini-grids that include diesel generators as backup present low LCOE than mini-grids powered 100% by renewable energy. It is also notable that hybrid systems that use local biogas resources as a backup have the potential for cost reductions compared to diesel generators as a backup, which are reliant on fuel prices.

4.3. Optimization and simulation tools applied for hybrid mini-grids

The design and optimization of hybrid systems face certain challenges due to factors such as technology, approach, resource availability, and models. However, the literature has addressed advancements in simulation and optimization methods, that help obtain an optimal technological sizing of the components for the hybrid system to minimize the costs and ensure the sustainability of the systems [109, 132–134]. Researchers have carried out the design and optimization of hybrid systems using various software tools. Among them, HOMER software is the most used, followed by Clean Energy Management Software (RETScreen), Transient Energy System Simulation Program (TRNSYS), Hybrid Power System Simulation Model (HYBRIDS), Improved Hybrid Optimization based on Genetic Algorithm (iHOGA), and Particle Swarm Optimization (PSO). However, each software has its characteristics, which may be highly determined by the inputs and the purpose of use. Table 5 presents a summary of the key features and limitations of these tools.

HOMER software requires input data such as resource data (meteorological data in case of wind, hydro, and solar resources), details of the components, load profile, and technical and economic data. The result is output data such as the optimal unit sizing and cost of energy (e.g.,

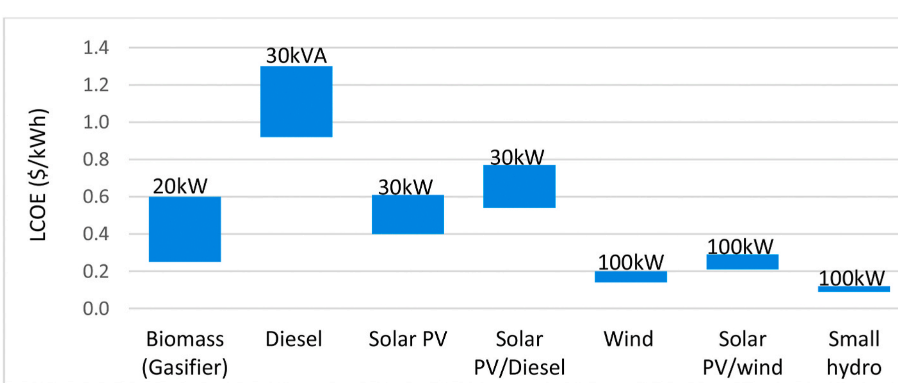

Fig. 4. LCOE (USD/kWh) of mini-grid and hybrid mini-grid options at different scales (kVA, kW). Based on [103,104,124,127].

Table 4
Comparison of LCOE based on various techno-economic studies for different HRESs in developing countries.

Project location	System configuration	Size (kW, kVA)	LCOE (USD/kWh)	Remarks	Ref.
Island of Bellavista, Ecuador	Small hydro/diesel	H – 26.8 kW DG – 10 kVA	0.22	Hybrid small hydro/diesel is the most cost-effective solution compared to other hybrid combinations. The operational cost of hydropower plants is low. However, hydro is highly site-specific.	[29]
Island of Bellavista, Ecuador	Solar PV/diesel	PV – 60 kW DG – 20 kVA	0.46	Hybrid solar PV/diesel mini-grids are cheaper than diesel-only mini-grids. However, this combination entails a high capital cost of solar PV and diesel fuel costs, and replacement costs (e.g., frequent replacement of batteries).	[29]
Island of Bellavista, Ecuador	Wind/diesel	W – 60 kW DG – 20 kVA	0.45	Wind power technology is site-specific. Operational costs of wind are high, which makes hybrid wind/diesel less cost-effective compared to hybrid hydro/diesel. However, this combination is cheaper than diesel mini-grids, which is highly dependent on fuel price.	[29]
Island of Bellavista, Ecuador	Solar PV/wind/diesel	PV – 35 kW W – 20 kW DG – 10 kVA	0.42	Compared to solar PV/diesel and wind/diesel combinations, hybrid solar PV/wind/diesel is more economically attractive as it consumes less diesel and benefits from solar and wind technologies.	[29]
			1.06		[128]

Table 4 (*continued*)

Project location	System configuration	Size (kW, kVA)	LCOE (USD/kWh)	Remarks	Ref.
Temajuk, Indonesia	Solar PV/wind/battery	PV – 1 kW W – 1 kW		100% renewable energy hybrid combinations are economically less attractive (high LCOE) than hybrid renewables/diesel combinations that can rely on diesel when one of the intermittent renewable resources is not available.	
Kadayam, India	Wind/solar PV/diesel/battery	W – 30 kW PV – 5 kW DG – 25 kW Battery – 48 V	0.76	Hybrid wind/solar PV/diesel/battery is less economically attractive than the hybrid systems, which include hydro. Solar PV highly affects the LCOE because their technologies have high capital costs at low conversion efficiencies.	[130]
Garissa, Kenya	Solar PV/wind/diesel	PV – 1 kW W – 10 kW DG – 1 kW	0.31	Hybrid combinations with diesel generators as a backup are the common solutions and economically viable compared to 100% renewable combinations. Nevertheless, the author compared diesel with biogas as a backup and found biogas economically more feasible than diesel.	[3]
Garissa, Kenya	Solar PV/wind/biogas	PV – 1 kW W – 10 kW Biogas–1 kW	0.25	Hybrid solar/wind systems with biogas as a backup seems to be more cost-effective than using diesel as a backup because biogas is produced locally by feeding	[3]

(*continued on next page*)

Table 4 (*continued*)

Project location	System configuration	Size (kW, kVA)	LCOE (USD/kWh)	Remarks	Ref.
				digester manure.	
Thlatlaganya, South Africa	Solar PV/diesel/wind/battery	PV – 14 kW DG – 50 kW W – 140 kW Battery – 150 kW	0.41	Reduction in solar potential will result in the increasing use of wind and diesel.	[131]
Lucingweni, South Africa	Wind/hydro/diesel	W – 60 kW H – 92 kW DG – 50 kW Battery – 200 kWh	0.08	Hydropower is the most cost-effective solution for power generation, compared to other sources.	[131]

LCOE, NPC, and renewable fraction) [135,136].

The software was widely applied for designing and planning purposes and is also used to analyze the effects of uncertainty parameters. It has also been used to compare different hybrid configurations, determine the size of the hybrid systems, and for feasibility and sensitivity analysis. Based on NPC, HOMER helps to optimize the systems for a determined set of constraints and sensitivity variables [135]. However, it cannot model aspects such as voltage and frequency stability, and environmental considerations [137].

Many researchers have employed HOMER software to assess the techno-economic performance and optimal planning of HRESs. Bahramara et al. [138] review the literature on optimal planning of HRESs and found that HOMER is widely applied to evaluate the performance of HRESs, especially for rural areas in developing countries. Sinha and Chandel [135] reviewed software tools for HRESs and found that HOMER was the most popular software. Bekele and Tadesse [139] used HOMER software for the optimization and sensitivity analysis of hybrid systems comprising six small scale hydropower with solar PV and wind. Borgohain and Mahapatra [140] applied HOMER for the design and optimization of hybrid solar PV-biomass-diesel system configurations. Amutha and Rajini [130] used HOMER to find the optimal hybrid system configuration for the electrification of a rural village in southern India. Ahmad et al. [8] used HOMER software to investigate the potential generation of hybrid solar PV-wind-biomass for a village in Pakistan. These studies indicate that HOMER is the best software to examine the techno-economic viable options for rural electrification.

Table 5
Summary of the main simulation and optimization tools used for HRESs: features and limitations.

Tool	Key features	Limitations	Ref.
HOMER	Deals with uncertainty parameters and can perform both technical and economic analysis; The only tool that allows comparison among systems coupled in DC and AC.	Depth of discharge of the battery not considered; Cannot model aspects such as voltage, frequency stability, and environmental considerations; Cannot perform multi-objective optimization.	[13,15,32,99,104,135,136,141–145]
RETScreen	Used for rough sizing, financial and emission analysis of the optimized system, as well as performance analysis; Performs risk and sensitivity analysis; Available library with various resource data.	The solar PV performance analysis does not account for the temperature effect; Does not support advanced calculations and has data haring problems; Does not provide the import of time-series data and has limited options for search.	[99,135,140,143,144]
HYBRID 2	Can perform technical and financial assessment; Simulations are very precise time.	Large data set is required; Less flexible and limited access to parameters; Black box coding limitations;	[32,99,132,143,145]
iHOGA	Has own database of meteorological parameters for several locations; Software in ongoing upgrading.	It does not perform sensitivity and probability analysis; Limitation on the daily load.	[32,135,146,147]
HYBRIDS	Carries out modeling and simulation of loads, sources, and power conversion devices with high precision; Design can be improved; Has been applied to evaluate the system performance.	Does not perform optimal sizing and optimization facilities.	[32,135,148]
TRNSYS	A simulation tool for analyzing the energy systems with high precision; It has been used for simulations and validation of experimentation, planning, performance, design, and analysis.	It cannot provide optimization facilities.	[99,135,149]
PSO	Perform sensitivity analysis; Reduces the power losses and voltage deviations of the system; Easy to use.	The software is subject to operating constraints.	[132,148,150]

4.4. Reliability of hybrid energy power systems

The reliability of power systems has been defined as the ability of the power systems to provide electricity in an adequate (ensure that the system delivers enough power output to satisfy the load demand, including transport systems to the loads), firm (availability of enough supply infrastructure when needed), and secure (system's ability to resist disturbances without compromising the operation circumstances) manner to the beneficiaries [150–152].

In the literature, the reliability and cost-effectiveness of power supply have been identified as the most important aspects to consider for a successful implementation of a hybrid power system. However, limited attention has been paid to specific factors that may affect the reliability and cost of hybrid systems, such as failures and outages of generation units.

The IPCC report [4] indicates that in designing autonomous systems, especially for rural communities, it is important to balance the reliability and costs of the systems because these systems face many challenges in ensuring a continuous supply. On the other hand, the recent study released by the World Bank (2019) [153] on electricity access in Sub-Saharan Africa pointed out that reliability of supply, in general, represented a major constraint in Africa, and argued that this issue must be addressed and prioritized to ensure good quality of supply.

In many developing countries, there have been efforts to boost the implementation of HRESs because they have proven to be cost-effective and present better reliability of supply compared to single generation sources. Additionally, can reduce the frequency and time length of power disruptions and increase the efficiency of power supply. An example of this is the hybrid micro-hydro/solar PV installed in Lukla hospital, located in Solukhumbu, Nepal. The hospital was initially served by micro-hydropower. However, due to the unreliable power supply in the winters, the hospital had to close for one or two months. As a solution, a solar PV power plant was added to the micro-hydro power, which enabled the hospital to obtain a reliable and continuous energy supply [154].

However, many issues arise when it comes to maintaining system reliability by delivering the planned levels of output to a certain number of customers [155]. For instance, in the 7.5 kW solar PV mini-grid installed in Qinghai Shenge village (China), the local population growth remained stable for years, which allowed the system to function properly because it was designed for a specific load—exceeding this load would have entailed expanding capacity, which would have been difficult or expensive. Additionally, the operating guide translated into the local language, and training for local installers and end-users were provided. Further, a young couple was recruited in the village to monitor the system, which contributed to maintaining the system's reliability. The failures and outages were immediately reported and resolved, which allowed the project to perform well [156].

Another example to highlight is the 202 kW hybrid solar PV/diesel installed in Tsumkwe (Namibia). In this case, an assessment of needs and demand and also technology options were performed, which contributed to the provision of 24-h power supply. Moreover, people pay in advance for electricity based on prepaid meters. These aspects make the system reliable and cost-effective [46].

While there have been some successful examples, there have also been some failures. For instance, in the 25 Wp solar PV system installed in Zimbabwe, several unreliability aspects were observed because the users were consuming more electricity than planned. The system experienced premature battery failure, and during days without sunshine, the electricity supply was sometimes interrupted [156].

To assess the reliability performance of hybrid energy systems, the literature presents different schemes such as loss of load probability (LOLP; also known as loss of power supply probability [LPSP]), loss of load expected (LOLE), loss of energy probability (LOEP), and loss of energy expected (LOEE; also called loss of load duration, loss of load frequency, and expected energy not served) [17,104,150,150,157–163]. The most common terms applied are LOLP, LOLE, LOEP, and LOEE, presented in Table 6.

From the equations presented in Table 6, LOE_i is the amount of loss of energy (kWh) when the system cannot be supplied expected energy at time step h; S is the total loss of load states of the system; H is usually taken as the annual time in hours (8760 h); LD is the load demand (kWh) at time step h; P_i is the probability that system-encountering state I; T_i is the time (hour) for which a load exceeds the production capacity; t_j is the percentage of time when the load exceeds the remaining generation capacity C_j; E_0 is the energy demanded ($E_0 = L_0$ x 1 h) in MWh; and L_0 is the expected load during 1 h.

The above indices have been applied in many studies to evaluate the reliability performance of HRESs. Bilal et al. [164] analyzed the optimal hybrid system design by minimization of both costs of the system and LPSP in Potou (Senegal). Javed and Ma [165] proposed a sizing methodology for off-grid hybrid solar/wind/battery systems based on the cost and system reliability. The reliability of the system has been assessed as an LPSP. The study recommended that off-grid applications can be initially energized considering small LPSP, which is more suitable as it decreases the initial cost of investments for limited load demand in rural communities. Jafar et al. [160] applied the LOEE and LOLE to assess the optimal sizing of hybrid solar PV/wind system with fuel cell for a stand-alone solution. They found that this combination lowers the cost and offer better reliability indices. In general, the reliability of supply and cost-effectiveness are the most important aspects to consider when designing HRESs to provide electricity in rural areas.

Table 6
Reliability indices mostly used for HRES.

Reliability indices	Key equation	Remarks
LOLP	$LOLP = \sum_j \frac{P_j * t_j}{100}$	LOLP occurs in case the load of the system surpasses the power generation available for use; If the cost of the system is high, then LOLP is low.
LOLE	$LOLE = \sum_{h=1}^{H} \sum_{i \in S} P_i * T_i$	LOLE is predicted the number of days or hours of which the load surpluses the power generation capacity, in a year.
LOEP	$LOEP = \sum_j \frac{E_j * p_j}{E_0}$	It is defined as a kWh that is likely not provided by the generating capacity of the system. Different sizes of the systems can be compared.
LOEE	$LOEE = \sum_{h=1}^{H} \sum_{i \in S} P_i * LOE_i$	Also known as expected energy not served. Represents the predicted amount of electric generation that has not been supplied to satisfy the load demand.

4.5. Operation mode: grid-connected and off-grid

The HRESs can operate in grid-tied and off-grid modes in a sustainable manner, minimizing environmental impacts such as carbon dioxide (CO_2) emissions from diesel use, lower the cost of electricity, and improve system reliability [10,23,24]. They offer the flexibility of being connected to the national grid over the periods of low demand and disconnected during periods of peak demand, and can also feed the excess power generated into the national grid. However, limited studies have covered the grid-connected mini-grids, as evident from Table 7, even though grid-connected mini-grids seem to be economically viable compared to the islanded mode. Ismail et al. [6] reviewed the existing literature on how to utilize excess energy in HRESs and found that the cost of energy can be minimized if the surplus energy is used. Rajbongshi et al. [140] performed the design and optimization of a hybrid PV/biomass/diesel system for different load profiles. The results of the study indicated that a system connected to the grid is economically more viable than that of off-grid within the same load profiles. Ahmad et al. [8] and Rajbongshi et al. [140] conducted studies on the techno-economic viability of grid-tied and off-grid hybrid systems. They concluded that the grid-connecting is economically viable compared to an off-grid system. However, for remote and sparsely populated areas, the off-grid solution may be more cost-effective compared to a grid-connected option. This means that for choosing an optimal layout for future HRESs, expected future developments of the main grid in the region in question should be taken into account.

4.6. The configurations of HRESs

Based on the literature, HRESs integrated with renewable technologies (solar PV, wind, biomass, and hydro) have been widely applied. They have been hybridized in most of the cases with diesel generators and battery as a storage device, resulting in the simultaneous reduction of the initial cost of investment of renewables and the amount of diesel that should be purchased for the generator (e.g., hybrid solar PV/diesel). These combinations can lower the negative environmental impacts of using diesel generators alone and improve the reliability of supply. However, despite its economic viability compared to other sources, less attention has been given to hybrid systems that include small hydro as presented in Table 7.

Shahzad et al. [9] analyzed the techno-economic performance of off-grid hybrid solar PV/biomass and found that the system is reliable and cost-effective as it can provide electricity at the lowest price. Maleki and Askarzadeh [16] modeled and optimized an off-grid hybrid PV/wind/diesel system for rural electrification in Rafsanjan (Iran). Their analysis reveals that this hybrid configuration is the most cost-effective solution for that region. Mamaghani et al. [166] analyzed the application of different hybrid systems for the electrification of three remote villages in Colombia. The results show that combining diesel generators with renewable sources considerably reduces the GHG emissions resulting from diesel. In addition, hybrid solar PV/wind/diesel and solar PV/diesel are the most economically viable solutions.

Table 7
Overview of HRES configurations found in the literature for different countries.

Type of analysis	Country/Region	Non-dispatchable and dispatchable resources						Converters	Storage	Operating modes		Ref.
		Solar PV	Wind	Biomass	Biogas	Hydro	DG	Converters	Battery	Off-grid	Grid-connected	
Techno-economic performance	Pakistan	✓	✓	✓	–	–	–	✓	✓	–	✓	[8]
Techno-economic performance	Pakistan	✓	–	✓	–	–	–	✓	✓	✓	–	[9]
Techno-economic performance	Bangladesh	✓	✓	–	✓	–	✓	✓	✓	✓	–	[10]
Techno-economic performance	Algeria	✓	✓	–	–	–	✓	✓	✓	✓	–	[11]
Techno-economic performance	Saudi Arabia	✓	✓	–	–	–	–	–	✓	–	✓	[13]
Size optimization	Oman	✓	✓	–	–	–	–	✓	✓	✓	–	[15]
Size optimization	Iran	✓	✓	–	–	–	✓	✓	✓	✓	–	[16]
Size optimization	Algeria	✓	–	–	–	–	✓	✓	✓	✓	–	[111]
Size optimization	India	✓	–	✓	–	–	✓	✓	✓	–	✓	[140]
Techno-economic performance	Malaysia	✓	–	–	–	–	✓	✓	✓	✓	–	[167]
Techno-economic performance	India	✓	–	✓	✓	✓	✓	✓	✓	✓	–	[168]
Optimization and economics	Turkey	✓	–	–	–	–	✓	✓	✓	✓	–	[169]
Size optimization	Senegal	✓	✓	–	–	–	✓	–	✓	✓	–	[170]
Techno-economic performance	Sub-Saharan Africa	✓	–	–	–	–	✓	–	✓	✓	–	[171]
Techno-economic performance	Mozambique	✓	–	✓	–	–	–	✓	✓	✓	–	[172]
Techno-economic performance	Colombia	✓	✓	–	–	–	✓	✓	✓	✓	–	[166]
Techno-economic performance	Malaysia	✓	✓	–	–	–	✓	✓	✓	✓	–	[173]
Techno-economic performance	Tunisia	✓	✓	–	–	–	✓	✓	✓	✓	✓	[174]

Therefore, by investigating their techno-economic performance and size optimization based on different criteria and comparisons, they conclude that HRES is technically and financially viable, especially for remote areas, compared to single sources.

5. Opportunities and barriers toward integration of mini-grids in developing countries

This section provides an overview of the opportunities and barriers for HRES integration based on the literature review. They have been clustered based on the PESTEL analytical framework. The framework can help the policy-makers, financial institutions, and project developers to identify and cluster the main opportunities and barriers for the deployment of these systems.

Among the barriers, the policy (including institutional), economic, technical, and legal aspects were the most mentioned compared to social and environmental facets. These barriers are evident in developing countries and represent the main aspect behind the failure of the projects. The main barriers have been summarized in Table 8 and include, for instance, the lack of specific legislation for mini-grids, weak involvement of local communities and private entities in decision-making, lack of credit line facilities, and insufficient financial mechanisms.

I) Policy aspects

Policy mechanisms are important for the successful integration of mini-grids. They were briefly discussed in numerous studies, such as the IPCC report [175], ARE [122], IRENA [26], Berkeley Lab [36], and USAID [33]. According to the studies, the lack of clear and transparent policies represents the main obstacles to the integration of mini-grids. Developing countries such as India and Tanzania have made significant progress by setting targets in their policies to speed up the integration of mini-grids considering their local conditions [21,29,56,81,176]. However, many developing countries still lack specific regulations to facilitate the integration of mini-grids.

Moreover, the inadequate planning process has been highlighted as a significant constraint for the integration of mini-grids. Governments must integrate elements for the implementation of HRES into their electrification plans, such as the selection of technologies, including what happens upon the arrival of the main grid in the village. For example, despite the successful implementation of mini-grids in Indonesia, there were no specific rules or policies about what happens upon the arrival of the main grid to the village supplied by mini-grids, resulting in the abandonment of some micro-hydropower projects [56].

The coordination among the energy sector stakeholders, the private sector, and local communities is important for the successful implementation of these projects. This can be effectively observed through a clear definition of roles and responsibilities among different stakeholders. For example, India has successful models implemented through the VEC in the states of West Bengal and Chhattisgarh. In contrast, under the country's Village Energy Security Program launched in 2004, many projects were discontinued by 2012 due to failures. Among the 65 projects commissioned, more than half were not operational. The lack of a clear definition of roles and responsibilities among the stakeholders, which resulted in non-ideal community participation, was the primary reason that led to the failure of the projects [163].

Therefore, the involvement of local communities right from project inception is important to increase awareness of HRES and ensure its sustainability and social acceptance. A successful example of the importance of having the local community involved from the establishment until the implementation stage of the project is observed in the 202 kW hybrid solar PV/diesel mini-grid Implemented in Tsumkwe (Namibia) in 2012, which is still operational [38].

Another example to highlight is the 48 kW solar PV/battery system implemented in Tanzania (2017). The project has the involvement of three persons from the community (two operators and one administrator) working permanently for the O&M of the project. Further, to

Table 8
Summary of key barriers for HRES deployments.

Category of barriers	Parameters assessed	Description of the barriers	Ref.
Policy barriers	Regulatory framework	Lack of specific policy and regulatory framework for mini-grids development, including the interconnection rules between mini-grid and main grid (upon grid arrival).	[4,33,122,178,179,186,194–198]
	Administrative	Lack of dedicated agencies for rural electrification; Scarce and inaccurate data; Lack of comprehensive planning process for the power sector; Poor coordination/communication among the institutions (stakeholders); Licensing and concession process complex (lengthy, bureaucratic, and unclear); Lack of stakeholders and local communities involved in the decision-making process.	
Economic barriers	Financial mechanisms	The low expected return on investment; Limited access to funding mechanisms; Lack of access to credit facilities; Unsecured revenue streams to fund operating costs.	[4,18,33,122,178,179] [194,198]
	Cost of the systems	The high initial cost of investment; High tariffs compared to tariffs for the main grid.	
	Willingness to pay	Low income (inability of the rural population to pay for energy services).	
Social barriers	Social acceptance	Lack of social acceptance of new technologies; Lack of awareness; Resistance to change.	[10,107,197,199]
Technical/technological barriers	Technical	Inadequate skills capacity; Lack of research and development transfer; Lack of provision for O&M; Lack of standards and certification; Population distribution patterns in remote areas affect the technical design specifications.	[34,109,178,183,184,195,198]
	Technological	Weak technological knowledge (installers, designers, and maintainers of HRES's installations).	
Environmental	resources	GHG emissions resulting from fossil fuels (e.g., diesel generators); Possible fugitive emissions resulting from geothermal plants and hydropower plants with reservoirs (CH_4 and CO_2); Very likely (CO_2, CH_4, and nitrous oxide) emissions related to agriculture and changes in the land-use in biomass energy production.	[175,186,200]
	Local pollution	Noise, and visual impact in the case of wind energy.	
Legal	legislation	Lack of clear and specific legislation for incentives (subsidy, tax exemption) for development of mini-grids; Uncertainty and inconsistent legal framework; Existing tariffs framework are not attractive or at least are prohibitive.	[2,18,79,105,188–190]

ensure the connection between the project and community, the Electricity Committee has been formed [165]. These examples can be applied for other projects in developing countries to ensure the continuous O&M of mini-grids.

Additionally, administrative aspects that include lack of dedicated agencies for rural electrification, scarce and inaccurate data availability, and bureaucratic licensing processes such as complicated, slow, or non-transparent permitting procedures, have been mentioned by the researchers as the primary factors that hinder the development of mini-grids [21,56,81]. A successful example of data availability is the mini-grid platform (www.minigrids.go.tz) developed by the Tanzanian government. This platform facilitates investments by providing information for investors [43].

II) Economic aspects

Economic barriers have been mentioned repeatedly in the literature. They include high capital costs, insufficient funding mechanisms, lack of appropriate subsidies, lack of access to credit line facilities, and market development barriers, such as lack of market competition among technology suppliers and lack of market development to repair the broken equipment [26,79,177].

In general, investments in mini-grids are characterized by high initial cost with a long payback period, which represents a barrier for the integration of mini-grids. To overcome this challenge, the authors in Refs. [4,29,178,179] suggested government subsidies to ensure the sustainability of the projects. High risk and high transaction costs have been considered by Ref. [87] as the main aspects that hinder the financing of mini-grids. On the other hand, the national tariffs are not attractive, which makes it difficult for private investments. An example is the non-cost-reflective national electricity tariffs established in Cameroon, making it hard for mini-grids to attract investors [164].

Ensuring the financial viability over the lifetime of the project has been considered important to maintain the functionality of the HRES. In some countries such as India, Nepal, Myanmar, and Senegal, members from local communities are designated to collect the revenue, and part of this revenue is used for the maintenance and operation of the systems. In contrast, despite the economic and technical viability of the hybrid solar PV/diesel installed in Sandwip (Bangladesh), the influence of community leaders in the project was minimal and the monthly payment, as per meter indication, was done through the bank, which is a less efficient payment mechanism because many customers do not pay on time. The willingness to pay for the systems is also a factor that hinders the financial feasibility of mini-grids.

Appropriate funding mechanisms are important for boosting the deployment of mini-grids. The author in Ref. [18] addressed the funding mechanisms as an important aspect to consider for the integration of mini-grids in Africa. Mozambique has identified (interview, 2018) the limited access to financial mechanisms such as capital, loans, and grants, associated with the current economic instability of the country, and also the lack of credit line facilities for SPPs through local banks as one of the factors that inhibit the implementation of mini-grids.

In addition to the aspects mentioned above, job creation and income are considered an opportunity in mini-grids integration. The HRES comprises a combination of multiple technologies that require more employees for installation and O&M, including project development and revenue collection [180]. Furthermore, the issue of local job allocation should be investigated. For example, in Mozambique (interview, 2018), due to the lack of capacities in rural communities, skilled personnel from urban areas are allocated for the projects' O&M. Only for small capacities (up to 4 kW), two or three local young personnel are trained and allocated for the maintenance of the systems. However, it has been challenging to retain people once trained because they immigrate to other places for better living conditions.

III) Social aspects

The HRES is mainly targeted to rural communities with low population density and dispersed houses. Therefore, the social impact of these systems is important, considering that access to electricity is important to improve the living conditions by helping develop healthcare, education, and access to information.

Social acceptance arises from the level of satisfaction of communities. Community acceptance plays an important role in the successful implementation of the project and highly influences the sustainability of these systems. However, it may be hindered by the lack of access to information, which contributes to the lack of awareness. For example, in Nepal, a lack of public awareness represents one of the hindrances to the development of renewable energy systems [181].

IV) Technological/technical aspects

The HRES is still new for developing countries with some technological and technical challenges for their integration. Lack of technical skills, insufficient knowledge about the technology and technical performance, inadequate selection of the site and components of the system, lack of standards and certification, and lack local trained capacities are considered factors that hinder the sustainability of mini-grids in developing countries [18,109,182]. The EEP report [18] suggested that local communities must be trained for O&M, including sales and marketing, to ensure the sustainability of mini-grid. Indeed, they need to be formulated and trained to be able to cooperate and be involved in the management of these systems. The training will entail minimal costs in the project but have a significant impact on its successful development [34,183,184]. Successful examples have been found in Nepal, where communities are trained to operate and maintain the systems, and in Uganda (2018) where 14 skilled professionals have been trained on fundamentals of installation and O&M of solar PV systems [185]. In contrast, at Nabouwalu–Vanua Levu (Fiji), a hybrid solar PV/wind/diesel project failed due to the lack of trained personnel [155].

V) Environmental aspects

In addition to guaranteeing access to energy, the implementation of HRES aims to lower GHG emissions resulting from existing fossil fuel power plants. As presented in this review, hybrid systems comprise power generators (renewables and conventional), storage devices, bus bars, and distribution networks. Although renewable energy technologies have the potential to lower emissions, it is important to consider the local environmental impacts of their implementation. Among the main renewable technologies, solar PV does not account for significant emissions. However, in the case of biomass, GHGs such as CO_2, methane (CH_4), and nitrous oxide resulting from agriculture and land-use are frequently mentioned, which should be taken into account. Impacts are strongly dependent on the biomass source and conversion technology used. For hydro and geothermal energy technologies, CH_4 and CO_2 emissions may occur from the hydropower reservoirs and geothermal plants during construction and operation, which are associated with local air, land, and water use. However, hydro projects less than 100 kW have generally far fewer impacts on the environmental ecosystem. Noise, and visual impacts are considered for wind energy [29,186].

Diesel fossil fuels are present in hybrid systems as a backup. They emit pollutants, thereby causing local air and noise pollution. However, hybridizing or replacing fossil fuels with renewable energy systems can help minimize the huge adverse environmental impacts by contributing to the emission reductions of nitrogen oxide and sulfur dioxide.

Batteries are also an important part of hybrid systems. However, they need constant replacement (6–8 years) and are dangerous for the environment if not correctly disposed of [29]. For example, in Nepal [59], the improper disposal of the non-functional batteries led to contaminated soil. Another example can be observed in Ghana, where due to lack of suitable policies such as recycling policy, the batteries are buried, causing the formation of acidic substances that contaminated the surrounding areas [187].

IV) Legal aspects

Many countries worldwide have designed incentive structures to attract private investments for the deployment of mini-grids. The investments are driven mainly by regulations such as pricing instrument (e.g., feed-in tariff and renewable portfolio standard), supported by fiscal and financial incentives [105,188].

The authors in Refs. [2,105,189] consider a strong system of incentives associated with the geographical location and availability of subsidies as the main factor to attract private investments. These incentives have been the success factors for the rapid development of mini-grids in many developing countries.

For example, in Mozambique, the government had developed broader incentives to encourage investments, generating employment, and promoting exports [72,190]. However, these incentives and tax benefits are not explicitly targeted at renewable energy sub-sector, and clear and specific incentives are needed in the country to attract private investments in both small and medium scale mini-grids. In Mozambique, renewable energy products, including for mini-grids, are charged at a high 17% VAT, unlike Tanzania, where the exemptions from VAT and import duty have encouraged the rapid implementation of mini-grids.

Another example of how important regulations are to the opportunities for private sector integration was demonstrated by Ref. [191] through a case study of six mini-grids owned and implemented by a private sector company in Thies (Senegal). In this example, the private company was willing to follow up on the project, which resulted in adequate O&M of the project. Moreover, the company had planned to ensure financing from the private sector to expand to a total of 30 mini-grids. However, due to unclear, unsuitable, and absent regulations, after 5–6 years, the company had to give up its work in the country. This situation was also influenced by the fact that the government of Senegal intended to develop regulations for a uniform electricity tariff and did not accept the electricity tariffs proposed by the company. In contrast, in India, electricity service providers can establish tariffs based on an agreement with the consumers [48,192,193].

6. Synthesis and discussions of the main steps for a successful implementation of HRES

An extensive literature review was carried out in this study, providing an overview of different aspects considered essential for the successful implementation of HRESs in developing countries. Covering many countries, the study reveals that the successful implementation of mini-grids has been influenced by elements such as policies and regulations targeted explicitly at mini-grids, dedicated rural electrification agencies, access to financial mechanisms, and community organization, as summarized in Fig. 5. These elements are categorized into four stages (policy and targets, the feasibility of the project, implementation, and

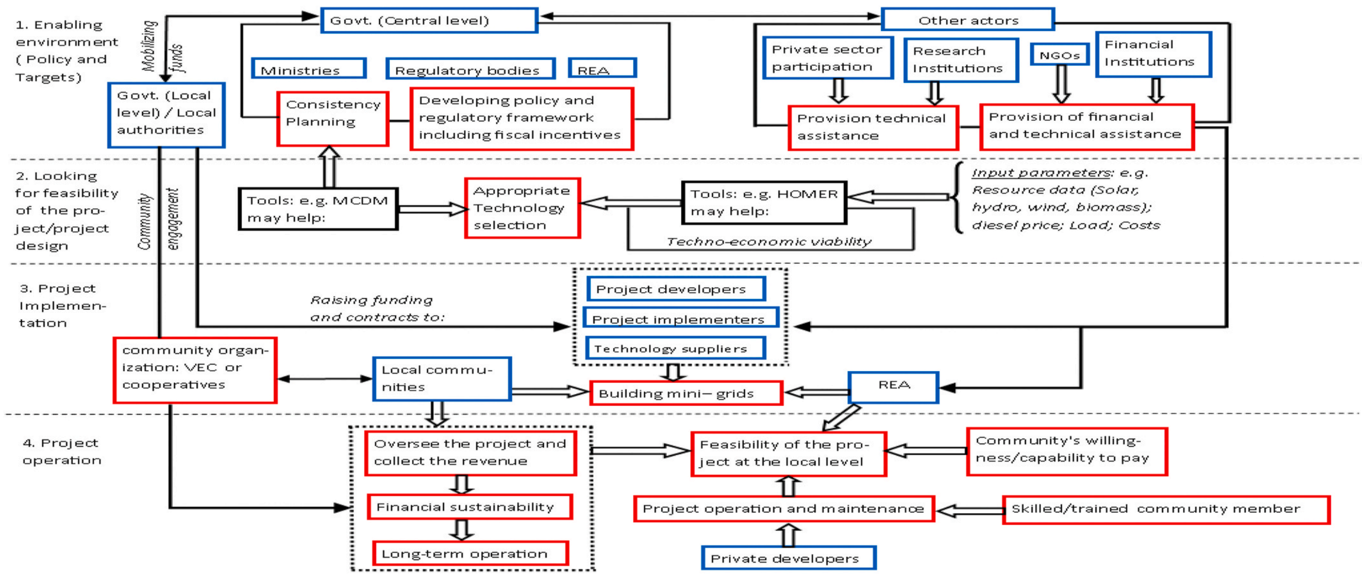

Fig. 5. Main steps for successful implementation of HRES in developing countries.
Fig. 5 presents an overview of the key aspects for the successful implementation of HRES in developing countries. The blue-lined shapes indicate the main authors, such as the government (central and local level), and other authors (private sector, NGOs, financial institutions, local communities), including project developers and implementers. The red-lined shapes indicate the key preconditions for the successful implementation of these systems, such as the provision of financial and technical support. The bi-directional arrows indicate that there must be a close interaction between the authors. The thick arrows indicate the outcomes. Finally, the black-lined shapes indicate the tools that may support decision-making in the design and selection of appropriate technology as well as the techno-economic assessment.

operation stage).

The policy and regulatory framework are instrumental for the successful deployment of mini-grids in developing countries. The results of this study indicate that developing countries that have incorporated mini-grids in their electrification plans have experienced significantly better outcomes compared to countries where regulations and incentives are absent for mini-grid development. For example, countries such as Nepal and Bangladesh have established capital subsidies to lower the upfront investment costs, making these systems economically viable, while India, Nigeria, and Tanzania have adopted policies with clear guidance for mini-grids' deployment. These instruments are crucial to encourage the private sector participation in the deployment of HRES and ensure the technical sustainability of these systems, as illustrated in Fig. 5. In contrast, the lack of clear and specific regulations for mini-grids' deployment has resulted in failed and abandoned projects in Senegal.

Some developing countries have set up REAs, which support the government in implementing their electrification plans and scaling up energy access in remote areas. The REAs also provide support through capital cost subsidies to boost private investments, capacity building, and technical assistance with the funding support of international donors to ensure the sustainability of mini-grids. This has significantly impacted the deployment of mini-grids in countries such as Tanzania and Nigeria. The study also indicated that a clear institutional arrangement is one of the aspects influencing the successful implementation of mini-grids. However, it requires better coordination and interaction among the authors involved in the rural electrification process, such as central and local government, financial institutions, NGOs, and private entities with a clear definition of their roles and responsibilities (what each actor does), which will also avoid duplication of efforts. For example, financial institutions and NGOs provide financial and technical assistance to REA and local communities to build mini-grids. However, project developers and implementers can also benefit from the technical and financial support as they also contribute to the successful implementation of HRES, as presented in Fig. 5.

In the second stage, after setting the policy mechanisms and institutional arrangement, it is necessary to consider the main elements to ensure the feasibility of mini-grids. The feasibility of HRES can be studied using different tools. For example, HOMER software is applied to find the optimal system architecture, which is economically viable to fits the electrification of a certain area. It is the most applied tool to analyze the techno-economic performance and size optimization of HRES, compared to other existing tools such as the TRNSYS and HYBRIDS. HOMER also deals with uncertainties and allows comparisons of different settings of the systems based on input data, such as resources (solar, wind, temperature, hydro, and biomass), load profile of a certain area, and costs of the systems. Apart from HOMER, the MCDM has been identified as an important method that may help decision-makers in energy planning and selection of appropriated technologies, according to the local conditions, to attain sustainability of HRES.

In the third stage, the successful implementation is contingent upon the access to financial mechanisms, which is instrumental in ensuring the economic viability of mini-grids. Based on the experiences reviewed in this study, most of the successfully implemented mini-grids have been supported through grants and loans provided by donors. For example, Indonesia successfully implemented mini-grids financed through grants, while in Mozambique, the insufficiency of these mechanisms has been highlighted as one of the factors that inhibit the development of mini-grids. Therefore, the central government, represented by ministries, regulatory bodies, and REAs, in coordination with the local authorities play a key role in mobilizing funds for the deployment of HRES in rural areas. They are also responsible for raising funding and contracts for the project developers and implementers for the design and implementation of these systems, as shown in Fig. 5. Moreover, community organization is important in this stage. It has been found that local communities play a vital role in the deployment of mini-grids (e.g., Sri Lanka). Although, the REAs have participated in building the mini-grids in countries like Tanzania.

The fourth step describes the critical aspects to ensure the successful operation of mini-grids. Based on the findings from this study, utilities, private sector, and local communities can operate and maintain the HRESs. The utility-based model is more applicable for grid-connected mini-grids and has the advantage of having the utility operating the main grid. In the private sector-based model, the private sector does not operate the main grid but has the advantage of having technical experience in O&M services. The community-based model is more appropriate where the private sector and utility are not feasible. It has the advantage of getting the community more involved in the project, ensuring their appropriation, which is important for the successful operation. Therefore, these models vary from community to community. Some models may work well in a particular community but may not apply to other communities. For example, in countries such as Sri Lanka and Nepal, the communities are trained to operate and maintain the systems, while in Tanzania, the mini-grids have been established by the private sector. In the community-based model, the communities mostly organized in cooperatives (e.g., Sri Lanka) or VEC (e.g., India) are responsible for ensuring the sustainable operation and social acceptance of these systems, as illustrated in Fig. 5. In these cases, a community leader or a member of the community is designated to manage the systems and collect the revenue, which is used to ensure the financial viability of these systems. Experiences from Nepal, Indonesia, Sri Lanka, and India indicated how communities are important to ensure the operation of mini-grids over the lifetime of the project. However, local communities may face challenges due to the lack of local skilled capacities to operate, manage, and maintain the system. Hence, they need to be formulated and trained to operate and maintain the systems. They must be involved from the early stage of project development, including in the decision-making process, to ensure the successful operation of mini-grids.

In general, the four steps are essential to ensure the successful implementation of HRESs in developing countries. However, the elements described in step one, such as ensuring a good environment for the deployment of mini-grids through the provision of regulations and incentives to attract private investment and financing, are the most critical as a starting point. The policymakers provide these elements in consultation with other authors such as the private sector, financial institutions, and local communities. Although these elements are the most important, it is necessary to ensure the feasibility during the project design (as described in step two), community organization during the project implementation, as well as building local capacities for proper O&M after the implementation to keep these systems operating over the project lifetime. These aspects are described in steps three and four, respectively.

7. Conclusions and recommendations

This study reviewed the literature on different aspects of the integration of HRES in developing countries. The following conclusions can be drawn in response to the three research questions addressed in this study.

The first research question addressed the current situation of mini-grids' deployment in different developing regions. The analyses show that, in general, Asian countries have been relatively successful in implementing mini-grids, with more people benefiting from these systems than those in African countries. The number of mini-grids implemented (mostly diesel-based, hydropower, and solar PV) has grown significantly from an estimated 0.2 million to 1.4 million across Africa and from approximately 3 million to 8.8 million across Asia between 2008 and 2016. This study also reveals that the success of HRES deployment is strongly dependent on local conditions such as the following: i) strong political commitment (e.g., Vietnam); ii) government support through clear and transparent policies (e.g., India); iii) establishment of dedicated REAs (e.g., Tanzania), and community organizations in village committees (e.g., Myanmar); iv) involvement of trained local communities to operate and maintain the systems (e.g., Nepal); and v) revenue collection encouraged by a bonus payment (e.g., Nepal) to ensure project sustainability. However, the sustainable operation of mini-grids has different approaches, which vary from country to country. Depending on the existing local conditions for the deployments of mini-grids, different ownership models have been adopted, which influence the successful operation of mini-grids, such as the private sector-based (e.g., Cambodia), utility-based (e.g., Namibia), community-based (e.g., Morocco), and hybrid community/private (e.g., Cape Verde). The community-based model has the advantage of getting the community more involved in the project. In the private-based model, a private entity, with its technical experience, plays a significant role in ensuring the successful implementation of HRES. However, its contribution is contingent upon government support, which is provided through incentives such as subsidies, exemption, and reduction in import taxes. For example, in Indonesia, private entities have been supported through the establishment of specific incentives for mini-grids' deployment, while in Sri Lanka, they receive a bonus payment for each successfully installed mini-grid.

The second research question addressed the techno-economic performance of mini-grids, which has been analyzed in this study through the LCOE metric. Recent studies indicate that, in general, the costs of mini-grids will continue to decline, making renewables (hydro, solar, wind, and biomass) even competitive at the utility-scale. For example, the LCOE of solar PV mini-grid ranged from USD 0.47/kWh to USD 0.92/kWh in 2015, while by 2035, it is expected that the LCOE will drastically decrease to the range between USD 0.19/kWh and USD 0.35/kWh. Hence, the use of HRES will increase in the coming years, as the cost of renewable technologies continues to fall, making these technologies even more attractive for hybridization. Diesel generators and solar PV mini-grids have the highest LCOE compared to hydro, biomass, and wind mini-grids. For example, the LCOE of 30 kVA diesel generators varies between USD 0.92/kWh and USD 1.3/kWh, and a 30 kW solar PV varies between USD 0.4/kWh and USD 0.61/kWh, both of which are economically less attractive than 100 kW of mini-hydro with LCOE ranging between USD 0.09/kWh and USD 0.12/kWh, 100 kW of wind ranging from USD 0.14/kWh to USD 0.20/kWh, and a 20 kW biomass gasifier ranging from USD 0.25/kWh to USD 0.60/kWh. Diesel generator has been reported as the first form of mini-grids in many countries such as Kenya and Mozambique. However, it is considered significantly more expensive than renewables due to fuel costs and transportation. As time passed, diesel has been gradually replaced or hybridized by renewable energy, coupled in some cases with the battery as a storage device. These hybrid systems are designed to solve the intermittency and upfront cost of using renewables alone, while reducing the fuel consumption and high costs of using diesel alone, increasing the reliability, affordability, and sustainability of electricity supply in rural communities. For example, the cost of a 30 kVA of diesel ranges from USD 0.92/kWh to USD 1.30/kWh, while a 30 kW of hybrid solar PV/diesel ranges from USD 0.54/kWh to USD 0.77/kWh, which is far more economical than diesel alone. The results of this study also indicated that hybrid mini-grids that include diesel generators as a backup are financially more attractive than mini-grids that derives its electricity from renewable sources alone. Less attention has been given to hybrid systems that include hydropower, despite the evidence that it is the most cost-effective solution compared to other sources such as diesel, solar, wind, and biomass. An example has been given comparing different hybrid systems within the same country conditions. The results indicated that a hybrid hydro/diesel has an LCOE of USD 0.22/kWh, which is economically viable compared to hybrids wind/diesel and solar PV/diesel with LCOE of USD 0.45/kWh and USD 0.46/kWh, respectively. However, hydro is highly dependent on resource availability. Hence, where the resource is available, hydro can provide continuous energy supply at a low cost.

The third research question addressed the aspects that can hinder or stimulate the successful implementation of mini-grids in developing countries. The analyses reveal that, despite the considerable growth in the number of mini-grids implemented across the globe, there are still barriers that hinder the successful implementation of these systems in developing regions. These barriers have been analyzed using the PESTEL framework, which has been applied in this study only as an inspiration to examine the policy, economic, social, technological, environmental, and legal aspects that can help decision-making in addressing the barriers for the implementation of these systems. From the institutional perspective, the lack of supportive policies, regulations, and the consistency in the planning process is the most mentioned barriers behind some examples of failure. These aspects can guide the rules for the development of HRES and facilitate the selection of appropriate technologies according to the local conditions. Meanwhile, many studies addressed the high capital cost associated with the lack of financial support as one of the major economic barriers that hinder the implementation of HRES in less developed countries. Additionally, being characterized by a high initial cost of investment, these systems are mainly targeted toward rural communities, with low capability or willingness to pay for the system, making it challenging to ensure financial sustainability. However, governments' incentives, designed to encourage private investments and ensure the commercial viability of mini-grids, prove to be instrumental in lowering the initial cost of investments, making these systems affordable for these communities.

Based on the experiences of mini-grids' integration in different countries, this study presents the following recommendations:

- One of the main findings of this study is related to the declining costs of renewable technologies compared to conventional forms, such as diesel, which makes hybrid renewables systems more appropriate and affordable options for electricity supply to rural communities. Many preconditions are fundamental to accelerate the deployment and sustainable operation of mini-grids in developing countries. These include policy and regulatory framework designed specifically for mini-grids, such as incentives to lower the upfront costs—which is key to encourage private investments— enhancement of stakeholder's involvement with a clear definition of what each actor does in the process—including the participation of local communities from the early stage of project development, which plays an important role in ensuring the financial sustainability and long-term operation of these systems—building local capacities to ensure continuous operation over the lifetime of these systems.
- The literature has hitherto focused more on HRESs that include diesel as a backup despite the high cost and long distances to transport diesel, which makes diesel less affordable and sustainable for rural areas. Therefore, it is recommended that further research might explore the use of hybrid systems with two or more renewables with sufficient battery storage devices to satisfy the load demand when the generation of renewables is insufficient. This will help avoid the use of diesel, making these systems even more sustainable for rural communities.
- This study covered different methods employed to support decision-making in providing affordable, reliable, and sustainable rural electrification services such as the MCDM used to support decision-makers in energy planning to define the best solution for electricity supply in remote areas. The method also evaluates, among different energy alternatives, the most suitable option for specific locations considering resource availability. Apart from the MCDM tool, this study also covered tools such as HOMER for the techno-economic analysis. HOMER provides insights on the optimal system configuration, cost analysis, as well as the environmental impact of the systems. The software can assist decision-makers in the selection of best technology options for certain conditions and also support the designers and operators of HRES. Therefore, considerably more work will need to be done in these tools to achieve the desired stage of mini-grids' deployment and effective power supply options for rural communities in developing nations.
- The extant literature, to date, pays more attention to the techno-economic viability of HRES, without considering their social and cultural impacts on the local communities in-depth. However, there are many methods and tools to evaluate the user-perceived value that may also be applied to rural electrification through HRES. Therefore, it is recommended that further investigation might also explore these methods to understand the level of satisfaction of the end-users concerning HRES, which also impacts the acceptance and success of these systems.

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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Appendix A. Status of mini-grids deployments

Mini-grids' development by country (developing countries).

Country	Year	Technology	Capacity	Nr. of Projects	Ref.
The Indian state of Uttar Pradesh	2018	Diesel generators, solar, biomass gasifiers, hydro	N/A	1850	[201]
Nepal	2017	Hydro, solar, wind, and biomass	5.8 MW	317	[43]
The Philippines	2019	Diesel	397 MW	896	[19,202]
Indonesia	2018	Diesel, small hydro, and solar PV	N/A	1300	[39]
Bangladesh	2017	Solar PV, diesel	N/A	7	[62]
Chile	2016	Solar	8.4 MW	N/A	[41]
Tanzania	2016	Solar, hydro, and biomass gasifier	157.7 MW	109	[59,79]
Nigeria	2018	Solar PV	N/A	30	[39]
Kenya	2017	Diesel, hybrid (diesel/solar and diesel/wind)	19.1 MW	21	[83]
Mali	2015	Hybrid (PV/diesel)	N/A	30	[60]
Mauritania	2015	Hybrid (solar PV/diesel)	N/A	6	[41]
Mozambique	2017	Solar PV, hydro, biomass (cogeneration)	3 MW	12	[73,74]
Malawi	2015	Hybrid solar/wind mini-grids	N/A	6	[72]
Cameroon	2015	Solar PV	23 MW	30	[41]

Appendix B. Examples of mini-grids installed in developing regions

Mini-grids has been deployed in many countries using different technologies, as shown in this table. These mini-grids have been selected from the literature to provide insights into the successfully implemented projects [18,21,22,39,45,46,48,72,185,203–207]. Most of these projects were pioneers in their countries and have been operating for many years. As an example, the 100 kW solar PV/diesel mini-grid in Sandwip was the first hybrid system successfully implemented in Bangladesh, and it is still operational. This system can be used as a role model of the successful economic and technical viability for future mini-grids. In general, the size of the systems presented ranges from 3 kW to 10 MW, and the most used resources are solar and hydro.

Region	Examples
Arab States	710 kW of solar PV in Palestine, 10 MW solar PV in Siwa (Egypt), 3 kW of solar PV in Aden (Yemen).
East Asia and the Pacific	6 MW of wind in Phu Quy (Vietnam), 15 kW of solar PV in Lamonae (Indonesia), 3.6 kW of solar PV in Mandalay (Myanmar), 10 MW of solar PV in Darkhan (Mongolia).
Europe and Central Asia	1.1 MW of solar PV in Pirallahi Island (Azerbaijan), 2 MW of solar PV in Kladovo (Serbia).
Latin America and the Caribbean	40 kW of micro-hydro in Tamborapa Pueblo (Peru).
South Asia	100 kWp solar PV/diesel in Sandwip Island (Bangladesh), 1 MW of hybrid solar PV/diesel in Bamiyan (Afghanistan), 132 kW of mini-hydro in Baglung (Nepal), 3.6 kW of solar PV in Mandalay (Myanmar).
Africa	216 kWp of hybrid solar PV/Diesel in Ouéléssébougou (Mali), 202 kW and 20 kW of hybrid PV/Diesel in Tsumkwe and Gobabeb respectively (Namibia), three power stations with a total of 1.3 MW Solar PV in Niassa (Mozambique), 1.6 MW of hybrid solar PV/diesel in Uganda, 40 kWp solar PV at Monte Trigo (Cape Verde), 14 kW of micro-hydro in Zimbabwe, Katse (540 kW) and Semonkong (180 kW) mini-hydropower plants in Lesotho, 750 kW mini-hydro in Zengamina (Zambia), 48 kW of solar PV/battery and 10 kW of hybrid solar PV/diesel in Tanzania, 60 kW of solar PV/battery in Luapula (Zambia).

References

[1] World Bank. Tracking SDG7: the energy progress report. 2018. Washington, DC.
[2] Khodayar ME. Rural electrification and expansion planning of off-grid microgrids. Electr J 2017;30:68–74. https://doi.org/10.1016/j.tej.2017.04.004.
[3] Sigarchian SG, Paleta R, Malmquist A, Pina A. Feasibility study of using a biogas engine as backup in a decentralized hybrid (PV/wind/battery) power generation system - case study Kenya. Energy 2015;90:1830–41. https://doi.org/10.1016/j.energy.2015.07.008.
[4] Sims R, Mercado P, Krewitt W, Bhuyan G, Flynn D, Holttinen H, et al. Integration of renewable energy into present and future energy systems. In: IPCC special report on renewable energy sources and climate change mitigation; 2011. Cambridge, United Kingdom and New York, NY, USA.
[5] Sims REH, Schock RN, Adegbululgbe A, Fenhann J, Konstantinaviciute I, Moomaw W, et al. Energy supply. In: Climate change 2007: mitigation. Contribution of working group III to the fourth assessment report of the intergovernmental panel on climate change; 2007. Cambridge, United Kingdom and New York, NY, USA.
[6] Ismail MS, Moghavvemi M, Mahlia TMI, Muttaqi KM, Moghavvemi S. Effective utilization of excess energy in standalone hybrid renewable energy systems for improving comfort ability and reducing cost of energy: a review and analysis. Renew Sustain Energy Rev 2015;42:726–34. https://doi.org/10.1016/j.rser.2014.10.051.
[7] Williams NJ, Jaramillo P, Taneja J, Ustun TS. Enabling private sector investment in microgrid-based rural electrification in developing countries: a review. Renew Sustain Energy Rev 2015;52:1268–81. https://doi.org/10.1016/j.rser.2015.07.153.
[8] Ahmad J, Imran M, Khalid A, Iqbal W, Ashraf SR, Adnan M, et al. Techno economic analysis of a wind-photovoltaic-biomass hybrid renewable energy system for rural electrification: a case study of Kallar Kahar. Energy 2018;148:208–34. https://doi.org/10.1016/j.energy.2018.01.133.
[9] Shahzad MK, Zahid A, Rashid T, Rehan MA, Ali M, Ahmad M. Techno-economic feasibility analysis of a solar-biomass off grid system for the electrification of remote rural areas in Pakistan using HOMER software. Renew Energy 2017;106:264–73. https://doi.org/10.1016/j.renene.2017.01.033.
[10] Das BK, Hoque N, Mandal S, Pal TK, Raihan MA. A techno-economic feasibility of a stand-alone hybrid power generation for remote area application in Bangladesh. Energy 2017;134:775–88. https://doi.org/10.1016/j.energy.2017.06.024.
[11] Kaabeche A, Ibtiouen R. Techno-economic optimization of hybrid photovoltaic/wind/diesel/battery generation in a stand-alone power system. Sol Energy 2014;103:171–82. https://doi.org/10.1016/j.solener.2014.02.017.
[12] Baneshi M, Hadianfard F. Techno-economic feasibility of hybrid diesel/PV/wind/battery electricity generation systems for non-residential large electricity consumers under southern Iran climate conditions. Energy Convers Manag 2016;127:233–44. https://doi.org/10.1016/j.enconman.2016.09.008.
[13] Ramli MAM, Hiendro A, Al-Turki YA. Techno-economic energy analysis of wind/solar hybrid system: case study for western coastal area of Saudi Arabia. Renew Energy 2016;91:374–85. https://doi.org/10.1016/j.renene.2016.01.071.
[14] Shi B, Wu W, Yan L. Size optimization of stand-alone PV/wind/diesel hybrid power generation systems. J Taiwan Inst Chem Eng 2017;73:93–101. https://doi.org/10.1016/j.jtice.2016.07.047.
[15] Al Busaidi AS, Kazem HA, Al-Badi AH, Farooq Khan M. A review of optimum sizing of hybrid PV-Wind renewable energy systems in Oman. Renew Sustain Energy Rev 2016;53:185–93. https://doi.org/10.1016/j.rser.2015.08.039.
[16] Maleki A, Askarzadeh A. Optimal sizing of a PV/wind/diesel system with battery storage for electrification to an off-grid remote region: a case study of Rafsanjan, Iran. Sustain Energy Technol Assessments 2014;7:147–53. https://doi.org/10.1016/j.seta.2014.04.005.
[17] Khan FA, Pal N, Saeed SH. Review of solar photovoltaic and wind hybrid energy systems for sizing strategies optimization techniques and cost analysis methodologies. Renew Sustain Energy Rev 2018;92:937–47. https://doi.org/10.1016/j.rser.2018.04.107.
[18] EEP Africa. Opportunities and challenges in the mini-grid sector in Africa - lessons learned from the EEP portfolio. 2018. Pretoria.
[19] ESMAP. Mini grids for half a billion people: market outlook and handbook for decision makers. Executive summary. Technical report 014/19. 2019. Washington, DC.
[20] ESMAP. Technical and economic assessment of off-grid, Mini-grid and grid electrification technologies. ESMAP Tech Pap 121/07 2007:324. https://doi.org/10.1039/b307345a.
[21] IRENA. Policies and regulations for private sector renewable energy mini-grids. 2016. Abu Dhabi.
[22] IRENA. Innovation Outlook. Renewable mini-grids. 2016. Abu Dhabi.
[23] Fs-UNEP Collaborating Centre. Global trends in renewable energy investments 2018. 2018. Frankfurt:.
[24] IRENA. Renewable power generation costs in 2017. 2018. Abu Dhabi.
[25] IRENA. The power to change: solar and wind cost reduction potential to 2025. 2016. Abu Dhabi.
[26] IRENA. REthinking Energy. Accelerating the global transformation, vol. 55; 2017. Abu Dhabi: 2017.
[27] IRENA and CPI. Global landscape of renewable energy finance 2018. 2018. Abu Dhabi.
[28] Alliance for Rural Electrification. Rural electrification with renewable energy technologies, quality standards and business models. 2011. Brussels, Belgium.
[29] Alliance for Rural Electrification. Hybrid mini-grids for rural electrification: lessons learned, vol. 2; 2014. Brussels.
[30] Hirmer S, Cruickshank H. The user-value of rural electrification: an analysis and adoption of existing models and theories. Renew Sustain Energy Rev 2014;34:145–54. https://doi.org/10.1016/j.rser.2014.03.005.
[31] Hirmer S, Guthrie P. Identifying the needs of communities in rural Uganda: a method for determining the 'User-Perceived Value' of rural electrification initiatives. Renew Sustain Energy Rev 2016;66:476–86. https://doi.org/10.1016/j.rser.2016.08.037.
[32] Mahesh A, Sandhu KS. Hybrid wind/photovoltaic energy system developments: critical review and findings. Renew Sustain Energy Rev 2015;52:1135–47. https://doi.org/10.1016/j.rser.2015.08.008.
[33] USAID. Practical guide to the regulatory treatment of mini-grids. 2017. Washington, DC.
[34] Lorenz G. Community-based Micro Grids: a common property resource problem. Brighton: STEPS Centre 2014. https://doi.org/10.1007/978-90-481-9594-7.
[35] Unicef. SWOT and PESTEL. UNICEF KE toolbox 2015:1–12. https://www.unicef.org/knowledge-exchange/files/SWOT_and_PESTEL_production.pdf (accessed August 12, 2018).

[36] Carvallo JP, Deshmukh R, Gambhir A. Sustainable development of renewable energy mini-grids for energy access: a framework for policy design. 2013. Berkeley, CA.
[37] Zalengera C, Blanchard RE, Eames PC, Juma AM, Chitawo ML, Gondwe KT. Overview of the Malawi energy situation and A PESTLE analysis for sustainable development of renewable energy. Renew Sustain Energy Rev 2014;38:335–47. https://doi.org/10.1016/j.rser.2014.05.050.
[38] IRENA. Innovation landscape for a renewable-powered future: solutions to integrate variable renewables. 2019. Abu Dhabi.
[39] IRENA. Policies and regulations for renewable energy mini-grids. 2018. Abu Dhabi.
[40] Alliance for Rural Electrification. Annual report 2018. 2018. Brussels, Belgium.
[41] IRENA. Off-Grid renewable energy systems: status and methodological issues. 2015. Abu Dhabi.
[42] Azimoh CL, Klintenberg P, Mbohwa C, Wallin F. Replicability and scalability of mini-grid solution to rural electrification programs in sub-Saharan Africa. Renew Energy 2017;106:222–31. https://doi.org/10.1016/j.renene.2017.01.017.
[43] Safdar T. Business models for mini-grids: technical report 9. 2017. Cambridge.
[44] RECP, EUEI PDF, Alliance for Rural Electrification, REN21. Mini-grid policy Toolkit_Policy and business framework for successful mini-grid roll-outs. Germany: Eschborn; 2014.
[45] ECREEE. Mapping & assessment of existing clean energy mini-grid experiences in west africa. 2016.
[46] Africa-EU Renewable Energy Cooperation Programme. Supportive framework conditions for mini-grids employing renewable and hybrid generation in the SADC Region Namibia Case Study Gap analysis and National Action Plan. 2014.
[47] Hevia T. The rural electrification in China and the impact of renewable energies. 2009. Shanghai.
[48] GNESD. Renewable energy-based rural electrification: the mini-grid experience from India. 2014. Copenhagen.
[49] Palit D, Sarangi GK. Renewable energy based mini-grids for enhancing electricity Access : experiences and lessons from India. Pattaya City; 2014. p. 19–21. Thailand.
[50] Schnitzer D, Deepa S, Carvalo JP, Ranjit D, Jay A, Daniel K. Microgrids for rural electrification : a critical review of best practices based on seven case studies. 2014. https://doi.org/10.1016/j.gene.2014.01.063.
[51] REN21. Renewables. Global status report. 2018. Paris: 2018. https://doi.org/978-3-9818911-3-3.
[52] IRENA. Renewable. Energy prospects for India. 2015. Abu Dhabi.
[53] OECD/IEA. Southeast Asia energy outlook 2017. IEA Publications, International Energy Agency; 2017. https://doi.org/10.1787/9789264285576-en.
[54] Bhattacharyya S, Palit D, GKS. Towards scaling up of electricity Access : summary and OASYS South Asia project. 2015. New Delhi.
[55] IRENA. Accelerating renewable mini-grid deployment: a study on the Philippines. 2017. Abu Dhabi.
[56] ESMAP. Mini-grids and arrival of the main grid: lessons from Cambodia, Sri Lanka, and Indonesia. Washington, DC. 2017. https://doi.org/doi:10.1596/29018.
[57] GVEP International. Policy briefing: the history of mini-grid development in developing countries, vol. 44; 2011. https://greenminigrid.afdb.org/history-mini-grid-development-developing-countries-policy-briefing-2011. [Accessed 10 September 2018].
[58] Bernard Tenenbaum, Greacen Chris, Tilak Siyambalapitiya JK. From the Bottom Up: how small power producers and mini-grids can deliver electrification and renewable energy in Africa, vol. 17; 2014. https://doi.org/10.1177/1070496508326432. Washington, DC.
[59] ESMAP, State. Of electricity access report. 2017. Washington DC.
[60] NREL. Technical Report NREL/TP-7A40-64460. Policies to spur energy access: case studies of public-private models to finance decentralized electricity access, vol. 2; 2015. Golden, CO.
[61] REN21. Renewable energy police network (REN).Renewables 2017: Global status report. vol. vol. 72. 2017. https://doi.org/10.1016/j.rser.2016.09.082.
[62] ESMAP. Mini grids in Bangladesh. 2017. Washington DC.
[63] World Bank. State of electricity access report 2017. 2017. Washington, DC.
[64] Asian Development Bank. Developing renewable energy mini-grids in Myanmar : a guidebook. 2017. Manila.
[65] Upscaling ESMAP. Mini-grids for low cost and timely access to electricity. 2017. Washington, DC.
[66] Asian Development Bank. Energy for all: Viet Nam's success in increasing access to energy through rural electrification. 2011. Manila.
[67] GIZ Energy Support Programme. Overview of the Vietnamese power market. Hanoi: A Renewable Energy Perspective; 2015.
[68] ESMAP. Mini grids in Cambodia a case study of a success story. 2017. Washington, DC.
[69] ESMAP. A reprospective analysis of the role of isolated and mini grids in power system development. 2017. Washington, DC.
[70] IEA. Rural electrification with PV hybrid systems: overview and recommendations for further deployment. 2013. Paris.
[71] Energising Development. Rwanda: off-grid sector status report 2017. Kigali; 2018.
[72] REN21. SADC renewable energy and energy efficiency: status report. 2015. Paris.
[73] SEI. Renewable energy mini-grids: an alternative approach to energy access in southern Africa. 2016. https://www.sei.org/mediamanager/documents/Publications/SEI-DB-2016-SADC-mini-grids.pdf. [Accessed 22 September 2018].
[74] REN21. SADC renewable energy and energy efficiency - status report. 2018. Paris.
[75] Mokveld K, Eije S von. Final energy report Mozambique. 2018. The Hague.
[76] Renewable FUNAE. Energy Projects Portfolio hydro and solar resources. second ed. Maputo; 2019.
[77] IRENA. Renewable power generation costs in 2017. 2018. https://doi.org/10.1007/SpringerReference_7300. Abu Dhabi.
[78] Moner-Girona M, Ghanadan R, Solano-Peralta M, Kougias I, Bódis K, Huld T, et al. Adaptation of Feed-in Tariff for remote mini-grids: Tanzania as an illustrative case. Renew Sustain Energy Rev 2016;53:306–18. https://doi.org/10.1016/j.rser.2015.08.055.
[79] Odarno Lily, Sawe Estomih, Mary Swai MJJK and AL. Accelerating mini-grids deployment in sub-saharan africa: lessons from Tanzania. 2017. Washington, DC.
[80] Nkiriki J, Ustun TS. Mini-grid policy directions for decentralized smart energy models in Sub-Saharan Africa. In: IEEE PES innov smart grid technol conf eur ISGT-europe 2017 - proc 2017; 2017; 2018. p. 1–6. https://doi.org/10.1109/ISGTEurope.2017.8260217. Janua.
[81] ESMAP. Mini Grids in Kenya - a case study of a market at a turning point. 2017. Washington DC.
[82] Pueyo A, DeMartino S. The impact of solar mini-grids on Kenya's rural enterprises. Energy Sustain Dev 2018;45:28–37. https://doi.org/10.1016/j.esd.2018.04.002.
[83] RECP, EUEI PDF, Alliance for Rural Electrification, REN21. Mini-grid policy toolkit- case study country: Kenya project: rural electrification with government-run mini-grids utility operator model n.d. http://minigridpolicytoolkit.euei-pdf.org/downloads.html. [Accessed 22 September 2018].
[84] RECP, EUEI PDF, Alliance for Rural Electrification, REN21. Mini-grid policy toolkit-case study country: Senegal project: ERSEN off-grid solar energy Programme hybrid utility-private operator model n.d. http://minigridpolicytoolkit.euei-pdf.org/downloads.html. [Accessed 30 September 2018].
[85] Africa progress panel. Lights power action. _Electrifying Africa; 2017.
[86] Alliance for Rural Electrification. Private sector driven business models for clean energy mini-grids: lessons learnt from South and South-East-Asia. 2019. Brussels, Belgium.
[87] UNEP. Increasing private capital investment into energy access: the case for mini -grid pooling facilities. 2015.
[88] Sandwell P, Wheeler S, Nelson J. Supporting rural electrification in developing countries. 2016.
[89] UNIDO. Renewable energy-based mini-grids: the UNIDO experience. 2017. Vienna.
[90] Pedersen MB. Deconstructing the concept of renewable energy-based mini-grids for rural electrification in East Africa. Wiley Interdiscip Rev Energy Environ; 2016. p. 570–87. https://doi.org/10.1002/wene.205.
[91] Palit PRK and D. Chapter 8: participatory business models for off-grid electrification. 2013. https://doi.org/10.1007/978-1-4471-4673-5.
[92] Pourbehzadi M, Niknam T, Aghaei J, Mokryani G. Electrical Power and Energy Systems Optimal operation of hybrid AC/DC microgrids under uncertainty of renewable energy resources : a comprehensive review. Electr Power Energy Syst 2019;109:139–59. https://doi.org/10.1016/j.ijepes.2019.01.025.
[93] IRENA. Electricity storage and renewables for island power. 2012. Abu Dhabi.
[94] Jaiswal A. Lithium-ion battery based renewable energy solution for off-grid electricity: a techno-economic analysis. Renew Sustain Energy Rev 2017;72:922–34. https://doi.org/10.1016/j.rser.2017.01.049.
[95] IRENA. Solar pv in africa: costs and markets. 2016. Abu Dhabi.
[96] Das BK, Zaman F. Performance analysis of a PV/Diesel hybrid system for a remote area in Bangladesh: effects of dispatch strategies, batteries, and generator selection. Energy 2019;169:263–76. https://doi.org/10.1016/j.energy.2018.12.014.
[97] Diouf B, Pode R. Potential of lithium-ion batteries in renewable energy. Renew Energy 2015;76:375–80. https://doi.org/10.1016/j.renene.2014.11.058.
[98] IRENA. Renewable mini-grids: innovation landscape brief. 2019. Abu Dhabi.
[99] Chauhan A, Saini RP. A review on Integrated Renewable Energy System based power generation for stand-alone applications: configurations, storage options, sizing methodologies and control. Renew Sustain Energy Rev 2014;38:99–120. https://doi.org/10.1016/j.rser.2014.05.079.
[100] Hamam Y, Member S. A comprehensive state-of-the-art survey operations and planning. IEEE Access 2020:1. https://doi.org/10.1109/ACCESS.2020.2988397.
[101] Planas E, Andreu J, Gárate JI, Martínez De Alegría I, Ibarra E. AC and DC technology in microgrids: a review. Renew Sustain Energy Rev 2015;43:726–49. https://doi.org/10.1016/j.rser.2014.11.067.
[102] Mirsaeidi S, Dong X, Said DM. Towards hybrid AC/DC microgrids: critical analysis and classification of protection strategies. Renew Sustain Energy Rev 2018;90:97–103. https://doi.org/10.1016/j.rser.2018.03.046.
[103] Brenna M, Foiadelli F, Longo M, Abegaz TD. Integration and optimization of renewables and storages for rural electrification. Sustain Times 2016;8. https://doi.org/10.3390/su8100982.
[104] Anoune K, Bouya M, Astito A, Abdellah A Ben. Sizing methods and optimization techniques for PV-wind based hybrid renewable energy system: a review. Renew Sustain Energy Rev 2018;93:652–73. https://doi.org/10.1016/j.rser.2018.05.032.
[105] REN21. Renewables. Global status report. Paris: REN21 Secretariat; 2018. 2018.
[106] Bhandari B, Lee KT, Lee CS, Song CK, Maskey RK, Ahn SH. A novel off-grid hybrid power system comprised of solar photovoltaic, wind, and hydro energy sources. Appl Energy 2014;133:236–42. https://doi.org/10.1016/j.apenergy.2014.07.033.
[107] Domenech B, Ferrer-Martí L, Lillo P, Pastor R, Chiroque J. A community electrification project: combination of microgrids and household systems fed by wind, PV or micro-hydro energies according to micro-scale resource evaluation

and social constraints. Energy Sustain Dev 2014;23:275–85. https://doi.org/10.1016/j.esd.2014.09.007.
[108] Mohammed YS, Mustafa MW, Bashir N. Hybrid renewable energy systems for off-grid electric power: review of substantial issues. Renew Sustain Energy Rev 2014;35:527–39. https://doi.org/10.1016/j.rser.2014.04.022.
[109] Dawoud SM, Lin X, Okba MI. Hybrid renewable microgrid optimization techniques: a review. Renew Sustain Energy Rev 2017;82:2039–52. https://doi.org/10.1016/j.rser.2017.08.007.
[110] Vivas FJ, De las Heras A, Segura F, Andújar JM. A review of energy management strategies for renewable hybrid energy systems with hydrogen backup. Renew Sustain Energy Rev 2018;82:126–55. https://doi.org/10.1016/j.rser.2017.09.014.
[111] Yahiaoui A, Benmansour K, Tadjine M. Control, analysis and optimization of hybrid PV-Diesel-Battery systems for isolated rural city in Algeria. Sol Energy 2016;137:1–10. https://doi.org/10.1016/j.solener.2016.07.050.
[112] Bhattacharyya SC. Mini-grids for the base of the pyramid Market : a critical review. Energies 2018. https://doi.org/10.3390/en11040813.
[113] Shivarama Krishna K, Sathish Kumar K. A review on hybrid renewable energy systems. Renew Sustain Energy Rev 2015;52:907–16. https://doi.org/10.1016/j.rser.2015.07.187.
[114] Blum NU, Sryantoro Wakeling R, Schmidt TS. Rural electrification through village grids - assessing the cost competitiveness of isolated renewable energy technologies in Indonesia. Renew Sustain Energy Rev 2013;22:482–96. https://doi.org/10.1016/j.rser.2013.01.049.
[115] IRENA. Renewable energy technologies: cost analysis series. Biomass Power Gener 2012;1:60. https://doi.org/10.1016/B978-0-08-098330-1.00011-9.
[116] Schlömer S, Bruckner T, Fulton L, Hertwich E, McKinnon A, Perczyk D, et al. Annex III: technology-specific cost and performance parameters. Cambridge and New York. In: Climate change: mitigation of climate change. Contribution of working group III to the fifth assessment report of the intergovernmental panel on climate change; 2014. https://doi.org/http://report.mitigation2014.org/report/ipcc_wg3_ar5_annex-ii.pdf.
[117] Kost C, Mayer JN, Thomsen J, Hartmann N, Senkpiel C, Philipps S, et al. Levelized cost of electricity: renewable energy technologies. Fraunhofer Inst Sol Energy Syst ISE 2013;50. https://doi.org/10.1613/jair.301.
[118] Collaborating FS, Finance SE. Renewable energy in hybrid mini-grids and isolated grids: economic benefits and business cases. 2015.
[119] Blum NU, Wakeling RS, Schmidt TS. Rural electrification through village grids — assessing the cost competitiveness of isolated renewable energy technologies in Indonesia. Renew Sustain Energy Rev 2013;22:482–96. https://doi.org/10.1016/j.rser.2013.01.049.
[120] IRENA. Renewable power generation costs in 2012 : an overview. Abu Dabi; 2012.
[121] Comello SD, Reichelstein SJ, Sahoo A. Enabling mini-grid development in rural India. World Dev 2017;93:94–107. https://doi.org/10.1016/j.worlddev.2016.12.029.
[122] Alliance for Rural Electrification. Risk Management for Mini-Grids: a new approach to guide mini-grid deployment. 2014. Brussels.
[123] ESMAP. Technical and economic assessment of off-grid, mini-grid and grid electrification technologies. 2007. Washington, DC.
[124] Ruud C. Why not go green ? - an analysis of the viability of solar PV mini-grids in Tanzania. Norwegian University of Life Sciences; 2013.
[125] Ondraczek J. Are we there yet? Improving solar PV economics and power planning in developing countries: the case of Kenya. Renew Sustain Energy Rev 2014;30:604–15. https://doi.org/10.1016/j.rser.2013.10.010.
[126] Deichmann U, Meisner C, Murray S, Wheeler D. The economics of renewable energy expansion in rural Sub-Saharan Africa. Energy Pol 2011;39:215–27. https://doi.org/10.1016/j.enpol.2010.09.034.
[127] Akker JHA Van Den. Overview of costs of sustainable energy technologies. Westerhoven; 2017.
[128] Hiendro A, Kurnianto R, Rajagukguk M, Simanjuntak YM, Junaidi. Techno-economic analysis of photovoltaic/wind hybrid system for onshore/remote area in Indonesia. Energy 2013;59:652–7. https://doi.org/10.1016/j.energy.2013.06.005.
[129] IPCC. Renewable energy sources and climate change mitigation: special report of the Intergovernmental Panel on Climate Change, vol. 49; 2012. https://doi.org/10.5860/CHOICE.49-6309.
[130] Amutha WM, Rajini V. Cost benefit and technical analysis of rural electrification alternatives in southern India using HOMER. Renew Sustain Energy Rev 2016;62:236–46. https://doi.org/10.1016/j.rser.2016.04.042.
[131] Azimoh CL, Klintenberg P, Wallin F, Karlsson B, Mbohwa C. Electricity for development: mini-grid solution for rural electrification in South Africa. Energy Convers Manag 2016;110:268–77. https://doi.org/10.1016/j.enconman.2015.12.015.
[132] Zahraee SM, Khalaji Assadi M, Saidur R. Application of artificial intelligence methods for hybrid energy system optimization. Renew Sustain Energy Rev 2016;66:617–30. https://doi.org/10.1016/j.rser.2016.08.028.
[133] Luna-Rubio R, Trejo-Perea M, Vargas-Vázquez D, Ríos-Moreno GJ. Optimal sizing of renewable hybrids energy systems: a review of methodologies. Sol Energy 2012;86:1077–88. https://doi.org/10.1016/j.solener.2011.10.016.
[134] Mas'Ud AA. The application of homer optimization software to investigate the prospects of hybrid renewable energy system in rural communities of sokoto in Nigeria. Int J Electr Comput Eng 2017;7:596–603. https://doi.org/10.11591/ijece.v7i2.pp596-603.
[135] Sinha S, Chandel SS. Review of software tools for hybrid renewable energy systems. Renew Sustain Energy Rev 2014;32:192–205. https://doi.org/10.1016/j.rser.2014.01.035.
[136] Upadhyay S, Sharma MP. A review on configurations, control and sizing methodologies of hybrid energy systems. Renew Sustain Energy Rev 2014;38:47–63. https://doi.org/10.1016/j.rser.2014.05.057.
[137] Asian Development Bank. Deployment of hybrid renewable energy systems in minigrids. Mandaluyong 2017. https://doi.org/https://doi.org/10.22617/TIM178889-2.
[138] Bahramara S, Moghaddam MP, Haghifam MR. Optimal planning of hybrid renewable energy systems using HOMER : a review. Renew Sustain Energy Rev 2016;62:609–20. https://doi.org/10.1016/j.rser.2016.05.039.
[139] Bekele G, Tadesse G. Feasibility study of small Hydro/PV/Wind hybrid system for off-grid rural electrification in Ethiopia. Appl Energy 2012;97:5–15. https://doi.org/10.1016/j.apenergy.2011.11.059.
[140] Rajbongshi R, Borgohain D, Mahapatra S. Optimization of PV-biomass-diesel and grid base hybrid energy systems for rural electrification by using HOMER. Energy 2017;126:461–74. https://doi.org/10.1016/j.energy.2017.03.056.
[141] Mohammed YS, Mustafa MW, Bashir N. Hybrid renewable energy systems for off-grid electric power : review of substantial issues. Renew Sustain Energy Rev 2014;35:527–39. https://doi.org/10.1016/j.rser.2014.04.022.
[142] Olatomiwa L, Mekhilef S, Ismail MS, Moghavvemi M. Energy strategies in hybrid renewable energy systems: a review. Renew Sustain Energy Rev 2016;62:821–35. https://doi.org/10.1016/j.rser.2016.05.040.
[143] Sinha S, Chandel SS. Review of recent trends in optimization techniques for solar photovoltaic-wind based hybrid energy systems. Renew Sustain Energy Rev 2015;50:755–69. https://doi.org/10.1016/j.rser.2015.05.040.
[144] Connolly D, Lund H, Mathiesen BV, Leahy M. A review of computer tools for analysing the integration of renewable energy into various energy systems. Appl Energy 2010;87:1059–82. https://doi.org/10.1016/j.apenergy.2009.09.026.
[145] Belmili H, Haddadi M, Bacha S, Almi MF, Bendib B. Sizing stand-alone photovoltaic-wind hybrid system: techno-economic analysis and optimization. Renew Sustain Energy Rev 2014;30:821–32. https://doi.org/10.1016/j.rser.2013.11.011.
[146] Ringkjøb HK, Haugan PM, Solbrekke IM. A review of modelling tools for energy and electricity systems with large shares of variable renewables. Renew Sustain Energy Rev 2018;96:440–59. https://doi.org/10.1016/j.rser.2018.08.002.
[147] Fadaeenejad M, Radzi MAM, AbKadir MZA, Hizam H. Assessment of hybrid renewable power sources for rural electrification in Malaysia. Renew Sustain Energy Rev 2014;30:299–305. https://doi.org/10.1016/j.rser.2013.10.003.
[148] Fathima AH, Palanisamy K. Optimization in microgrids with hybrid energy systems - a review. Renew Sustain Energy Rev 2015;45:431–46. https://doi.org/10.1016/j.rser.2015.01.059.
[149] Shrivastava RL, Kumar V, Untawale SP. Modeling and simulation of solar water heater: a TRNSYS perspective. Renew Sustain Energy Rev 2017;67:126–43. https://doi.org/10.1016/j.rser.2016.09.005.
[150] Tezer T, Yaman R, Yaman G. Evaluation of approaches used for optimization of stand-alone hybrid renewable energy systems. Renew Sustain Energy Rev 2017;73:840–53. https://doi.org/10.1016/j.rser.2017.01.118.
[151] Bukar AL, Tan CW. A review on stand-alone photovoltaic-wind energy system with fuel cell: system optimization and energy management strategy. J Clean Prod 2019;221:73–88. https://doi.org/10.1016/j.jclepro.2019.02.228.
[152] Ramos A. Decision support models in electric power: generation reliability. 2018. https://www.iit.comillas.edu/aramos/. [Accessed 14 December 2018].
[153] Blimpo MP, Cosgrove-Davies M. Electricity access in sub-saharan africa: uptake, reliability, and complementary factors for economic impact. Washington, DC: World Bank; 2019. https://doi.org/10.1596/978-1-4648-1361-0.
[154] Alliance for Rural Electrification. Best Practises of the Alliance for Rural Electrification: what renewable energies can achieve in developing and emerging markets. 2013. Brussels.
[155] Dutt PK, Macgill I. Addressing some issues relating to hybrid mini grid failures in Fiji. In: c2013 IEEE glob. Humanit. Technol. Conf. South Asia satell. GHTC-SAS 2013; 2013. p. 106–11. https://doi.org/10.1109/GHTC-SAS.2013.6629898.
[156] IEA. 16 Case. Studies on the deployment of photovoltaic technologies in developing countries. 2003. http://www.iea-pvps.org. [Accessed 15 January 2019].
[157] Boroujeni Hasan Fayazi, Eghtedari Meysam, Mostafa Abdollahi EB. Calculation of generation system reliability index: loss of load probability hasan. Life Sci J 2012;9:4903–8.
[158] Adefarati T, Bansal RC. Reliability assessment of distribution system with the integration of renewable distributed generation. Appl Energy 2017;185:158–71. https://doi.org/10.1016/j.apenergy.2016.10.087.
[159] Tian Z, Seifi AA. Reliability analysis of hybrid energy system. Int J Reliab Qual Saf Eng 2014;21:1450011. https://doi.org/10.1142/S0218539314500119.
[160] Jafar M, Moghaddam H, Kalam A, Arabi S. Optimal sizing and energy management of stand-alone hybrid photovoltaic/wind system based on hydrogen storage considering LOEE and LOLE reliability indices using flower pollination algorithm. Renew Energy 2019;135:1412–34. https://doi.org/10.1016/j.renene.2018.09.078.
[161] Adefarati T, Bansal RC, Justo JJ. Reliability and economic evaluation of a microgrid power system. Energy Procedia 2017;142:43–8. https://doi.org/10.1016/j.egypro.2017.12.008.
[162] Kazem HA, Khatib T. A novel numerical algorithm for optimal sizing of a photovoltaic/wind/diesel generator/battery microgrid using loss of load probability index. Int J Photoenergy 2013;2013. https://doi.org/10.1155/2013/718596.

[163] Bhandari B, Lee KT, Lee GY, Cho YM, Ahn SH. Optimization of hybrid renewable energy power systems: a review. Int J Precis Eng Manuf - Green Technol 2015;2: 99–112. https://doi.org/10.1007/s40684-015-0013-z.
[164] Bilal BO, Sambou V, Ndiaye PA, Kébé CMF, Ndongo M. Optimal design of a hybrid solar e wind – battery system using the minimization of the annualized cost system and the minimization of the loss of power supply probability. LPSP) 2010; 35:2388–90. https://doi.org/10.1016/j.renene.2010.03.004.
[165] Javed MS, Ma T. Techno-economic assessment of a hybrid solar-wind-battery system with generic algorithm. Energy Procedia 2019;158:6384–92. https://doi.org/10.1016/j.egypro.2019.01.211.
[166] Haghighat Mamaghani A, Avella Escandon SA, Najafi B, Shirazi A, Rinaldi F. Techno-economic feasibility of photovoltaic, wind, diesel and hybrid electrification systems for off-grid rural electrification in Colombia. Renew Energy 2016;97:293–305. https://doi.org/10.1016/j.renene.2016.05.086.
[167] Halabi LM, Mekhilef S, Olatomiwa L, Hazelton J. Performance analysis of hybrid PV/diesel/battery system using HOMER: a case study Sabah, Malaysia. Energy Convers Manag 2017;144:322–39. https://doi.org/10.1016/j.enconman.2017.04.070.
[168] Bhatt A, Sharma MP, Saini RP. Feasibility and sensitivity analysis of an off-grid micro hydro-photovoltaic-biomass and biogas-diesel-battery hybrid energy system for a remote area in Uttarakhand state, India. Renew Sustain Energy Rev 2016;61:53–69. https://doi.org/10.1016/j.rser.2016.03.030.
[169] Yilmaz S, Dincer F. Optimal design of hybrid PV-Diesel-Battery systems for isolated lands: a case study for Kilis, Turkey. Renew Sustain Energy Rev 2017;77: 344–52. https://doi.org/10.1016/j.rser.2017.04.037.
[170] Ould Bilal B, Sambou V, Ndiaye PA, Kébé CMF, Ndongo M. Study of the influence of load profile variation on the optimal sizing of a standalone hybrid PV/Wind/Battery/Diesel system. Energy Procedia 2013;36:1265–75. https://doi.org/10.1016/j.egypro.2013.07.143.
[171] Tsuanyo D, Azoumah Y, Aussel D, Neveu P. Modeling and optimization of batteryless hybrid PV (photovoltaic)/Diesel systems for off-grid applications. Energy 2015;86:152–63. https://doi.org/10.1016/j.energy.2015.03.128.
[172] Garrido H, Vendeirinho V, Brito MC. Feasibility of KUDURA hybrid generation system in Mozambique: sensitivity study of the small-scale PV-biomass and PV-diesel power generation hybrid system. Renew Energy 2016;92:47–57. https://doi.org/10.1016/j.renene.2016.01.085.
[173] Hossain M, Mekhilef S, Olatomiwa L. Performance evaluation of a stand-alone PV-wind-diesel-battery hybrid system feasible for a large resort center in South China Sea, Malaysia. Sustain Cities Soc 2017;28:358–66. https://doi.org/10.1016/j.scs.2016.10.008.
[174] Maatallah T, Ghodhbane N, Ben Nasrallah S. Assessment viability for hybrid energy system (PV/wind/diesel) with storage in the northernmost city in Africa, Bizerte, Tunisia. Renew Sustain Energy Rev 2016;59:1639–52. https://doi.org/10.1016/j.rser.2016.01.076.
[175] Summary for policymakers. In: Edenhofer O, Pichs-Madruga R, Sokona Y, Seyboth K, Matschoss P, Kadner S, Zwickel T, Eickemeier P, Hansen G, Schlömer S, C von S, editors. IPCC special report on renewable energy sources and climate change mitigation. New York: United Kingdom and; 2011.
[176] IRENA, IEA. REN21. Renewable energy policies in a time of transition. 2018.
[177] Baurzhan S, Jenkins GP. Off-grid solar PV: is it an affordable or appropriate solution for rural electrification in Sub-Saharan African countries? Renew Sustain Energy Rev 2016;60:1405–18. https://doi.org/10.1016/j.rser.2016.03.016.
[178] Indragandhi V, Subramaniyaswamy V, Logesh R. Resources, configurations, and soft computing techniques for power management and control of PV/wind hybrid system. Renew Sustain Energy Rev 2017;69:129–43. https://doi.org/10.1016/j.rser.2016.11.209.
[179] Milis K, Peremans H, Van Passel S. The impact of policy on microgrid economics: a review. Renew Sustain Energy Rev 2018;81:3111–9. https://doi.org/10.1016/j.rser.2017.08.091.
[180] IRENA. Renewable energy and jobs - annual review 2016. 2016. Abu Dhabi.
[181] Ghimire LP, Kim Y. An analysis on barriers to renewable energy development in the context of Nepal using AHP. Renew Energy 2018;129:446–56. https://doi.org/10.1016/j.renene.2018.06.011.
[182] Yaqoot M, Diwan P, Kandpal TC. Review of barriers to the dissemination of decentralized renewable energy systems. Renew Sustain Energy Rev 2016;58: 477–90. https://doi.org/10.1016/j.rser.2015.12.224.
[183] Action Practical. Poor people's energy outlook 2017: financing national energy access: a bottom-up approach. 2017. https://doi.org/10.3362/9781780446813.
[184] Moner-Girona M, Solano-Peralta M, Lazopoulou M, Ackom EK, Vallve X, Szabó S. Electrification of Sub-Saharan Africa through PV/hybrid mini-grids: reducing the gap between current business models and on-site experience. Renew Sustain Energy Rev 2018;91:1148–61. https://doi.org/10.1016/j.rser.2018.04.018.
[185] Alliance for Rural Electrification. Energy access from the bottom up: start-up and SME showcase 2018. 2018. Brussels.
[186] Edenhofer O, Pichs-Madruga R, Sokona Y, Seyboth K, Eickemeier P, Matschoss P, et al. IPCC, 2011: summary for policymakers. In: IPCC special report on renewable energy sources and climate change mitigation; 2011. https://doi.org/10.5860/CHOICE.49-6309.
[187] Feron S. Sustainability of off-grid photovoltaic systems for rural electrification in developing Countries : a review. Sustainability 2016:1–26. https://doi.org/10.3390/su8121326.
[188] Meier P, Vagliasindi M, Imran M. The design and sustainability of renewable energy incentives: an economic analysis. 2014. https://doi.org/10.1596/978-1-4648-0314-7.
[189] African Union. Africa strategy for green mini-grids 2016;2030. December 2016.
[190] Cuamba BC, Cipriano A, dos S, Turatsinze RHJ. Investment incentives for Africa : the case of Mozambique. 2013. https://www.aler-renovaveis.org/contents/lerpublication/investment-incentives-for-renewable-energy-in-sout-201301-boaventura-chongo-cuamba-amilcar-dos-santos-cipriano-ruth-henrique-jaime-turatsinze.pdf.
[191] Muchunku C, Gichungi H, Kirubi G, Wanyama K, Saini A. Solar mini-grids and solar lantern renting : drivers and barriers for sustainability and replication. 2017. p. 1–20.
[192] Ulsrud K, Rohracher H, Winther T, Muchunku C, Palit D. Pathways to electricity for all: what makes village-scale solar power successful? Energy Res Soc Sci 2018; 44:32–40. https://doi.org/10.1016/j.erss.2018.04.027.
[193] Ministry of Law and Justice of India. The electricity act 2003. 1925. p. 1–134. http://www.cercind.gov.in/act-with-amendment.pdf.
[194] Sustainable Energy for All. SE4All high impact opportunity clean energy mini-grids : mapping of clean energy mini-grids support providers and programmes. 2015.
[195] Wainstein ME, Bumpus AG. Business models as drivers of the low carbon power system transition: a multi-level perspective. J Clean Prod 2016;126:572–85. https://doi.org/10.1016/j.jclepro.2016.02.095.
[196] Mohammed YS, Mustafa MW, Bashir N. Status of renewable energy consumption and developmental challenges in Sub-Sahara Africa. Renew Sustain Energy Rev 2013;27:453–63. https://doi.org/10.1016/j.rser.2013.06.044.
[197] Williams NJ, Jaramillo P, Taneja J, Ustun TS. Enabling private sector investment in microgrid-based rural electrification in developing countries: a review. Renew Sustain Energy Rev 2015;52:1268–81. https://doi.org/10.1016/j.rser.2015.07.153.
[198] Wyman O. Auctions as a potential mechanism to accelerate green mini-grids in africa. 2017.
[199] Rahman MM, Paatero JV, Lahdelma R. Evaluation of choices for sustainable rural electrification in developing countries: a multicriteria approach. Energy Pol 2013; 59:589–99. https://doi.org/10.1016/j.enpol.2013.04.017.
[200] New Climate Institute and Verra. ICAT. Renewable Energy Guidance: guidance for assessing the greenhouse gas impacts of renewable energy policies. 2018. 2018.
[201] ESMAP. Mini Grids in Uttar Pradesh: a case study of a success story. 2017. Washington, DC.
[202] PwC. Electricity beyond the grid Accelerating access to sustainable power for all, vol. 24; 2016. https://www.pwc.com/gx/en/energy-utilities-mining/pdf/electricity-beyond-grid.pdf. [Accessed 20 February 2018].
[203] Aziz S, Ahmed S, Groh S. The success of solar diesel minigrids in Bangladesh : a case study of Sandwip island. Energy Procedia 2016;103:316–21. https://doi.org/10.1016/j.egypro.2016.11.292.
[204] RECP, EUEI, Alliance for Rural Electrification, REN21. Mini-grid policy toolkit – case study Country : Cape Verde n.d. http://minigridpolicytoolkit.euei-pdf.org/downloads.html. [Accessed 14 August 2018].
[205] RECP, EUEI, Alliance for Rural Electrification, REN21. Mini-grid policy toolkit-case study Country : Rwanda n.d. http://minigridpolicytoolkit.euei-pdf.org/downloads.html. [Accessed 16 November 2018].
[206] RECP, EUEI PDF, Alliance for Rural Electrification, REN21. Mini-grid policy toolkit- case study Country : Namibia n.d. http://minigridpolicytoolkit.euei-pdf.org/downloads.html. [Accessed 16 November 2018].
[207] Foster R, Woods T, Hoffbeck I. Bamiyan 1 MWp solar mini-grid (Afghanistan). Daegu: Sol. World Congr.; 2015. https://doi.org/10.18086/swc.2015.05.17.