Smart Grid and Renewable Energy, 2018, 9, 171-185
http://www.scirp.org/journal/sgre
ISSN Online: 2151-4844
ISSN Print: 2151-481X

PV-Hybrid Off-Grid and Mini-Grid Systems for Rural Electrification in Sub-Saharan Africa

Jordy Charly Isidore Rabetanetiarimanana, Mamy Harimisa Radanielina, Hery Tiana Rakotondramiarana

Institute for the Management of Energy (IME), University of Antananarivo, Antananarivo, Madagascar
Email: jordycharly6@gmail.com, radanielin@yahoo.fr, rktmiarana@yahoo.fr

How to cite this paper: Rabetanetiarimanana, J.C.I., Radanielina, M.H. and Rakotondramiarana, H.T. (2018) PV-Hybrid Off-Grid and Mini-Grid Systems for Rural Electrification in Sub-Saharan Africa. *Smart Grid and Renewable Energy*, **9**, 171-185.
https://doi.org/10.4236/sgre.2018.910011

Received: September 13, 2018
Accepted: October 19, 2018
Published: October 22, 2018

Abstract

Rural electrification remains a great challenge for Sub-Saharan Africa (SSA) as access to electricity is a prerequisite to accelerate its development. The present paper reviews the measures adopted to promote access to electricity in rural and remote areas of SSA. The main barriers to rural electrification in these developing countries are presented before showing technologies used for the aforementioned purpose. Then, adopted methods for enhancing the use of renewable energy in SSA are shown. Moreover, the policy adopted by decision makers and project planners are also highlighted. In addition, the optimal solutions proposed by researchers are given such as the cost-effective off-grid system type that might be a viable alternative to diesel power generation.

Keywords

Rural Electrification, Renewable Energy, Developing Countries, Sub-Saharan Africa, PV, Microgrid, Off-Grid

1. Introduction

Rural electrification remains a common challenge for many developing countries and especially in Sub-Saharan Africa (SSA) [1] [2] [3]. Indeed, the rate of electrification in SSA is only 32% to 35% [4] of which only 14% are related to rural electrification [5] [6]. Approximately 20% of the world's population lack access to electricity [7] [8] and they will not have access by 2030 [4] [9]. In SSA, only 290 million out of 915 million people have access to modern energy services and major party of rural populace lives in the darkness [10]. Nowadays, household electrification rates of the Global South remain below 15% to 20% [11] while the continent of Africa consumption is only 3.2% of the world's primary energy consumption [12]. SSA is marked by a low power consumption (less than 1 kWh per capita per day) [10]. Additionally, SSA is often characterized by insufficient power grids [11]. Indeed, improving access to electricity in SSA rural areas is crucial, access to electricity occurs generally good result such positive health, education and income consequences and social welfare [5]. Energy sufficiency is a prerequisite for achieving the economic development of a country [4] [5] [13]. Moreover, access to sustainable energy services allows the expansion of commercial and educational activities at night and will improve the standard of living of the local population [13]. Therefore, a United Nations project named Sustainable Energy Project for All (SE4All) has been implemented with the aim of providing electricity to all by 2030, especially in SSA where electricity demand is often modest [14]. However, planners and policy makers always faced many barriers to supply electricity in remote areas. Section 2 highlights the main barriers in electrifying embedded areas. Several studies were done to trace the effective solutions and to facilitate rural access to electricity. In this paper, some strategies and solutions implemented in SSA and in some other developing countries located in South Asia and Latina America are shown in Section 3. Section 4 presents the cost-effective schemes that research studies have occurred during the last decades.

2. Main Barriers to Rural Electrification in SSA

The main barriers to rural electrification in SSA are: the population affordability and low income [15], rural inaccessibility due to the road difficulties [16] [17] and remoteness [18] [19] [20], low population densities and dispersed households [21] [22], low project profitability [1], fiscal deficit, scarcity of energy resources [23] [24], population growth, lack of professionalism, and over-dependence on subsidies [25] [26] [27] [28].

Firstly, households in southern countries still suffer from the unequal distribution of electricity and low electricity generation capacity [11]. For a long time, urban electrification has been prioritized over rural electrification [4] [5] [9] [11]. This situation increased the rate of rural-urban migration in SSA [10].

Secondly, the fossil energy resources such as oil and natural gas will eventually be depleted and the environmental issues caused by their use [20], are increasing day by day. Brownouts and blackouts are very common in developing countries, as supply cannot meet demand [26] [29] [30] [31] [32]. These are the main motivating factors to use renewable energy resources [16] [33] [34]. Project planners and policy makers strive to use renewable energy as alternatives due to the increasing fossil fuel prices. SSA is also marked by higher electricity prices, with an average of 26 US cents per kWh [14]. However, renewable energy resources cannot fully guarantee demand [33] [35] [36] [37]. In addition, the use of some renewable energy resources is highly dependent on the variability of wind speed and intensity of sunshine [38] [39]. Supplying remote areas are complex because data on population distribution [40] [41] and electric load demands and geographic location are lacking [13] [39] [42] [43]. Hence, the use of software is not easy due to lack of data on electric load in SSA [10]. Energy planners in SSA are often poorly informed and lack skills, knowledge, documented experiences and open source quality data on renewable mini-grids. Therefore, they must rely on grid extension projects for the electrification of rural communities [10]. Moreover, off-grid and mini-grid system installations are often complex and expensive in SSA because of the administrative processes to follow [10].

Most of infrastructures present in developing countries such as SSA are constructed during colonial period [11]. Indeed, the transmission lines are outdated and cannot handle the distribution of high voltage power. Much of the electricity distributed across the national interconnected grid is lost through transmission lines. With current infrastructure conditions, transmission to embedded zones is only increasing the loss [13].

Moreover, another barrier to rural electrification is the price difference between rural and urban areas. Customers in the rural area are engaged in high investments and high operational costs compared to those in the urban area. In addition, there are technological complexities which lead to sustainability issues. [1] [18] [20] [39] [44] [45]. The regional disparity is another big dilemma for the electrification of rural and remote areas [30].

Furthermore, the combination of political instability and commercial risks discourages private investors from seizing opportunities in the field of decentralized rural electrification [21] [45] [46].

In developing countries, measurement error and lack of precision have often shattered estimates of network coverage and network connectivity [47]. Increasing of fuel prices is also an issue of rural electrification [36] [46] [48].

3. Methods

Many strategies and solutions have been implemented in many different developing countries to overcome the barriers mentioned in Section 2. There are large scales of policy in developing countries especially SSA.

3.1. Software Use for the Implementation of PV and Renewable Energy

There are many approaches for rural electrification [49]. Nowadays, several tools related to electricity supply in rural area are available commercially or for free. A comprehensive modeling of an electrification project is done using software such as HOMER Energy [16], Network Planner and GEOSIM [43]. Understanding the consumer profile, identifying the potential site and local resources are the first step in developing an electrification strategy [15] [50]. Therefore, geographical analysis is required, the type of renewable energy to be implemented is obtained from an analysis of the structure of the terrain by using a satellite image [15] [51]. The HOMER Energy modeling tool is a key element especially for the implementation of scenarios [15] [38]. HOMER has been used by planners and decision makers to evaluate the design issue [52] and the techno-economic viability of renewable energy systems [13]. Moreover, a certain number of load scenario must be designed in order to improve simulation [13]. Nevertheless, additional research is highly recommended due the limitation of available software (HOMER, RET, LCOE) as Onyeka *et al.* show in their article [9]. In order to locate the consumers and to know if their area is electrified or not, a spatial modeling and a GIS (Geographic Information System) database are applied [42]. The zones with higher solar resources can also be identified by using maps of solar resource based on GIS database [53]. In addition, the use of global solar radiation data from the NASA can be helpful while deploying renewable energy technologies [13].

Nowadays, the level of electrification can be measured by the night-time lights [54]. The remote-sensing data or data obtained by this new process when administrative archives are absent or unreliable are auspicious resources [54].

3.2. The Decentralized System Based on Renewable and PV-Hybrid Technologies

As in many developing nations, power supply mostly depends on diesel generations [13] though the rate of carbon dioxide emission of Africa is less than 4% of the global emissions [9]. However, climate change mitigation can now be considered as the essential factor that can influence the rates of renewable energy deployment in SSA [4]. In fact, in developing countries, the consumption per capita might increase for the next decades [55]. Indeed, in order to recover the demand forecasting, development of renewable energy technologies as alternatives to replace fossil fuels has become imperative [6] [55].

The continent of Africa has unlimited resources in term of renewable and nonrenewable energy sources [12]. Despite its high potential [6], the implementation of PV (Photovoltaic) electricity generation still remains non-considerable [10]. Many papers show that researchers try to study the cost of PV system and reduce its cost to enhance the rural access to electricity. Otherwise, the result proposes that current cost of PV technologies is cost-effective for policy makers, besides PV has the ability to repay its financing loan [9]. Now, the PV price reduction is about 22% according to findings of [4] [10].

Moreover, the decentralized system is efficient for a remote village [17] [56] [57]. In order to provide electricity in scattered sectors, the use of decentralized systems such as small diesel power generations and renewable technologies such as biomass, PV systems, small wind and small hydro power systems are currently used [49]. The decentralized system uses some components like batteries, diesel generators, pedal generators and so on [58]. Furthermore, by considering the PV-Wind system [16], the wind and solar intensity variation can be mitigated [39] due to complementation between solar and wind system [59] [60]. Sometimes hybrid system such as PV-wind-diesel systems can be used [38] [61]. H. Kim and T. Yong [13] proposed in their research article several types of hybrid system that can be utilized, such as PV-diesel generator system, PV-ESS

(Energy Storage System), PV-Hydropower system [13] [62]. Otherwise, the use of the local resources available such as solar system [48] [63] [64], wind system [65], biomass [30] [66] and micro-hydropower system [67] enhances the decentralized system deployment, however its nature depends on the area [30] [38] [68].

Furthermore, over 90% of renewable energy in SSA is assumed by hydropower [12]. Small hydropower is entirely considered as renewable energy and has more potential than large hydropower to contribute to poverty reduction [12]. In SSA excluding South Africa, the use of Concentrating Solar Power (CSP) plants is also a promising way to increase rural electrification rate. CSP is a generating electricity system that exploits the heat from the sun [6]. Another study suggests the use of biomass (charcoal, wood) coupled with wind and solar power systems such that the system capacity is up to 20 kW [55].

3.3. The Microgrid and Off-Grid System for Rural Electrification

In addition, microgrid is one of the strategies implemented to electrify rural areas [65]. Microgrids are small electrical grids based on renewable resources. It is a kind of decentralized system that uses renewable energies and low carbon-resources [15]. Indeed, microgrid plays a major role in improving access to electricity in embedded area [10] as it is also an autonomous grid system [40]. In the Global South, central grid cannot reach remote areas [15] [69] [70]. Hence, SSA needs to establish an alternative for the grid extension. Off-grid solar system is estimated to have great potential in SSA [14]. Paulo *et al.* [55] show off in their paper different off-grid system type that can be implemented in remote areas. Furthermore, installed renewable energy systems must be revisited about 12 years after installation to check if goals have been reached or not [44].

Moreover, the choice of off-grid system to be implemented in isolated area is made by considering certain conditions [43] [48] [67]. The opinion of the end-users [67] and their needs and wishes should be considered in order to improve rural electrification policy [41] [63] [71] [72]. Technical maintenance and financial management are required within an installed decentralized network [73]. Hence, each village in which technologies are installed should have an administrator and an operator who have received training [56].

3.4. The Energy Market in SSA

Researches about energy market in SSA have been spearheaded by Bensch *et al.* [14], their study reveals that solar market has known significant revolutions in terms of technologies and business models since 2012. They also emphasize that energy market in SSA is entirely characterized by non-branded products. Otherwise, lower taxes will strengthen the distribution of renewable energy in the sub-Saharan African market [10].

3.5. The Role of Democracy and Government in Rural Electrification

Furthermore, in SSA, democracy promotes rural electrification [5]. It has been found that it is at the level of public services such as education and health that democratic states invest the most. Therefore, multipartism accelerates rural electrification [5]. Moreover, government must establish support schemes and regulatory frameworks to facilitate the share of renewable energy [10]. Hence, institution also plays key role in rural electrification project. In each country, energy policy must be installed [74]. Access in remote areas led by the government is important because government support coupled with strong political measures is important for the implementation of an electrification project [41] [75]. Some countries such as Tanzania start the grid extension project by electrifying the headquarters and then the distribution line promotes the villages access to electricity [67].

3.6. The External Factors Influence on Rural Electrification

Moreover, external factors have a great influence on rural electrification projects, especially renewable energy projects [12]. As an example, it can be cited the case of a fee-for-service model chosen by European Union to facilitate access for the poorest households to the energy technology [14]. In order to double access to electricity in SSA, Power Africa is aiming to add 60 million new electrical connections. Additionally, the project supports both renewable and non-renewable energy projects and aims to increase the installed capacity by 30,000 MW by 2030 [4]. Furthermore, to encourage private investors, policymakers and planners in developing countries need to design an attractive project in terms of lower investment costs [15].

Another approach is to create local cooperatives that implement a decentralized system and therefore offer attractive alternatives to the public sector or the private sector [49].

Table 1 summarizes the strategies and solutions provided in developing countries to overcome the barriers in rural electrification.

4. The Existing Cost-Effective Schemes for Rural Electrification

Researchers proposes that Africa requires between US$41 billion to US$55 billion annually until 2030 to achieve access on electricity for all [4], findings show that there is a strong hope for SSA to attain the massive electrification within the next decades. Researchers agree that renewable option is economically viable in developing countries [13]. By reducing renewable energy cost such as PV and CSP cost in the energy market and establishing regulatory frameworks and institutions, SSA's rural electrification rate have increased. For instance, since 2012, the number of PV projects implemented has increased [10]. Furthermore, solar technology has been accepted as a sustainable future alternative to replace fossil fuel [9] [14]. Researchers also confirm that implementation of energy systems requiring higher investment than diesel-only generators will be rare [13]. Diesel-only scenario is the most expensive system to generate electricity. They

Table 1. Strategies and solutions for rural electrification in developing countries.

Strategies and solutions	Examples
The use of software and new technology	HOMER [16]: used by planners and decision makers to evaluate the design issue [52] and the techno-economic viability of renewable energy systems GIS: used to locate the consumers, to know if their area is electrified or not [42] and to identify the zone with higher solar resources [13] The use of remote-sensing data: the night-time lights to evaluate the level of electrification [54], the global solar radiation data from the NASA for deploying PV [13]
The use of decentralized systems	Small diesel power generations, biomass, small wind and small hydropower systems, PV systems [49], CSP [6] PV-Hybrid systems: PV-diesel generator system, PV-ESS system, PV-hydropower system [13]
The use of micro-grids and off-grid systems	A kind of decentralized system that uses renewable energies and low carbon-resources [15]
Study of energy market in SSA	Study about how to reduce the cost of renewable energy such as PV and how to enhance the distribution of renewable energy [10]
The establishment of a democratic institution and support schemes by the government	A series of study proposed by P. A. Trotter [5] shows that democracy works well with the provision of public services such as rural electrification. Moreover, Schillebeeckx *et al.* [41] highlighted that the success of an electrification project depends largely on significant government support and strong political will [75].
Cooperation with major economic powers and international donors	The case of a fee-for-service model chosen by European Union to facilitate access for the poorest households to the energy technology [14]. Power Africa who aims to increase the installed capacity by 30,000 MW by 2030 [4].

also highlight that hybrid diesel/PV with the Energy Storage System (ESS) is the optimum scenario [52]. PV coupled with ESS costs the highest [13] for a hybrid system but it is also a viable alternative for energy technology [55]. Furthermore, in terms of cost-effectiveness, even non-branded products are the most used in SSA, non-branded products perform significantly better than branded products due to considerably lower prices [14]. Moreover, democratic institutions have influences in rural electrification, reduce the inequality of rural and urban electrification in SSA [5]. In addition, cooperation with international community and developed countries also improves energy access to rural areas. Chirambo *et al.* [4] highlighted the aid that China brings toward SSA, there is also Power Africa which is the U.S government initiative.

5. Discussion

Rural electrification improves access to education, health, safety and water supply [46] [76] [77]. Access to electricity leads to improved quality of life and higher standard of living [3] [78]. RESs (Renewable Energy Systems) have advantages such as: faster procurement, sometimes more economical than grid connection, and clean for the environment [44]. The advantage of decentralized system is the utilization of the local resources, it avoids the inefficient transmission losses and it is often not expensive, and suitable for low-load factors projects [56]. Moreover, the use of batteries provides fast-access to electricity, no pre-installation work needed, independent from either site-specific or source available, suitable for loads used frequently [58]. Furthermore, biomass use for electrification reduces disparity in remote areas [30] [79]. Moreover, microgrids ease maintenance compared to SHSs [80]. Besides, exploitation of hydroelectric resources could alleviate chronic energy shortages and lower energy prices [81].

The decentralized model will be cheap if the consumption in the areas is low and the centralized model is cheap in high consumption region depending on the available resources and the model using a grid extension depends on the number of factors and geographical distributions of the target population [56]. As an example, for a low consumption (up to 400 KW): the cost of electricity using microgrid is about 24.2742 EUR/MWh [82] while for the case of Madagascar the electricity cost is 122.5 EUR/MWh for grid extension [83].

6. Extension Scheme for Rural Electrification Model

The figures presented below show the existing rural electrification models. **Figure 1** represents the decentralized model using both renewable and non-renewable energy. Microgrid systems which are designed to supply electricity for loads such as small village [82] are presented by **Figure 2**. Furthermore, the grid extension suitable for a high consumption is presented by **Figure 3**.

7. Conclusion

One finds that in SSA, only 290 million out of 915 million people have access to modern energy services [10] and major party of rural populace lives in the darkness. Many of those who do not have electricity are in remote and rural areas, consequently rural electrification is a serious subject for many governments around the world. Thus, there are two methods to extend the electrification in the rural areas: the decentralized model and the grid extension. The latter approach is more cost-effective for high consumption level and the decentralized model is more cost-effective for lower consumption level. Electricity in the

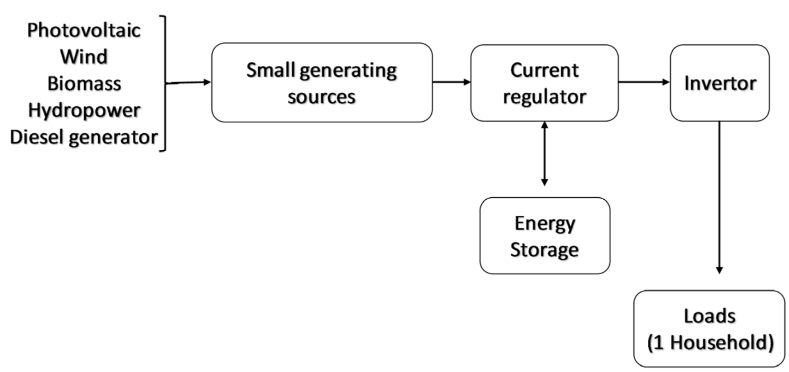

Figure 1. Example of a decentralized model.

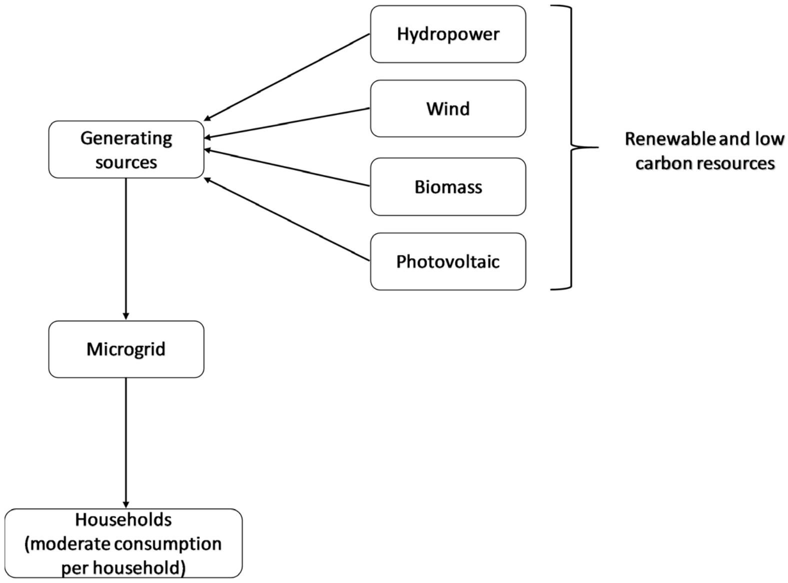

Figure 2. Example of a decentralized model using microgrid system.

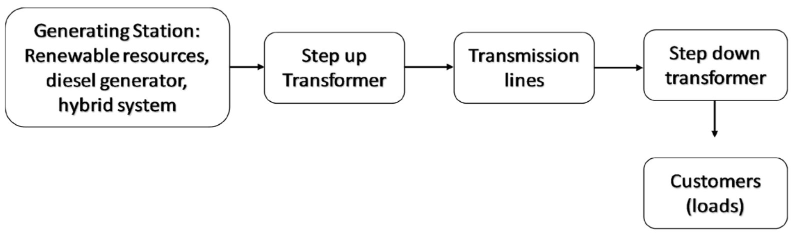

Figure 3. Grid extension schematic representation.

farming sector offers the possibility to improve the suppliers of welfare department, and economic directed advantages. Rural electrification and its associated impact on income and quality of life may not be sufficient to reduce rural-urban migration flows and other drivers of migration such as aspirations for the glamorous urban life depicted on television or for an elite education, need to be targeted and addressed to reduce stress on cities in developing countries today. It is debatable if renewable energy-based rural electrification programs are more feasible, cheaper, and less problematic solutions for improving electricity access in remote rural areas of developing countries than grid extension electrification programs based on fossil fuel, hydro, or nuclear.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Shyu, C.W. (2012) Rural Electrification Program with Renewable Energy Sources: An Analysis of China's Township Electrification Program. *Energy Policy*, **51**, 842-853. https://doi.org/10.1016/j.enpol.2012.09.036

[2] Salmon, C. and Tanguy, J. (2016) Rural Electrification and Household Labor Supply: Evidence from Nigeria. *World Development*, **82**, 48-68. https://doi.org/10.1016/j.worlddev.2016.01.016

[3] Van Ruijven, B.J., Schers, J. and Van Vuuren, D.P. (2012) Model-Based Scenarios for Rural Electrification in Developing Countries. *Energy*, **38**, 386-397. https://doi.org/10.1016/j.energy.2011.11.037

[4] Chirambo, D. (2018) Towards the Achievement of SDG 7 in Sub-Saharan Africa: Creating Synergies between Power Africa, Sustainable Energy for All and Climate Finance in Order to Achieve Universal Energy Access before 2030. *Renew. Sustain. Energy Rev.*, **94**, 600-608. https://doi.org/10.1016/j.rser.2018.06.025

[5] Trotter, P.A. (2016) Rural Electrification, Electrification Inequality and Democratic Institutions in sub-Saharan Africa. *Energy for Sustainable Development*, **34**, 111-129. https://doi.org/10.1016/j.esd.2016.07.008

[6] Seshie, Y.M., N'Tsoukpoe, K.E., Neveu, P., Coulibaly, Y. and Azoumah, Y.K. (2018) Small Scale Concentrating Solar Plants for Rural Electrification. *Renewable and Sustainable Energy Reviews*, **90**, 195-209. https://doi.org/10.1016/j.rser.2018.03.036

[7] IEA (International Energy Agency) (2010) Energy Poverty: How to Make Modern Energy Access Universal? International Energy Agency, Paris, p. 2010.

[8] Bhattacharyya, S.C. (2006) Energy Access Problem of the Poor in India: Is Rural Electrification a Remedy? *Energy Policy*, **34**, 3387-3397. https://doi.org/10.1016/j.enpol.2005.08.026

[9] Okoye, C.O. and Oranekwu-Okoye, B.C. (2018) Economic Feasibility of Solar PV System for Rural Electrification in Sub-Sahara Africa. *Renewable and Sustainable Energy Reviews*, **82**, 2537-2547. https://doi.org/10.1016/j.rser.2017.09.054

[10] Moner-Girona, M., Solano-Peralta, M., Lazopoulou, M., Ackom, E.K., Vallve, X. and Szabó, S. (2018) Electrification of Sub-Saharan Africa through PV/Hybrid Mini-Grids: Reducing the Gap between Current Business Models and On-Site Experience. *Renewable and Sustainable Energy Reviews*, **91**, 1148-1161. https://doi.org/10.1016/j.rser.2018.04.018

[11] Hasenöhrl, U. (2018) Rural Electrification in the British Empire. *History of Retailing and Consumption*, **4**, 10-27. https://doi.org/10.1080/2373518X.2018.1436220

[12] Nyiwul, L. (2018) Income, Environmental Considerations, and Sustainable Energy Consumption in Africa. *International Journal of Green Energy*, **15**, 264-276. https://doi.org/10.1080/15435075.2018.1439037

[13] Kim, H. and Jung, T.Y. (2018) Independent Solar Photovoltaic with Energy Storage Systems (ESS) for Rural Electrification in Myanmar. *Renewable and Sustainable Energy Reviews*, **82**, 1187-1194. https://doi.org/10.1016/j.rser.2017.09.037

[14] Bensch, G., Grimm, M., Huppertz, M., Langbein, J. and Peters, J. (2018) Are Promotion Programs Needed to Establish Off-Grid Solar Energy Markets? Evidence from Rural Burkina Faso. *Renewable and Sustainable Energy Reviews*, **90**, 1060-1068. https://doi.org/10.1016/j.rser.2017.11.003

[15] Xu, Z., Nthontho, M. and Chowdhury, S. (2016) Rural Electrification Implementation Strategies through Microgrid Approach in South African Context. *International Journal of Electrical Power & Energy Systems*, **82**, 452-465. https://doi.org/10.1016/j.ijepes.2016.03.037

[16] Haghighat, A., Alberto, S., Escandon, A., Naja, B., Shirazi, A. and Rinaldi, F. (2016) Techno-Economic Feasibility of Photovoltaic, Wind , Diesel and Hybrid Electrification Systems for Off-Grid Rural Electrification in Colombia. *Renewable Energy*, **97**, 293-305. https://doi.org/10.1016/j.renene.2016.05.086

[17] Müller, M.F., Thompson, S.E. and Kelly, M.N. (2016) Bridging the Information Gap: A Web-GIS Tool for Rural Electrification in Data-Scarce Regions. *Applied Energy*, **171**, 277-286. https://doi.org/10.1016/j.apenergy.2016.03.052

[18] Gurung, A., Prakash, O. and Eun, S. (2011) The Potential of a Renewable Energy Technology for Rural Electrification in Nepal: A Case Study from Tangting. *Renewable Energy*, **36**, 3203-3210. https://doi.org/10.1016/j.renene.2011.03.012

[19] Fuso, F., Howells, M., Bazilian, M. and Gomez, M.F. (2014) Energy for Sustainable Development Rural Electrification Options in the Brazilian Amazon: A Multi-Criteria Analysis. *Energy for Sustainable Development*, **20**, 36-48. https://doi.org/10.1016/j.esd.2014.02.005

[20] Mollik, S., Rashid, M.M., Hasanuzzaman, M., Karim, M.E. and Hosenuzzaman, M. (2016) Prospects, Progress, Policies, and Effects of Rural Electrification in Bangladesh. *Renewable & Sustainable Energy Reviews*, **65**, 553-567. https://doi.org/10.1016/j.rser.2016.06.091

[21] Slough, T., Urpelainen, J. and Yang, J. (2015) Light for All? Evaluating Brazil's Rural Electrification Progress, 2000-2010. *Energy Policy*, **86**, 315-327. https://doi.org/10.1016/j.enpol.2015.07.001

[22] Bambawale, M.J., Agostino, A.L.D. and Sovacool, B.K. (2011) Realizing Rural Electrification in Southeast Asia: Lessons from Laos. *Energy for Sustainable Development*, **15**, 41-48. https://doi.org/10.1016/j.esd.2010.11.001

[23] Javadi, F.S., *et al*. (2013) Global Policy of Rural Electrification. *Renewable & Sustainable Energy Reviews*, **19**, 402-416. https://doi.org/10.1016/j.rser.2012.11.053

[24] Kamalapur, G.D. and Udaykumar, R.Y. (2012) Electrical Power and Energy Systems Rural Electrification in India and Feasibility of Photovoltaic Solar Home Systems. *International Journal of Electrical Power & Energy Systems*, **33**, 594-599. https://doi.org/10.1016/j.ijepes.2010.12.014

[25] Lahimer, A.A., Alghoul, M.A., Sopian, K., Amin, N. and Asim, N. (2012) Research and Development Aspects of Pico-Hydro Power. *Renewable and Sustainable Energy Reviews*, **16**, 5861-5878. https://doi.org/10.1016/j.rser.2012.05.001

[26] Hirmer, S. and Cruickshank, H. (2014) The User-Value of Rural Electrification: An Analysis and Adoption of Existing Models and Theories. *Renewable & Sustainable Energy Reviews*, **34**, 145-154. https://doi.org/10.1016/j.rser.2014.03.005

[27] Jimenez, R. (2017) Barriers to Electrification in Latin America: Income, Location, and Economic Development. *Energy Strategy Reviews*, **15**, 9-18. https://doi.org/10.1016/j.esr.2016.11.001

[28] Cook, P. (2011) Infrastructure, Rural Electrification and Development. *Energy for Sustainable Development*, **15**, 304-313. https://doi.org/10.1016/j.esd.2011.07.008

[29] Yadoo, A. (2012) Delivery Models for Decentralised Rural Electrification: Case Studies in Nepal, Peru and Kenya. International Institute for Environment and Development, London, 68.

[30] Herran, D.S. and Nakata, T. (2012) Design of Decentralized Energy Systems for Rural Electrification in Developing Countries Considering Regional Disparity. *Applied Energy*, **91**, 130-145. https://doi.org/10.1016/j.apenergy.2011.09.022

[31] Baurzhan, S. and Jenkins, G.P. (2016) Off-Grid Solar PV: Is It an Affordable or Appropriate Solution for Rural Electrification in Sub-Saharan African Countries? *Renewable & Sustainable Energy Reviews*, **60**, 1405-1418. https://doi.org/10.1016/j.rser.2016.03.016

[32] Howe, P.H. and Lawrence, J. (2012) SolarAid: Revolutionizing the Way to Make Energy Affordable for Everyone. Hult International Business School Publishing, 17 p.

[33] Singh, B.G.A. and Baredar, P. (2015) Computation Simulation & Optimization of a Solar, Fuel Cell and Biomass Hybrid Energy System Using HOMER Pro Software. *Procedia Engineering*, **127**, 743-750. https://doi.org/10.1016/j.proeng.2015.11.408

[34] Sen, R. and Bhattacharyya, S.C. (2014) Off-Grid Electricity Generation with Renewable Energy Technologies in India: An Application of HOMER. *Renewable Energy*, **62**, 388-398. https://doi.org/10.1016/j.renene.2013.07.028

[35] Eroglu, M., *et al.* (2011) A Mobile Renewable House Using PV/Wind/Fuel Cell Hybrid Power. *International Journal of Hydrogen Energy*, **36**, 7985-7992. https://doi.org/10.1016/j.ijhydene.2011.01.046

[36] Triadó-Aymerich, J., Ferrer-Martí, L., García-Villoria, A. and Pastor, R. (2016) MILP-Based Heuristics for the Design of Rural Community Electrification Projects. *Computers & Operations Research*, **71**, 90-99. https://doi.org/10.1016/j.cor.2016.01.010

[37] Leonard, C., Klintenberg, P., Wallin, F., Karlsson, B. and Mbohwa, C. (2016) Electricity for Development: Mini-Grid Solution for Rural Electrification in South Africa. *Energy Conversion and Management*, **110**, 268-277. https://doi.org/10.1016/j.enconman.2015.12.015

[38] Shaahid, S.M. and El-Amin, I. (2009) Techno-Economic Evaluation of Off-Grid Hybrid Photovoltaic-Diesel-Battery Power Systems for Rural Electrification in Saudi Arabia—A Way forward for Sustainable Development. *Renewable & Sustainable Energy Reviews*, **13**, 625-633. https://doi.org/10.1016/j.rser.2007.11.017

[39] Seraphim, O.J., Siqueira, J.A.C., Putti, F.F., Filho, L.R.A.G., Cremasco, C.P. and Daltin, R.S. (2014) Energetic Exploitation from a Hybrid PV-Wind Power Micro-Generation Rural Electrification. *Energy Procedia*, **57**, 1475-1484. https://doi.org/10.1016/j.egypro.2014.10.092

[40] Williams, N.J., Jaramillo, P., Taneja, J. and Ustun, T.S. (2015) Enabling Private Sector Investment in Microgrid-Based Rural Electrification in Developing Countries: A Review. *Renewable & Sustainable Energy Reviews*, **52**, 1268-1281. https://doi.org/10.1016/j.rser.2015.07.153

[41] Schillebeeckx, S.J.D., Parikh, P., Bansal, R. and George, G. (2012) An Integrated Framework for Rural Electrification: Adopting a User-Centric Approach to Business Model Development. *Energy Policy*, **48**, 687-697. https://doi.org/10.1016/j.enpol.2012.05.078

[42] Bertheau, P., Cader, C. and Blechinger, P. (2016) Electrification Modelling for Nigeria. *Energy Procedia*, **93**, 108-112. https://doi.org/10.1016/j.egypro.2016.07.157

[43] Cader, C., Blechinger, P. and Bertheau, P. (2016) Electrification Planning with Focus on Hybrid Mini-Grids—A Comprehensive Modelling Approach for the Global South. *Energy Procedia*, **99**, 269-276. https://doi.org/10.1016/j.egypro.2016.10.116

[44] Hong, G.W. and Abe, N. (2012) Sustainability Assessment of Renewable Energy Projects for Off-Grid Rural Electrification: The Pangan—An Island Case in the Philippines. *Renewable & Sustainable Energy Reviews*, **16**, 54-64. https://doi.org/10.1016/j.rser.2011.07.136

[45] Steurer, E., Manatsgruber, D. and Prudence, E. (2016) Risk Clustering as a Finance Concept for Rural Electrification in Sub-Saharan Africa to Attract International Private Investors. *Energy Procedia*, **93**, 183-190. https://doi.org/10.1016/j.egypro.2016.07.168

[46] Narula, K., Nagai, Y. and Pachauri, S. (2012) The Role of Decentralized Distributed Generation in Achieving Universal Rural Electrification in South Asia by 2030. *Energy Policy*, **47**, 345-357. https://doi.org/10.1016/j.enpol.2012.04.075

[47] Lee, K., *et al.* (2016) Electrification for "Under Grid" Households in Rural Kenya. *Development Engineering*, **1**, 26-35. https://doi.org/10.1016/j.deveng.2015.12.001

[48] Sowe, S., Ketjoy, N., Thanarak, P. and Suriwong, T. (2014) Technical and Economic Viability Assessment of PV Power Plants for Rural Electrification in the Gambia. *Energy Procedia*, **52**, 389-398. https://doi.org/10.1016/j.egypro.2014.07.091

[49] Yadoo, A. and Cruickshank, H. (2010) The Value of Cooperatives in Rural Electrification. *Energy Policy*, **38**, 2941-2947. https://doi.org/10.1016/j.enpol.2010.01.031

[50] Domenech, B., Ferrer-martí, L. and Pastor, R. (2015) Hierarchical Methodology to Optimize the Design of Stand-Alone Electrification Systems for Rural Communities Considering Technical and Social Criteria. *Renewable & Sustainable Energy Reviews*, **51**, 182-196. https://doi.org/10.1016/j.rser.2015.06.017

[51] Lhendup, T. (2008) Rural Electrification in Bhutan and a Methodology for Evaluation of Distributed Generation System as an Alternative Option for Rural Electrification. *Energy for Sustainable Development*, **12**, 13-24. https://doi.org/10.1016/S0973-0826(08)60434-2

[52] Andrić, I., Pina, A., Ferrão, P., Fournier, J., Lacarrière, B. and Le Corre, O. (2017) Assessing the Feasibility of Using the Heat Demand-Outdoor Temperature Function for a Long-Term District Heat Demand Forecast. *Energy Procedia*, **116**, 460-469. https://doi.org/10.1016/j.egypro.2017.05.093

[53] Hernández-escobedo, Q., Fernández-garcía, A. and Manzano-agugliaro, F. (2017) Solar Resource Assessment for Rural Electrification and Industrial Development in the Yucatan Peninsula (Mexico). *Renewable & Sustainable Energy Reviews*, **76**, 1550-1561. https://doi.org/10.1016/j.rser.2016.11.200

[54] Dugoua, E., Kennedy, R. and Urpelainen, J. (2018) Satellite Data for the Social Sciences: Measuring Rural Electrification with Night-Time Lights. *International Journal of Remote Sensing*, **39**, 2690-2701. https://doi.org/10.1080/01431161.2017.1420936

[55] Paulo, J., Tamo, P., Ulrich, M. and Fournier, J. (2017) Temperature Function for Demand Forecast a Long-Term District Heat of Lacarrière Appropriate Feedstock in Wood Gasification for Rural Electrification Assessing the Feasibility of Using the Heat Demand-Outdoor. *Energy Procedia*, **138**, 488-493.

[56] Lillo, P., Ferrer-martí, L., Boni, A. and Fernández-baldor, Á. (2015) Energy for Sustainable Development Assessing Management Models for Off-Grid Renewable Energy Electrification Projects Using the Human Development Approach: Case Study in Peru. *Energy for Sustainable Development*, **25**, 17-26. https://doi.org/10.1016/j.esd.2014.11.003

[57] Chaurey, A. and Chandra, T. (2010) Assessment and Evaluation of PV Based Decentralized Rural Electrification: An Overview. *Renewable & Sustainable Energy Reviews*, **14**, 2266-2278. https://doi.org/10.1016/j.rser.2010.04.005

[58] Levin, T. and Thomas, V.M. (2016) Can Developing Countries Leapfrog the Centralized Electrification Paradigm? *Energy for Sustainable Development*, **31**, 97-107. https://doi.org/10.1016/j.esd.2015.12.005

[59] Joseph Kenfack, A.L., Neirac, F.P., Tatietse, T.T., Mayer, D. and Fogue, M. (2009) Microhydro-PV-Hybrid System: Sizing a Small Hydro-PV-Hybrid System for Rural Electrification in Developing Countries. *Renewable Energy*, **34**, 2259-2263. https://doi.org/10.1016/j.renene.2008.12.038

[60] Bala, B.K. and Siddique, S.A. (2009) Optimal Design of a PV-Diesel Hybrid System for Electrification of an Isolated Island—Sandwip in Bangladesh Using Genetic Algorithm. *Energy for Sustainable Development*, **13**, 137-142. https://doi.org/10.1016/j.esd.2009.07.002

[61] Saheb-koussa, D., Koussa, M., Haddadi, M. and Belhamel, M. (2011) Hybrid Options Analysis for Power Systems for Rural Electrification in Algeria. *Energy Procedia*, **6**, 750-758. https://doi.org/10.1016/j.egypro.2011.05.085

[62] Akikur, R.K., Saidur, R., Ping, H.W. and Ullah, K.R. (2013) Comparative Study of Stand-Alone and Hybrid Solar Energy Systems Suitable for Off-Grid Rural Electrification: A Review. *Renewable & Sustainable Energy Reviews*, **27**, 738-752. https://doi.org/10.1016/j.rser.2013.06.043

[63] Sharif, I. and Mithila, M. (2013) Rural Electrification Using PV: The Success Story of Bangladesh. *Energy Procedia*, **33**, 343-354. https://doi.org/10.1016/j.egypro.2013.05.075

[64] Vitoriano, B. (2016) Design of Maintenance Structures for Rural Electrification with Solar Home Systems. The Case of the Moroccan Program. *Energy*, **117**, 47-57. https://doi.org/10.1016/j.energy.2016.10.073

[65] Camblong, H., *et al.* (2009) Micro-Grids Project, Part 1: Analysis of Rural Electrification with High Content of Renewable Energy Sources in Senegal. *Renewable Energy*, **34**, 2141-2150. https://doi.org/10.1016/j.renene.2009.01.015

[66] Hiremath, R.B., Shikha, S. and Ravindranath, N.H. (2007) Decentralized Energy Planning: Modeling and Application—A Review. *Renewable & Sustainable Energy Reviews*, **11**, 729-752. https://doi.org/10.1016/j.rser.2005.07.005

[67] Ahlborg, H. and Hammar, L. (2014) Drivers and Barriers to Rural Electrification in Tanzania and Mozambique e Grid-Extension, Off-Grid, and Renewable Energy Technologies. *Rene*, **61**, 117-124. https://doi.org/10.1016/j.renene.2012.09.057

[68] Mainali, B. and Silveira, S. (2012) Renewable Energy Markets in Rural Electrification: Country Case Nepal. *Energy for Sustainable Development*, **16**, 168-178. https://doi.org/10.1016/j.esd.2012.03.001

[69] Díaz, P., Peña, R., Muñoz, J., Arias, C.A. and Sandoval, D. (2011) Field Analysis of Solar PV-Based Collective Systems for Rural Electrification. *Energy*, **36**, 2509-2516. https://doi.org/10.1016/j.energy.2011.01.043

[70] Mazzola, S., Astolfi, M. and Macchi, E. (2016) The Potential Role of Solid Biomass for Rural Electrification: A Techno Economic Analysis for a Hybrid Microgrid in India. *Applied Energy*, **169**, 370-383. https://doi.org/10.1016/j.apenergy.2016.02.051

[71] Hirmer, S. and Guthrie, P. (2016) Identifying the Needs of Communities in Rural Uganda: A Method for Determining the "User-Perceived Value" of Rural Electrification Initiatives. *Renewable & Sustainable Energy Reviews*, **66**, 476-486. https://doi.org/10.1016/j.rser.2016.08.037

[72] Kadri, Y. and Abdallah, H.H. (2016) Performance Evaluation of a Stand-Alone Solar Dish Stirling System for Power Generation Suitable for Off-Grid Rural Electrification. *Energy Conversion and Management*, **129**, 140-156. https://doi.org/10.1016/j.enconman.2016.10.024

[73] Levin, T. and Thomas, V.M. (2014) Utility-Maximizing Financial Contracts for Distributed Rural Electrification. *Energy*, **69**, 613-621. https://doi.org/10.1016/j.energy.2014.03.057

[74] Barnes, F.G. (2001) Rural Electrification in the Developing World: A Summary of Lessons from Successful Programs, Barnett.

[75] Van Gevelt, T. (2014) Energy for Sustainable Development Rural Electrification and Development in South Korea. *Energy for Sustainable Development*, **23**, 179-187. https://doi.org/10.1016/j.esd.2014.09.004

[76] Nurlaila, I., Yuliar, S., Kombaitan, B. and Eko, A. (2015) Asia Pacific International

Conference on Environment-Behaviour Studies Public Participation: Energy Policy Aspect to Support Rural Electrification Program in West Java. *Procedia—Social and Behavioral Sciences*, **168**, 321-327. https://doi.org/10.1016/j.sbspro.2014.10.237

[77] Obermaier, M., Szklo, A., Emilio, L., Rovere, L. and Rosa, L.P. (2012) An Assessment of Electricity and Income Distributional Trends Following Rural Electrification in Poor Northeast Brazil. *Energy Policy*, **49**, 531-540. https://doi.org/10.1016/j.enpol.2012.06.057

[78] Deichmann, D., Meisner, U., Murray, C. and Wheeler, S. (2011) The Economics of Renewable Energy Expansion in Rural Sub-Saharan Africa. *Energy Policy*, **39**, 13. https://doi.org/10.1016/j.enpol.2010.09.034

[79] Bouffaron, P., Castagno, F. and Herold, S. (2011) Straight Vegetable Oil from *Jatropha curcas* L. for Rural Electrification in Mali e A Techno-Economic Assessment. *Biomass and Bioenergy*, **37**, 298-308. https://doi.org/10.1016/j.biombioe.2011.11.008

[80] Millinger, M., Mårlind, T. and Ahlgren, E.O. (2012) Energy for Sustainable Development Evaluation of Indian Rural Solar Electrification: A Case Study in Chhattisgarh. *Energy for Sustainable Development*, **16**, 486-492. https://doi.org/10.1016/j.esd.2012.08.005

[81] Adebayo, E., Sovacool, B.K. and Imperiale, S. (2013) It's about Dam Time: Improving Microhydro Electrification in Tanzania. *Energy for Sustainable Development*, **17**, 378-385. https://doi.org/10.1016/j.esd.2013.03.003

[82] Dulau, L.I. and Bica, D. (2018) Optimization of Generation Cost in a Microgrid. *Procedia Manufacturing*, **22**, 703-708. https://doi.org/10.1016/j.promfg.2018.03.101

[83] http://www.jirama.mg/templates/JiramaElec-Tarif.htm

Appendix-Acronyms

CSP	Concentrating Solar Power
ESS	Geographic Information System
GIS	Geographic Information System
HOMER	Hybrid Optimizations Model for Electrical Renewable
LCOE	Levelized Cost of Energy
PV	Photovoltaic
REA	Rural Electrification Administration
RESs	Renewable Energy Systems
RET	Renewable Energy Technology
SHSs	Solar Home Systems
SSA	Sub-Saharan Africa
USA/U.S	United States of America