**POLITECNICO DI MILANO**

**School of Industrial and Information Engineering**

**Master of Science in Management Engineering**

# Evaluation of investment options in microgrids developed for rural application in Nigeria

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ID number: 884600

Academic year:2017-2018

## Table of contents

**LISTS OF FIGURES**

## List of abbreviations

| | |
|---|---|
| RES | Renewable energy source |
| REA | Rural electrification agency |
| PV | Photovoltaic |
| LCOE | Levelized cost of electricity |
| NPC | Net present cost |
| PBT | Payback time |
| IRR | Internal rate of return |
| NPV | Net present value |
| IEA | International energy agency |
| GDP | Gross domestic product |
| CAGR | Compound annual growth rate |
| OECD | Organisation for economic co-operation and development |
| DG | Distributed generation |
| DOD | Deep of discharge |
| AC | Alternating current |
| DC | Direct current |
| MW | Megawatt |
| GW | Gigawatt |
| ESS | Energy storage system |
| WACC | Weighted average cost of capital |
| DC | Developing countries |
| MTF | Multi-tier framework |
| HDI | Human development index |
| PU | Predominantly urban |
| PR | Predominantly rural |
| IN | Intermediate |
| CHP | Combined heat and power |
| RESCO | Renewable energy service company |
| PPA | Power purchasing agreement |
| USD | United States dollar |
| VAT | Value added tax |
| SIB | Social impact bond |
| NGO | Non-governmental organization |
| LF | Load factor |
| CFL | Compact fluorescent lamp |
| EDL | Economic distance limit |
| DF | Diversity factor |
| SHS | Solar home systems |
| PPP | Power purchasing parity |
| CBN | Central bank of Nigeria |
| LPG | Liquified petroleum gas |
| LED | Light emitting diode |
| OPEC | Organization of petroleum exporting countries |
| SHP | Small Hydropower plant |

| | |
|---|---|
| ECN | Electricity corporation of Nigeria |
| NEPA | National electric power authority |
| NESI | Nigerian electricity supply industry |
| KV | Kilovolt |
| TCN | Transmission company of Nigeria |
| NERC | Nigerian electricity regulatory company |
| NEP | Nigeria electrification project |
| REFIT | Renewable energy feed in tariff |
| MYTO | Multi-year tariff order |
| CAPEX | Capital expenditure |
| OPEX | Operating expenditure |
| REF | Rural electrification fund |
| SA | Sensitivity analysis |
| WTP | Willingness to pay |
| BOI | Bank of industry |
| GHI | Global horizontal irradiance |
| HH | Householder |

# Abstract

The present work aims to investigate the techno-economic feasibility of isolated microgrids, serving power to previously unelectrified communities, located in rural areas of developing countries. In the first part of the thesis, it is provided a detailed overview of the main characteristics related to microgrids and other options for rural electrification. In the second part, the work is based on the analysis of a rural electrification project in Nigeria. Despite of a large abundance of renewable and conventional energy resources, this country suffers of extremely low electrification rate. Starting from a database listing unelectrified villages, provided by “Rural Electrification Agency”, it has been randomly chosen a location where perform the analysis. The analysis regards the evaluation of an investment consisting in installing an isolated microgrid serving power to the village selected. The study is performed taking the point of view of a hypothetic private investor. The economic results are estimated also in light of the current state on Nigerian regulatory framework related to microgrid and rural electrification projects. The analysis foresees the comparison among three different configurations for power production and two possible cases regarding the typology of electricity demand present in the village. The three configurations explored are: Solar microgrid (photovoltaic plant plus energy storage systems), microgrid relying entirely on diesel generators and a hybrid microgrid (mixing PV power generation with diesel generators and storage systems). Thus, it is studied which configurations can guarantee the lowest power generation costs. Costs of electricity are compared through LCOE and NPC. Additionally, it is examined the impact on economic results of two potential assumptions for the electric load of the village. The first scenario implies the only presence of householders as electricity users of the microgrid. Conversely, in the second scenario of load, it is assumed that are connected to the microgrid also productive load (small rural firms). These users, consuming electricity during the day, enhance load factor of the systems. The simulations of the different cases analysed are performed through HOMER Pro software, which is largely employed in similar assessment found in literature. This software provides the optimal mix, among microgrid components, capable of meet the load at the lowest cost, in function of the imposed values of technologies costs and performances. HOMER results are further developed, through fixing a potential electricity tariff for microgrid users. In this way, it is possible to estimate economic outcome of the projects (NPV, PBT and IRR). Finally, on these indicators, it is performed a sensitivity analysis based on different assumptions regarding future costs that will be sustained during project outline.

**Keywords:** Rural electrification, Microgrid, Distributed generation, Hybrid systems, Investment evaluation, Nigeria, LCOE, Photovoltaic, Regulatory framework.

# Sommario

Lo scopo di questo lavoro è svolgere un'analisi tecnico-economica relativa a microreti elettriche isolate. Le microreti prese in considerazione forniscono elettricità a villaggi, precedentemente non elettrificati, situati in aree rurali di paesi in via di sviluppo. Nella prima parte dello studio, l'obiettivo è di fornire una descrizione completa delle caratteristiche principali relativa a microreti ed altre opzioni per l'elettrificazione rurale. Nella seconda parte la tesi converge sull'analisi di una microrete operante nelle aree rurali della Nigeria. Questo paese soffre di tassi di elettrificazione medi molto bassi, nonostante abbia un grande potenziale per quanto riguarda le fonti energetiche rinnovabili e convenzionali. Il punto di partenza dell'analisi è un database sviluppato dall' agenzia per l'elettrificazione rurale, nel quale sono elencate le località identificate come elegibili per progetti di elettrificazione basati su microreti. Da questo è stato selezionato casualmente un villaggio. L'analisi consiste nella valutazione di un investimento in una microrete adibita a fornire elettricità al villaggio selezionato. Lo studio è condotto dal punto di vista di un ipotetico investitore privato interessato a portare avanti tale progetto di elettrificazione. I risultati sono basati anche sulla revisione del quadro normativo nigeriano relativo a progetti di elettrificazione rurale. Lo studio prevede il confronto tra tre configurazioni alternative per produrre elettricità all'interno della microrete: microrete basata su produzione fotovoltaica e sistemi di stoccaggio di energia, microrete producente elettricità tramite generatori a diesel ed infine un sistema ibrido (basato sulla combinazione di produzione fotovoltaica e fossile). Lo scopo del confronto è stabilire quale configurazione garantisce i minori costi di generazione all'investitore. Questi sono confrontati utilizzando indicatori quali l'LCOE ed il NPC. Inoltre, è stato valutato l'impatto sui costi della tipologia di domanda presente nel villaggio. Per fare ciò sono stati comparati due possibili scenari attribuibili al consumo elettrico del villaggio. Nel primo scenario l'elettricità è consumata solamente da profili residenziali. Nel secondo scenario, invece, sono state aggiunte unità di consumo produttive (piccole aziende rurali), le quali contribuiscono ad aumentare il consumo medio del villaggio. Le simulazioni sono state eseguite tramite HOMER Pro, un software ampiamente utilizzato in studi simili raccolti revisionando la letteratura, il quale stabilisce la dimensione ottimale di ogni componente del sistema, tenendo conto delle assunzioni riguardanti il costo delle tecnologie e la domanda elettrica. I risultati del software sono stati successivamente sviluppati. Infatti, è stata fissata una tariffa applicabile agli utenti in modo da poter calcolare i risultati economici attesi dal progetto (VAN, TIR). Su questi indicatori è stata condotta un'analisi di sensitività, in modo da stabilire come i risultati possono variare modificando i costi futuri relativi ad alcune tecnologie.

**Parole chiave**: Elettrificazione rurale, Microrete, Generazione distribuita, Sistemi ibridi, Valutazione economica, Nigeria, LCOE, Fotovoltaico, Quadro normativo.

# Introduction

Nowadays, nearly one billion of people in the world lack of access to electricity. United Nations identifies the access to an affordable, reliable and sustainable energy services for all the populations, as one of the Millennium Development Goals for 2030. The geographical locations, with the lowest electrification rates, are rural areas of developing countries. In these areas, public sector has failed in extending centralized electric grid towards all the regions of the country. As a matter of fact, electricity transmission towards remote areas, implies relevant expenditures, not affordable for the budget of developing countries, which it is usually limited. Furthermore, rural areas, are usually characterized by a modest electricity demand. Thus, the large investment that would be needed to extend the grid, it is likely to be not counterbalanced by heavy and stable electricity sales. In developing countries, even in areas where electric grid is present, it is often characterized by low level of reliability. As a matter of fact, electric grid of developing countries, typically suffer of: low frequency of maintenance activities, shortages of fossil fuel in power plants, vandalization of the infrastructure, fraud and maintenance undertaken by unskilled workers operating with poor equipment. Electricity unavailability, in rural areas of developing countries, lead to a level of low human development. This link is mainly triggered by the negative impact that lack of electricity has on: human health, human education and on the likelihood to set up income generating activities. However, the process of technological improvement, is enabling the creation of new opportunities for rural electrification. New opportunities are based on the concept of "distributed power generation". This term represents the generation of electricity through small-scale plants, positioned close to the final consumers and, usually, not connected to the centralized grid. Through Off-grid power systems it is possible to avoid large investment for extending transmission network. This concept can be applied realizing isolated microgrids or stand-alone systems serving rural areas. Microgrids are a set of distributed energy sources, loads and energy storage systems interconnected by a low-voltage distribution network. Microgrids are designed to serve more than one energy users. On the other hand, stand-alone systems provide electricity to just one power consumers. These systems, often, are grounded on the exploitation of renewable energy plants. Indeed, RES plants, have recently achieved a high degree of technology maturity, that allow them to be cost-competitive with fossil fuel power production. It is important to remark that RES, like Photovoltaic, generate electricity without any fuel expense. Thus, adopting a life-cycle perspective, the high investment cost of PV panels, can be offset by a reduction in operating costs. Improvement in energy efficiency are another driver for the feasibility of rural electrification projects. As a matter of fact, modern appliances or LED lights, can satisfy basic electricity needs with few Watt installed. Hence, permitting to reduce investment cost for power generation and distribution. Electrification projects in rural areas may be also enabled by the diffusion of technologies for system control, monitoring and management. These technologies allow to perform these tasks without visiting the remote site where the Off-grid systems is installed. Thus, are further contributing to reduce operating and management costs. In synthesis, technology improvement is leading to an overall depletion of costs required to implement an Off-grid electrification project. This cost reduction may attract private sector investors, which recognize the opportunity to implement a profitable business model. Private capital is less constrained than public one, thus, there is large potential to extend rural areas electrification rate relying on private investment. In order to effectively permit private sector investment, it is fundamental the role of regulatory framework of hosting countries. Legislation must be well-defined and guarantee to private investors the needed supporting mechanisms, required to implement these risky projects.

# Methodology

The objective of this thesis is to analyze techno-economic feasibility of electrification projects in rural areas of developing countries. In this chapter, it is explained the methodology followed during the research, it is clarified the structure of the work, are defined the hypothesis made to restrict the boundaries of the analysis and it is compared this work with similar assessment gathered trough literature review.

## Thesis structure and methodology used in each chapter

The thesis is subdivided into two main section: "State of the art analysis" and "Techno-economic analysis". The first part is composed by five chapters, while, the second one, is divided in 2 chapters. In the following of the paragraph are listed the main features explained in each chapter. Moreover, are outlined the assumptions made and the methodology followed in each part of the work.

**State of the art analysis**: in this part is has been followed a methodology oriented towards literature analysis. The scope of this part is to provide an overview of the problem and of the possible solutions to it. According to the methodology followed, for the main important topics, have been develop some tables summarizing main findings from literature. In these tables theoretic concepts are linked to real case studies or examples.

**Chapter 1**: the first chapter is called "Overview of the problem". In this chapter, it is introduced the issue analyzed in this thesis: the low electrification rate of rural areas in developing countries. Thus, it is firstly provided a detailed definition of energy access. After, have been researched, among literature, evidences of the link between electrification and human development. Analyzing data of reports, it is evident that, rural areas are the ones which are mainly suffering of low electrification rate. Hence, it has been provided a definition of rural area and an explanation of the energy needs of these areas. The chapter ends by briefly listing benefits and barriers of electrification in rural areas.

**Chapter 2**: the second chapter is called "Opportunities for rural electrification". In this chapter are introduced some concepts that, according to latest report, are contributing to enhance electrification rate of rural areas. These factors are: the diffusion of "distributed generation", the power production through small-scale plants located close to final consumers; the achievement of technological maturity of renewable energy plant.

**Chapter 3**: this chapter is called "Microgrid for rural electrification". It provides an overview of the main aspects related to microgrid systems. Firstly, are analyzed different definitions, with the aim of point out the main features of a microgrid system. According to these definitions, are introduced the enabling technologies for microgrid installations. Then, microgrid are classified according to: the tier of service provided to users and the presence of centralized grid interconnection. In this way, it is possible to restrict the field to the application suitable for rural areas electrification. Moreover, are listed the operating model usually employed in microgrid systems. Finally, it is explained how revenues are usually collected in microgrid based in rural areas, with the aim of understand which revenues model is more suited to serve low-income segment.

**Chapter 4**: This chapter is called "Private sector investment in rural microgrid". Analyzing different articles and reports, it is emerged that, in order to promote rural electrification projects, it is fundamental to increase the penetration of private sector investment. Thus, it is analyzed a rural microgrid project from the point of view of private investors, defining three categories of barriers which are usually faced. Afterwards are listed possible mechanisms which can support investors to overcome these challenges.

**Chapter 5**: It is called "Other options for rural electrifications". In this chapter, are briefly explained the characteristics of centralized grid extension and stand-alone solar systems. As a matter of fact, according to literature, these are the two main alternatives to microgrid for rural electrification projects. It is provided a comparison of these two alternatives with a microgrid project. Moreover, are identified the variable that drive the choice for an electrification project rather than another.

**Techno-economic analysis**: The second part of the work follow a methodology more practical and applicative. It is oriented towards calculation and simulation based on real data from Nigerian country. In function of main findings that has emerged from the theoretical analysis, it has been looked for quantitative evidence. Simulations are performed through "HOMER Pro" software which is globally recognized in literature (main features of HOMER are presented Appendix A). The objective of this section is to evaluate a private sector investment into a microgrid operating in rural area of Nigeria. The objectives are to establish: which are the variables that mostly impact on economic performance of microgrid; which microgrid configuration guarantee the lowest costs; if Nigerian regulatory framework is favorable for private investors.

**Chapter 6**: This chapter is called "Country overview, Nigeria". In this chapter is provided an analysis of the Nigerian country. The analysis starts with a description of the socio-economic context. Then, the analysis shift to consider the energy sector. Foremost, is investigated the state of conventional and renewable energy resource in the country. In the following, the focus is directed towards Nigerian power sector. It is analyzed current state of electricity supply chain and the off-grid power segment. The chapter ends with an analysis of the regulatory framework related to renewable energy plant and microgrid electrification projects. The aim, analyzing regulation, is to figure out which support instruments are available for microgrid projects.

**Chapter 7:** This chapter is called "Microgrid project simulation". The chapter starts selecting the location for the study. In order to carry out a realistic analysis, the village has been randomly chosen among the ones indicated by REA (Rural Electrification Agency) as suitable for a rural electrification project. Afterwards, have been gathered inputs data for the calculations. Assumptions regarding load profile and technological input are fixed considering average values from similar studies and report. The analysis consists in a comparison of two different scenarios for load of the village: low-consumption scenario and high-consumption scenario. In this way, the aim is to assess the impact of the presence of productive load, on economic performance of the microgrid. At the same time, the analysis is based on the comparison among three possible microgrid configuration: PV plus storage, diesel based microgrid and Hybrid systems (PV, storage and diesel generator). With this comparison the aim is to understand which configurations can satisfy demand at the lowest cost. The indicator used to compare microgrid costs are LCOE and NPC (which are explained in the Appendix B). Afterwards, it has been selected one case, among the ones analyzed, in order to take into account also considerations related to electricity tariff. Establishing the tariff, it is possible to estimate future revenues and calculate project indicators, like NPV, IRR and PBT. Finally, is performed a sensitivity analysis to understand which are the variable that strongly impact on economic performance of a microgrid project.

## Boundaries definition

In both the theorical and practical part of this work, it has been carried out some hypothesis to set precise boundaries to the research. Without properly setting boundaries, it is not possible to provide a detailed analysis. The first hypothesis made to narrow down the research, regard the power generation sources investigated into the analysis. Secondly, as far as concern rural electrification projects, they can be implemented in three different way: centralized grid extension, microgrid and stand-alone system (serving only one user). Among these three configurations, it has been selected just one of them (the microgrid) that is studied with a higher degree of detail respect to the others two. Thirdly, in order to perform an analysis specific to a real geographical context, it has been selected one African country, Nigeria, where perform the study.

### Hypothesis on electricity production source

As said before, the aim of this work is to study rural electrification options. Awareness is directed on the implementation of small-scale off-grid plant leveraging on renewable energy as power generation source. Among the possible renewable energy sources, it has been taken the decision to focus on solar energy. There are different reasons for this choice. Foremost, solar energy is largely available at every latitude of the world, even considering that there are some locations which are more suitable for PV electricity production, since benefits of a high number of irradiation hours. Other RES, like hydropower, wind and geothermal are instead characterized by a high degree of site-specificity. For instance, hydropower implementation is confined to neighborhood of water basin or river and wind energy can be exploited with success only in areas with high wind speed and intensity. Hence, other renewable energy sources cannot guarantee a systemic approach towards rural area electrification. Moreover, PV technology, has advantages, over other RES, in the installation and utilization phase. As a matter of fact, PV technology is easier to be installed respect to other RESs. Indeed, PV panel are simple to be transported, even in remote locations thanks to their shape and limited weight. PV do not require difficult intervention to prepare the site. For example, comparing with wind energy plant, turbines are typically bulky to be transported. Moreover, turbines, require preparation of the site in order to eliminate physical obstacles in a range of 150 meters that, otherwise, prevent an optimal performance. PV plants are characterized by simplicity in operation phase and low need for maintenance activities. This aspect is relevant in rural areas, where may not be present skilled technicians for perform frequently maintenance activities. Furthermore, thanks to PV panel modularity and flexibility it is possible to tailor the systems in order to cope with different size of demand. Thus, in the techno-economic simulations carried out in the practical part of the work, will only be considered the possibility to use PV plant as renewable energy source. However, also diesel generator will be considered in the calculation, since are largely employed in off-grid electrification [1], [2]. Thus, it is interesting, either to compare solar microgrid with diesel microgrid, or to evaluate the possibility to use, jointly, PV plant, storage systems and diesel generator in hybrid microgrid systems. Below can be seen a schematic representation of a Hybrid microgrid, as will be considered in techno-economic analysis.

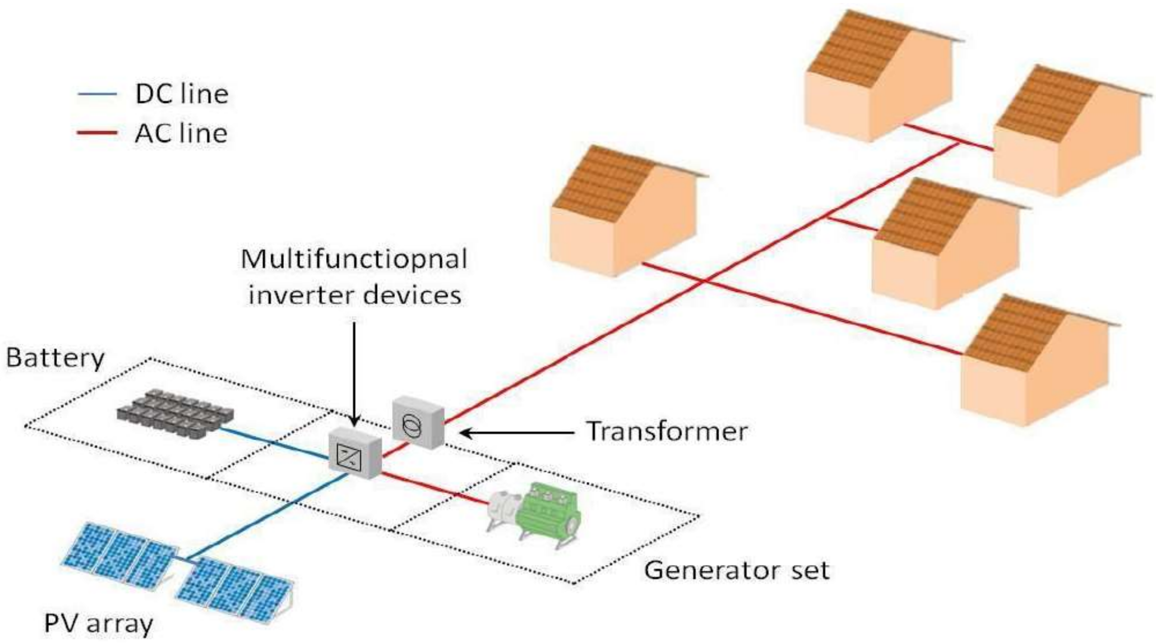


*Figure 1, Schematic view of a PV / diesel hybrid system for rural electrification.*

## Focus on microgrid configuration

Microgrid technology is the opportunity for rural areas electrification to which is allocated the highest focus in this work. There are different reasons for this interest allocated towards microgrid, respect to others rural electrifications opportunities (grid extension and stand-alone solar system):

- Microgrids, according to World Energy Outlook of IEA, in nearly the 50% of the cases, are the best strategy (from an economic perspective) to provide electricity access to currently unelectrified areas [3].
- Isolated microgrid respect to grid extension allow to avoid investment in long transmission lines and permit to minimize transmission losses [4].
- Microgrid configuration guarantees scale advantages respect to stand-alone systems. Considering an equal investment per householders, microgrid are able to provide a level of service of higher tier respect to stand-alone systems. The cost effectiveness of microgrid is given by economies of scale in procurement of technologies and operation and maintenance activities. Moreover, cost advantage of microgrid is stressed by the concept of diversity factor [5], [6]. (which is explained in chapter 5.3.3)
- Through the spreading of technology for management, monitoring and control, microgrid business models can be easily implemented. As stated in "Energy Access Outlook" of 2017, new business models, based on isolated microgrid and the exploitation of digital technologies or mobile platform, has an elevated potential to increase electricity access in the short-term [7].
- Microgrid are becoming interest thanks to the decreasing costs of renewable power generation technologies and energy storage systems [8].
- There is global interest towards microgrid. Large investment from energy companies and by companies with strong technological know-how. For example, Microsoft and Facebook which established the "Microgrid Investment Accelerator" [9].

Thus, for this reasons, microgrid configuration is investigated more in depth. Hence, the first, qualitative part of the work, will analyze more in detail microgrid than grid extension and stand-alone systems. The second, quantitative part of the work, will be based exclusively on the techno-economic performance of rural microgrid, evaluating the investment from the point of view of private investors.

## Selection of the geographical location for simulation

The second part of the work is based on simulations starting from real data. Thus, it has been necessary to select a geographical location to be used as reference for calculations. In order to asses a geographical context congruent with the scope of research, it has been followed the process explained in the next. The starting point has been to understand which are the geographical areas that are suffering of the lowest values of electrification rate. For this purpose, has been used the database from "World Energy Outlook 2017" provided by International Energy Agency. The continent characterized by lowest electrification rate is Africa. This continent appears also suitable for studying off-grid PV technologies since has, on average, high solar irradiation.

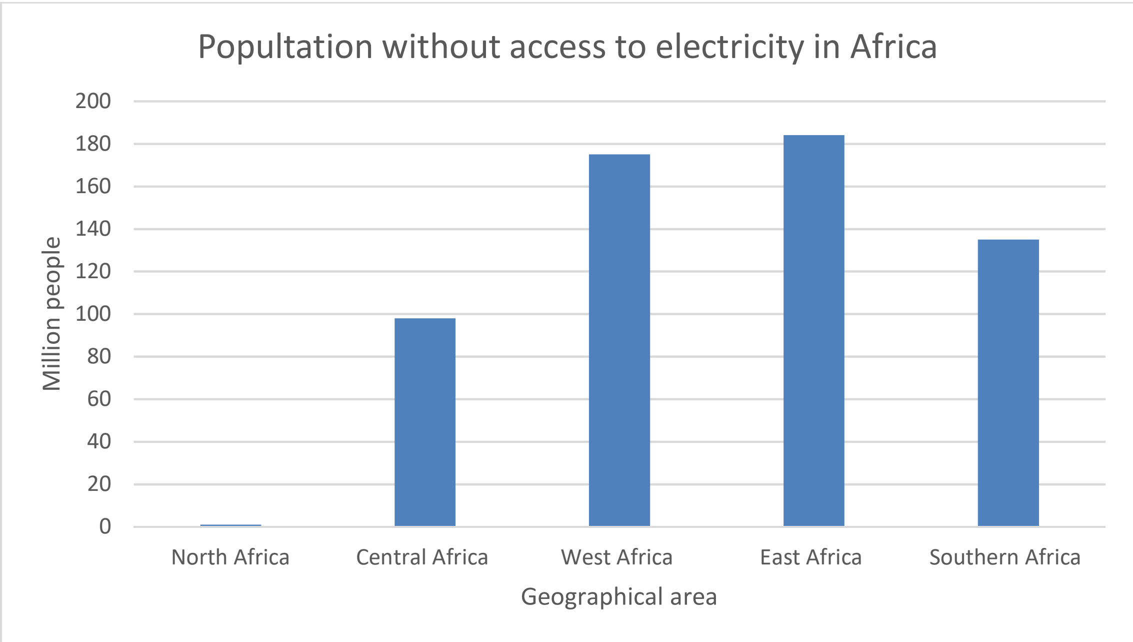


*Figure 2,People without access to electricity in African regions.*

The African continent can be subdivided in macro-areas in: North Africa, Central Africa, East Africa, West Africa and Southern Africa. For each areas IEA provides data on the number of people without access to electricity, as shown in the figure above [10]. According to the data, the most critical area, considering the number of people without access to electricity, are West and East Africa. I suppose to analyze database looking at the "number of people without electricity" rather than "electrification rate" in order to take into account also the size of the population. Within this subset of countries, Kenya, Ethiopia, Sudan, Nigeria and Uganda are the ones where are present the most critical situations. Among these, has been selected Nigeria for the following reasons. Foremost, Nigeria has the highest number of people without electricity: 74 million, located for the 66% in rural areas. Moreover, Nigeria is suitable for investigating feasibility of off-grid solar projects since has a high solar irradiation. Moreover, Nigeria has a growing economy that it is likely to attract private investment. According to Rural Electrification Agency (REA), Nigeria is the most attractive location in Africa for solar microgrid and solar stand-alone systems [11]. Additionally, in a recent report from ESMAP, Nigeria is indicated as an ideal location for rural microgrid projects [12]. In the same direction goes GOOGLA, which state that in Nigeria there is a large share of demand that can be served through solar off-grid technology [13]. The report of REA justifies its statement through the following data:

1. Nigeria has the biggest economy among Sub-Saharan Africa with 405 billion $ of GDP. Furthermore, economy is growing (CAGR of 15% from 2000). Hence, there is potential for future electricity demand.
2. More than the 50% of the people do not have access to electricity. Thus, there is potential to scale up projects towards high numbers of beneficiaries.
3. Where electricity provision is available, it is usually achieved thanks to very inefficient fossil fuel generators. Off-grid local business pays on average 0,70 $/kWh for power. There is so potential of substitute this energy source, achieving both economic and environmental benefits.

## Literature review methodology

A fundamental step, in order to have a complete overview of the topic under analysis, is the analysis of the correlated literature. In this work, the analysis of the literature has been carried out following the steps below:

1. **Research of the related publications**. The first step is the selection of the keywords to be used as input for online research engines. At the beginning, in order to take over a comprehensive knowledge of the topic, have been used keywords such as: "rural electrification", "developing countries", "off-grid electric systems", "distributed generation", "microgrid", "renewable electric systems". These keywords have been used in order to gather different categories of results: paper on scientific journal, conference paper, scientific report, chapter of book and database. The material has been gathered leveraging on internet platform: *Scopus*, *Science direct, Google Scholars* and *Research Gate*. In particular, *Scopus* has been employed on a priority base, since allow to rank results in function of different criteria like relevance, number of citations in peer publication and age of publications. The majority of the paper selected has been published on the following journals: *Energy policy, Renewable energy, Sustainability, Sustainable cities and society, Renewable and Sustainable Energy Reviews* and *Energy economics.* Together with the above-mentioned platform, has also been collected report and database, linked to rural electrification, from website of international agency and organizations. Among them it is worth to mention: IRENA (International renewable energy agency), IEA (International energy agency), The World Bank, GOGLA (Global off-grid Lighting association) and ESMAP (Energy sector management assistance program).
2. **Filtering of the results**. Once gathered the results have been screened and filtered according to different criteria. Foremost, it has been considered the consistency with the scope of the work. For example, some results, related to the implementation of renewable microgrid and stand-alone systems in developed countries, has been neglected. Indeed, are not coincident with the objective of the thesis. Techno-economic assessment related to other renewable energy sources, different from PV, has not been considered according to the hypothesis on the

boundaries made in the previous paragraph. Then, in order to choose the most important publications, the choice has privileged “most cited” articles or the one with the highest “relevance”.  Even the date of publication has been used to filter the results. In particular, in case of paper containing quantitative results, has been avoided to use it as reference in case the publication date was before 2010. As a matter of fact, technology improvement nowadays proceeds at fast rate, thus, aged techno-economic analysis, has been considered less consistent with current scenarios. On the other hand, in case of paper with a more qualitative content, like classification or definition, have been considered also older sources. Finally, in order to evaluate the value of the journals, it has been used the ranking of scientific journals developed by AiIG for the year 2018 (“Associazione Italiana Ingegneria Gestionale”). This ranking label each journal as “Gold”, “Silver”, “Bronze” and “Copper”.

3. **Review and synthesis of the results**. After having selected the most relevant results, the process entered in the real phase of literature review. Main findings from paper and most relevant data from report have been highlighted and summarized. In the first period, the methodology followed was grounded on writing few lines for each paper revised. In this way, the main content of each paper was easy to be recalled in the second phase of the work.
4. **Reclassification of the results according to the scope of the work**. The section “State-of-the-art analysis” is based on a process of reclassification of the literature analyzed. Hence, for each chapter, the material gathered have been rearranged in order to underline the main features, advantages or drawbacks of a specific configuration. During reclassification of results, particular attention has been given to link main theoretic findings to practical examples and case studies from papers or reports.

### Temporal distribution of sources considered

In the graph below can be seen the temporal distribution of the sources analyzed along the years of publication. As emerge from the graph, priority in the filtering phase has been given to source belonging to the second decade of 21$^{st}$ century. The aim is to try to consider results coinciding with current scenario of the topic analyzed. On average, about 18 sources per year belong to the period between 2010 and 2018, 4 sources per year has been taken from the first decade of 21$^{st}$ century and finally, just 0.7 source per year come from the period 1990-1999.

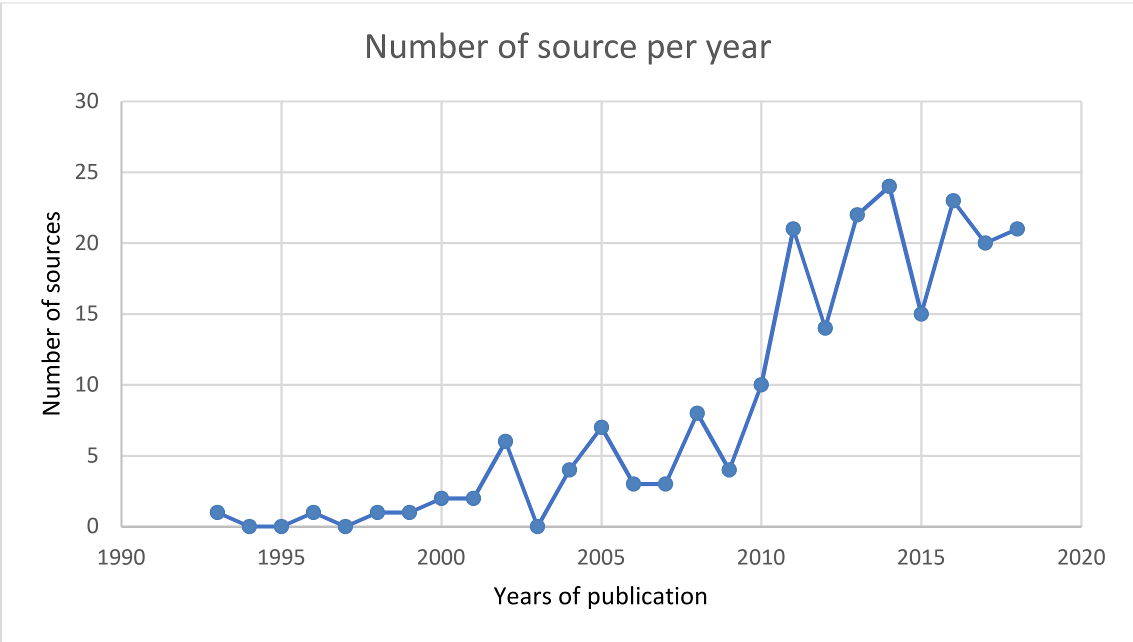


*Figure 3, Number of sources analysed per year.*

## Gap From literature review

The objective of the second part of this work is to develop an accurate techno-economic analysis related to an investment into a microgrid operating in rural areas of developing countries. The starting point of this work are similar analysis of microgrid investment presented into the table below. Analyzing these publications, it has been selected some features that, in my opinion, is worth to analyze more in detail:

- There is usually low focus on regulatory framework of hosting country. Nevertheless, in order to conduct a complete techno-economic analysis of the investment, it is fundamental to examine potential supporting mechanism and limitation deriving from regulation. Thus, in relation to the country selected for simulations, it has been studied in what measure government support private sector investment and which decision, related to the investment, may be influenced by the current state of regulatory framework.
- Similar studies are usually based on the analysis of cost, with low attention towards estimation of cash inflows that microgrid will realize. Thus, it has been included reasoning on tariff setting in function of electricity users' willingness to pay. Fixing the tariff permit to calculate economic indicator of the project: NPV, IRR and PBT. These indicators allow to clearly evaluate an investment from private sector point of view.

In synthesis, the techno-economic analysis undertaken in this work try to embrace the aspects (regulatory framework, tariff considerations, economic results estimation) which are usually neglected in similar researches. Similar studies are presented in the table below, where it is presented: a brief description of the paper, the location of the analysis and the year of publication.

## Main techno-economic analysis of rural microgrid from reviewed literature

| First Author surname | Brief description of the paper | Location of the analysis | Year of publication | Source |
|---|---|---|---|---|
| Olatomiwa | Economic analysis of Hybrid microgrid in rural area of Nigeria | Nigeria | 2015 | [14] |
| Hafez | Analysis of break-even distance for microgrid | Canada | 2012 | [15] |
| Oviroh | Cost analysis of diesel generator or hybrid system to power telecommunication stations | Nigeria | 2018 | [16] |
| Afona-Mensah | Economic impact given by an enhancement of load diversity factor in designing rural microgrid | Ghana | 2015 | [6] |
| Kim | Simulation for microgrid serving small island | South Korea | 2017 | [17] |
| Longe | Load assessment and economic analysis for RES microgrid in poor municipality | South Africa | 2014 | [18] |
| Oladeji | Sizing of a Hybrid microgrid for a remote village | Nigeria | 2015 | [19] |
| Rehman | Economic calculation for a Hybrid microgrid different level of PV penetration in a rural location | Saudi Arabia | 2010 | [20] |
| Sepulveda | Cost of energy calculation for hybrid microgrid serving off-grid communities | Brazil | 2016 | [1] |
| Robert | Economic analysis of microgrid serving an anchor customer | India | 2017 | [21] |
| Azimoh | Simulation and sensitivity analysis on renewable based microgrid serving unelectrified areas | South Africa | 2016 | [22] |

| First Author surname | Brief description of the paper | Location of the analysis | Year of publication | Source |
|---|---|---|---|---|
| Chaurey | Techno-economic analysis comparing solar microgrid and SHS for basic services provision | India | 2010 | [5] |
| Blum | Load assessment and LCOE calculation for microgrid to extend electrification rate in rural areas | Indonesia | 2013 | [23] |
| Guo | Economic comparison of microgrid based on different generation technologies | China | 2017 | [24] |
| Nguyen | Economic analysis of off-grid technologies for rural electrification | Vietnam | 2007 | [25] |
| Numata | Techno-economic calculation for isolated microgrid for different load level | Myanmar | 2018 | [9] |
| Moghavvemi | Comparison of LCOE obtained with PV, hybrid and diesel for rural villages | Malaysia | 2016 | [26] |

*Figure 4, Techno-economic analysis of rural microgrid from literature.*

# State of the art analysis

As said in the methodology, in this part the aim is to analyze and classify the most relevant results from literature.

# Chapter 1: Overview of the problem

**Low electrification rate in rural areas of developing countries**

## 1.1 Energy access definition

As stated by sustainable development report of United Nations in 2017, one of the goals for 2030 is to reach universal access to affordable, reliable and sustainable energy services. In order to meet this objective is needed to guarantee electricity provision to all the population and provide clean fuels and technologies for cooking [27].

As far as concern electrification, according to the data of The World Bank, currently there are nearly 1 billion people who lack access to electricity [28].

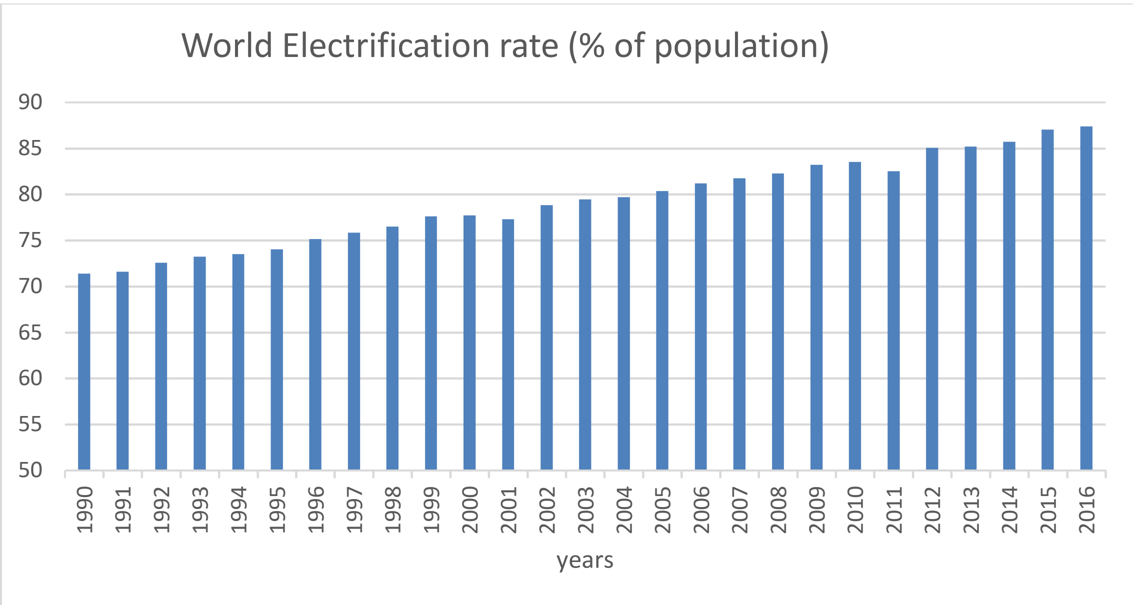


*Figure 5,World Electrification rate, The world bank 2017*

Thus, even considering the positive trend of electrification rate, that shifted from 71,4 % to 87,4 % in the period from 1990 to 2017, the full electrification objective is still distant. The problem of low electrification is concentrated, almost for the totality in developing countries, which has an electrification rate equal to 82 % [10]. Conversely, OECD member reached, starting from 2013 an electrification rate higher than the 99% [28].

The definition of energy access as always been tricky. Traditionally, it has been used a binary approach in order to define the presence or not of energy provisions. However, this approach do not provide detailed information on the situation. Indeed, it is not considered the level of service available for the energy users. Many people have a theoretical energy access, even if the service level that they receive is quite low. It is estimated that 2.4 billion people receive an unreliable or intermittent electricity provision caused by undersized and undeveloped electric grid of some areas [29]. For this reason, it has been recently developed, by the non-profit organization SE4ALL, a e new multi-tier framework (MTF) for the definition of energy access. The new framework is based on three key principles [30].

1. Foremost, it poses the attention on the service level analyzed from the user's perspective. MTF does not only sign if the user is receiving or not energy provision, but in which measure the energy can be used by the users considering quality and quantity of the service. Hence in order to properly evaluate the service, considering electricity provision, the method defines eight attributes [31]: the peak capacity available for one user (W), the hours of service during one day (h/day), the hours of electricity availability during the evening (h/evening), the reliability of the service (number of outages per period), the quality of the electricity delivered (frequency of voltage drops), the affordability for the users (percentage of expenditures for basic services on consumer's income), the legality of the electricity supplying and finally the safety of the system (considering possibility of incident). The attributes can be similarly defined also for cooking purpose, however, considering the scope of this work, cooking activity will not be taken into account.

2. Assumptions that electricity provision can be defined in tiers, according to the different level of service level. MTF subdivide energy service in five tiers. Starting from tier 0, where no electricity service is provided, until to tier 5, where users benefits of the highest level of all the attributes. Tier 1 envisage the availability of the basic services, like few hours of lighting and the possibility to charge mobile phone. Moving towards upper level of the tiers, increase the durability of the services and the capacity and so it is possible to power appliances and using electricity for productive functions.
3. Technology neutral method: the MTF do not consider through which technology the service is provided. The focus is on the attributes that characterize each tier. For example, electricity coming from centralized electric grid may be classified in lower tiers respect to a solar home system if the service delivered by the latter has higher attributes values.

The results given by the Multi-tier framework related to a specific area may be seen as disaggregated. Indeed, when the aim is to measure the energy access of a given area, this method provide as results the division of the inhabitants in the different tier of services. However, in order to arrive to a unique indicator, the number that represent the tier can be weighted with the percentage of householders belonging to that tier. The result will be only one index which give an average idea of the situation in the area [32]. The Multi-tier framework representation, applied to the case of householder electricity access, can be seen in the table [33].

| Tier of service | 0 | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| **Power (W)** | - | >3 W | >50 W | >200 W | >800 W | >2000W |
| **Daily consumption (Wh)** | - | >12Wh | >200Wh | >1000Wh | >3400Wh | >8200Wh |
| **Duration (h/day)** | - | >4h | >4h | >8h | >16h | >23h |
| **Evening Duration (h/evening)** | - | >1h | >2h | >3h | >4h | >4h |
| **Reliability (Disruption/week)** | - | - | - | - | <14 | <3 |
| **Quality** | - | - | - | - | Voltage problems do not affect use of appliances | Voltage problems do not affect use of appliances |
| **Affordability** | - | - | - | Cost of standard consumption package (365 kWh) is less than 5% of household income | Cost of standard consumption package (365 kWh) is less than 5% of household income | Cost of standard consumption package (365 kWh) is less than 5% of household income |
| **Legality** | - | - | - | - | Bill or prepaid card from authorized representative | Bill or prepaid card from authorized representative |
| **Safety** | - | - | - | - | No previous accidents, no risk for future | No previous accidents, no risk for future |

*Figure 6, Multi-tier framework for householder electricity access*

## 1.2 Electrification and human development: evidence from literature

The availability of electricity in a given zone has always been directly link with the level of human well-being and socio-economic development. These attributes are not easy to be quantified, however, can be used aggregate indexes. In order to properly consider social dimension, the most common used index is the Hunan development index (HDI). This index takes into account different factors. It is considered the average longevity of population in a country, measured considering life expectancy. It is also considered the level of knowledge of the population, which is estimated using as proxy the rate of illiterate among adults and the average number of years of school for the children. The third variable that is considered is the living standard of population, which can be measured by considering the real purchasing power of the citizens [34]. GDP it is instead used in order to carry out an analysis which is purely focused on the economic dimension of a given country. The positive impact of the electricity consumption on GDP and HDI it has been stated in many studies. Kanagawa in 2008 studied the relationship between electricity consumption per capita and the two indexes in 120 countries, achieving as a result a positive correlation between the variables [35]. This correlation can be explained by considering the impact of electricity availability on health, education and income.

Starting from health, electricity supply enables to avoid the inhalation of dangerous pollutants generated by burning solid biomass (crop, dung, charcoal and wood) within houses. This fuel is typically employed for cooking or lighting purposes, thus the most exposed to diseases are women that spend much time within houses [36]. Warwick et al. studied the consequences of the usage of solid biomasses with inefficient cookstoves. They link 1.6 million death per year in developing countries to the smoke generated during cooking [37]. Moreover, electricity reduces the need for labor work of children and women that, without electricity availability, are forced to transport fuel wood for long distances. Modern energy permits to properly store food and drugs in refrigerator avoiding deterioration. Power supply enables to carry out communication campaign through TV or radio in order to make citizens aware of the risk of infectious illness, like AIDS and malaria [38].

As far as concern the impact of electricity on education, it allows the spreading of knowledge and favors communication thanks to internet and digital devices. Moreover, modern lighting availability permit to children to study even when natural light is not available and in better visual conditions than using kerosene lamp. The importance of have a availability of electricity for children education has been studied by Jacobson in Kenya villages. In its research, he focuses on the utilization of Solar home systems for rural electrification. His work state that, for children in houses with large system installed (>25W), it is more probable to benefit of lighting for evening studies than children in houses with smaller solar system installed (<25W). This happens since in the second case most electricity results allocated to television (the 54%), reducing at the minimum the energy for lighting [39].

Considering the impact on the income generation or equally poverty reduction, electricity permits the growth and development of firms which provide employment to local workers. As a matter of fact, the enterprises are able to increase the production rate and improve the quality of the output relying on the mechanization of the process, substituting human and animal labor [40], [41]. A study which demonstrated this intuitive link is proposed by Kirubi, who monitored for 13 years, the process of electrification of a Kenyan village thanks to a diesel generator. He monitored the impact of electricity on productivity and revenues of a group of locally SMEs, operating in different sector: food processing, retail, repairing, metal and grain milling. The results that he noticed are an increase, for all the firms, of the productivity per worker of a percentage ranging from the 100% to 200%, and an increase in the revenues in an interval between 25% and 125% [38]. Considering agricultural sector, Barnes et al. analyze the impact of the introduction of an electric pump for irrigation in a farm in rural India, previously unelectrified. The introduction of the pump brought an increase in revenues of almost 11000 rupees per year, in front of a payment for electricity equal to 2000/3000 rupees per year. Thus, could be a profitable investment, especially in case of presence of subsides for capital cost of pump and presence of groundwater, as in the case study considered [42]. Moreover, introduction of modern supply of energy, allows to save time which is wasted in covering long distances transporting biomass and other fuels. Hence, this time can be employed in productive activity guaranteeing income. Studies shows that dwellers of Indian villages employ, on average, from 2 to 6 hours in transporting 10 Kg of wood and similar along distances between 4 and 8 kilometers [41].

## 1.3 Rural area definition

For a complete analysis, it is interesting to understand when a geographical area can be defined as rural. According to the OECD report on regional typology, the methodology necessary to classify territory is based on three steps [43]:

1. Foremost are defined the local units, which are administrative entities. Then, local units, can be classified as rural if the population is distributed on the territory with a density lower than 150 inhabitants per $Km^2$.
2. The second step aggregate the small local unit in regions that can be declared as: “predominantly urban (PU)”, when the percentage of rural local units (RLU) is under the 15% of the total rural units; “intermediate (IN)”, when the share of rural local units is in the interval between 15% and 50%; “predominantly rural (PR)”, when in the region there is a percentage of rural local units higher than the 50%.
3. In the third level of the process are considered the size of the larger urban centers within the region. A region classified, at the end of the second step, as PR can be reclassified as IN if contains an urban center with a population higher than 200000 inhabitants. Similarly, a region judged intermediate in the previous step, can be reclassified as PR if is present in the region at least one urban center with more than 500000 inhabitants.

This first classification based on three tiers has been recently extended. It has been introduced also the concept of accessibility, in order to evaluate the real remoteness of a given region. The new classification allows to better categorize rural areas of non-OECD countries. The analysis of the accessibility addresses the average driving time needed, by the majority of the population (>50%), to reach a center with at least 50000 inhabitants. Thus, an intermediate area, can be judged as “intermediate close to a city” (INC), if the defined driving time is lower than 60 minutes. Conversely, if the driving time exceed 60 minutes, the intermediate area is defined as “intermediate remote” (INR). As far as concern the predominantly rural, can be further subdivided, in the same way, in PR close to a city (PRC) and PR remote (PRR) [44]. Summing up, the extended classification implies five categories: Predominantly urban, Intermediate close to a city, Intermediate remote, Predominantly rural close to a city and Predominantly rural remote. These five categories are summarized in the table below. The socio-economic dimension of rural areas of developing countries is, usually, characterized several issues. As a matter of fact, inhabitants of rural zones, has typically low and irregular sources of income coming from simple and traditional activities like animal husbandry, agriculture, fishing or woodcraft. Moreover, rural areas, has typically a relevant share of illiterate people and scarce or no access to basic healthcare services and clean water.

| **Category** | **Definition** |
|---|---|
| **Predominantly urban** | % of RLU<15 |
| **Intermediate close to a city** | 15 < % of RLU<50 ∩ Driving time<60 m |
| **Intermediate remote** | 15 < % of RLU<50 ∩ Driving time>60 m |
| **Predominantly rural close to a city** | % of RLU>50% ∩ Driving time<60 m |
| **Predominantly rural remote** | % of RLU>50% ∩ Driving time>60 m |

*Figure 7, Classification of territory, OECD*

## 1.4 Rural areas electrification rate

As said before, the countries that mainly suffer of a low electrification rate are developing countries. Within this subset, the most critical rates of electricity provision are in rural areas. As a matter of fact, according to the estimation of International energy agency (IEA), the 84% of the people who do not have access to electricity live in rural areas [10]. According to the same database, rural areas has an electrification rate of the 70 % in developing countries, while the one of urban areas is equal to the 94 %. Deepening the analysis of rural areas, it is possible to discover that the most critical situation is in Africa. This continent has an average rural electrification rates equal to 32%, which fall till to 23% circling on Sub-Saharan Africa. Rural areas of developing Asia have an electrification rate of the 81 % but, excluding China, the value drop to 77%. Finally, Central-South America and middle East has a rural electrification rate respectively of the 86% and 81%. These values are summarized in the graph below:

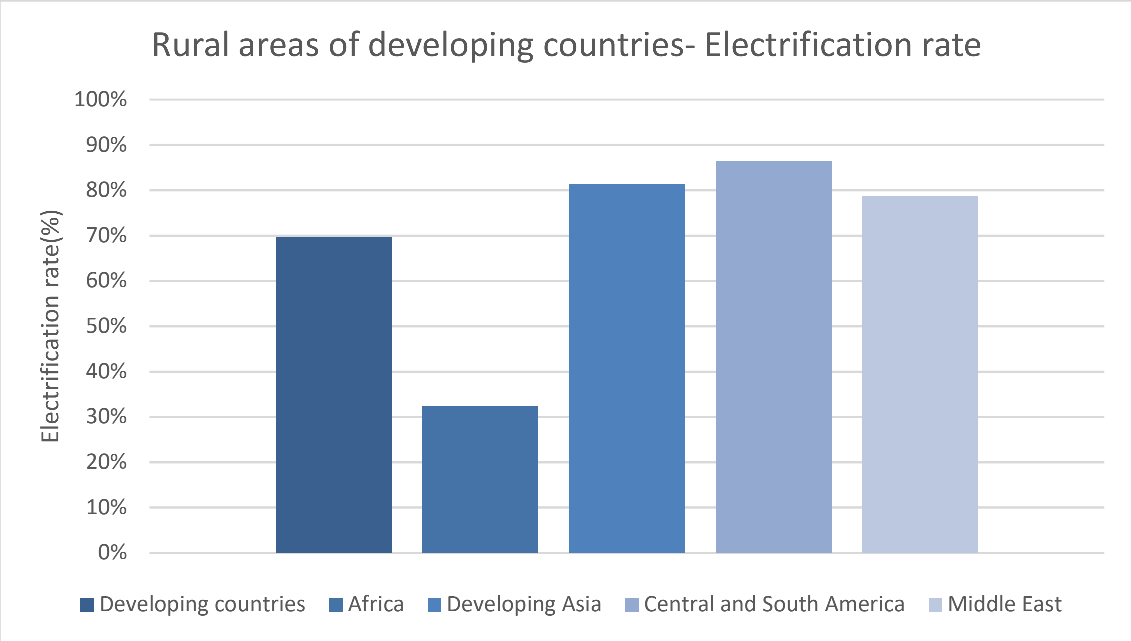


*Figure 8:Electrification rate of rural areas in developing countries, IEA-International energy agency.*

It is important to point out that, even if a rural area, like a village, result nominally electrified since it is connected to the grid, it may be not available electricity provision for all the householders. This mismatch can be explained considering that the connection of each house is costly and would be translated in too high monthly fees, unsustainable for the low-income segment of users present in rural areas [45].

## 1.5 Definition of rural areas energy uses

The energy needs of rural areas can be subdivided in three categories according to the literature considered, [46], [47], [48]:

- **Energy for satisfy the basic need of householders**: this category account for the bulk of the totality of energy consumed in rural areas. The most important energy usage done by dwellers is employed in cooking food, lighting and space heating. Starting from considering cooking application, it accounts for the 80% of the householder's energy needs in rural zones [47]. The solution used vary at worldwide level. The common objective for the dwellers is to minimize costs and risks related to cooking activities. The typical equipment, employed in rural areas for cooking purpose, are cook stoves which can be feed with biomass like residual crops, fuel wood, charcoal or animal dung [46]. The usage of this kind of fuels, directly in the houses, for cooking and heating purposes, imply damages and disease to respiratory system. Moreover, this kind of solution is characterized by a low value of efficiency: stoves using wood has an efficiency nearly the 10%, while in case of charcoal the efficiency is of almost 20%. Householders with a higher income usually rely on LPG. However, the opportunity in future can be the diffusion of induction cookstoves that, working with electricity, avoid an inefficient and unhealthy combustion [49].

As far as concern lighting, it is typically satisfied in rural areas unelectrified relying on kerosene lamps or candles, [36]. Purchasing kerosene, may represent a relevant expenditure for poor householders and the output lights is dim. In alternative to kerosene, for lighting purpose, can be used dry-cell portable batteries which require that users have to travel towards charging points and then can be used in battery operated devices, like torches.

Space heating is performed by burning wood, residues, dung and sometimes coal [48]. The reasoning related to negative consequences for human health is similar to cooking activities.

After lighting, cooking and space heating, which are energy usage satisfying primary needs, there are other possible uses of energy which can bring important social benefits to the inhabitants of small remote villages. It is the case of the usage of energy in order to power television, radio, mobile phone or small appliances. The first three permits to avoid the sense of isolation from the rest of the society, while appliances can be used to simplify daily activities in the houses. These needs are satisfied through electricity where available or, in alternative, low consumption devices may also be powered through portable batteries.

- **Energy for community services**: this category is composed by the energy needed to permit delivery of public services. Basic public services that villages aim to provide are: a school for children education, a small local healthcare for emergencies, the provision of public lighting and pumping clean water [46]. The provision of these services it is fundamental to foster development and reduce inhabitant's poverty. This category of energy needs can be satisfied mainly through electricity, when available. In alternative can be used large kerosene lamps for public lighting, obviously, offering a lower service level and increasing wildfire risks [47]. However, the provision of the others community services mentioned above, is not possible at all without electricity availability.

- **Energy for productive uses**: also called energy for income-generating activities. This category indicates all the business activities that guarantee to an individual a frequent cash flow by selling products or providing services, regardless of the type of activity and size [50]. Rural areas mainly rely on agriculture as productive activities. The presence or not of a stable and reliable source of electricity can be a decisive driver for the improvement of farming production. Indeed, power allow to improve both the quality of the production and the quantity of the agricultural production. Indeed, electricity, permit to carry out ancillary processes like land preparation, irrigation, weeding, harvest and post-harvest treatment. The mechanization of these activities, thanks to electricity, allows to reduce human and animal labor as input and increase the productivity [48]. Moreover, the electrification of rural zones can foster the growth of small local business which could provide employment to dwellers and avoid the incentive of migrate towards urban areas. These small firm are typically called "Rural industries" and can be further subdivided in agriculture based and non-agriculture-based industries. The former consists of firm which process fruits, vegetables, rice or tobacco while, the latter category, is made mainly of manufacturer, for example, charcoal or brick manufacturing firms. Rural industries have three main energy needs: lighting, heating necessary for the processes and power for motor systems. Lighting, as said before, is met by kerosene or electricity. Process heating is achieved burning wood or other biomasses. Motive power is delivered by electricity, or in alternative human labor [47].

In the table below, it is present an overview of the energy uses of rural area. It is pointed out how a specific need is satisfied in two different scenarios. The first scenario is related to the absence of electricity. While the second scenario is designed with electricity availability. When the electricity is available is supposed that there is an elevated income level that permit to the community the purchasing of electricity. Even in case of needs which are not commonly satisfied with electricity, like space heating or cooking, it has been supposed that the householders have an income level high enough to afford the purchasing of LPG and coal.

| **Energy use** | **No electricity availability Supposing Low-income** | **Electrification scenario Supposing High-income** |
|---|---|---|
| **Household basic needs** | | |
| Cooking | Wood, dung, residues, charcoal | Charcoal, LPG, induction stoves |
| Lighting | Kerosene, candles, torch with removable batteries | Electricity |
| Space heating | Wood, dung, residues | Wood, dung, residues, coal |
| Mobile phone charge | Charging stations or none | Electricity |
| Basic appliances | None or portable batteries for low power appliances | Electricity |
| **Community services provision** | | |
| Public lighting | Kerosene lamps | Electricity |
| Appliances for public services (healthcare, education) | None | Electricity |
| **Productive activities** | | |
| Mechanization (also agricultural activities) | Human and animal labor | Electricity |
| Process heating | Wood, residues | Coal, charcoal, wood |

*Figure 9, How energy needs are satisfied in rural areas: with a without electricity availability.*

## 1.6 Benefits and barriers of electrification in rural areas

Summarizing what already explained in the previous paragraphs, to reach a complete electrification in rural areas, would means to achieve an important set of benefits, [42], [39], [51], [52], [53]:

- Poverty mitigation: birth of new opportunity for local communities coming from the birth of small companies based on the exploitation of local resources and tourism. Furthermore, electricity can be employed in order to reinforce the existing activities, like agriculture.
- Reduce migration towards cities: the rise of new business opportunities locally can be an incentive for dwellers to remain in the rural village, instead of moving towards larger center. Thus, could help to prevent the depopulation of rural areas.
- Health condition enhancement: there are many situations when the electricity turns helpful for this purpose. Prevent the generation of harmful emission within the houses, replacing with electricity traditional lighting sources based on combustion. Moreover, it helps to obtain clean water availability. To maintain sterilization in hospital and so avoid the risk of infections. Finally, refrigerator permit a safer storage of the food so as decreasing the risk that dwellers will feed their selves with breakdown food.
- Education level improvement: the population and, in particular, the children can have the access to a huge source of knowledge thanks to the usage of mobile digital devices and TVs.
- Saving of time which is usually used in order to collect fuel like biomass and transport it towards houses.

On the other hand, there are significant barriers that prevent that many villages, island and remote areas can benefit of electricity availability [51], [54], [55], [56]:

- Inability to pay for the service: the inhabitants of rural areas live usually very close to a condition of poverty, so without governmental aids for them is impossible to acquire electricity. Electrification project, both off-grid and grid extension, that target low-income segment, risk of receiving an insufficient level of revenues.

- Low presence of private sector investments: for entrepreneurs who aim to undertake a rural electrification project, there are difficulties in gathering external sources of capital since, traditional banks, are not generally willing to finance a project which is characterized by serious uncertainty.
- Geographical barrier: The distance from the centralized grid, in some cases, results to be too large and, thus, the grid extension investment would be expensive. A large distance to be covered for electricity transmission could not be the only geographical challenge. Indeed, can subsist problem of inaccessibility of the territory since are present obstacles, like mountain, deserts or the sea, in case of an island. In this condition, it could be a better strategy to push on a local energy production based on renewable sources, if available.
- Low population densities: the low concentration of inhabitants which characterize rural areas means that would be required a high unitary cost to provide electricity to each householder relying on the national grid expansion. For these reasons, even when the rural area is connected to the centralized grid, the electricity can turn out to be economically affordable only for high income inhabitants or small business.
- Low demand: rural zone, in most of the case, are characterized by low electricity demand, since, dwellers' basic needs, can be satisfied providing them only few watts per day for lighting or for power the scarce number of appliances available. For this reason, electricity generation and distribution company are deterred from investing money in these zones, where the expected return from investment is likely to be low-down. Of course, the low power demand would remain until there will not occur economic and social growth in rural areas, together with electrification. It is a sort of paradox: until there is not economic development in rural areas there is no incentive in bringing electricity to these areas since the demand is not enough elevated to justify the investment. On the other hand, without electrification, the economic growth of this area is not likely to happen soon, since electricity is the backbone of all productive activities.
- Lack of technical skills: in DCs remote areas could be not present the technical competences which are needed to correctly operate and maintain the power generation and distribution technology.

# Chapter 2: Opportunities for rural electrification

**Distributed generation and RES exploitation can contribute to enhance electrification rate**

## 2.1 Leapfrog effect in developing country

For a successful implementation of rural electrification projects, is required the adoption of a set of enabling technologies. The affordability of these technologies, for rural areas of developing countries, has been a barrier for long time. Nevertheless, in the last years, the democratization of technologies, is opening the possibility of benefitting of the most advanced equipment even to lower income segment. In particular, developing country may be subject to the, so called, “Leapfrog” effect. This phenomenon represents a disruptive pathway towards technological innovation. More in detail, it encompasses the adoption by developing countries of the most advanced technologies, without passing through all the steps of growth that developed countries have undertaken in the past. The belief behind the concept of leapfrog effect is that, the existence in developed countries of aged industrial systems and infrastructures, slows down the process of technological adjournment and innovation. Conversely, in places which are in a lower stage of development process, this obstacle does not exist [57]. A common example of technology which is following this trend is the large spreading of mobile phones in Africa, where the fixed-line phones have not encountered a large diffusion. In the past, it was believed that mobile phones would have not penetrated African market, for a long time, due to the average low-income of inhabitants. However, the recent trend shows a totally different reality. In 2017 there was 420 million subscribers of mobile phone card in Sub-Saharan Africa, with a penetration rate equal to the 43%. This number are expected to grow until 500 million in 2020, making this market as the one which is growing at the fastest rate in the world [58]. The drivers for this quick propagation are: the diffusion of pre-paid payment model, the commercialization of low-cost devices and liberalization of telecommunication market. The lesson given by this example is that, technological improvement, coupled with the development of proper business model and a favorable regulatory framework, can deliver the opportunity to low-income segment to purchase innovative services and benefit of its [59]. The Leapfrog effect, regarding the energy sector, refers to the usage of the most advanced generation plants, based on renewable sources. In this way, the growth can be grounded on cleaner technologies. Thus, a development pattern which is different from the one followed by European countries, that has been based on polluting fossil fuel. Moreover, technology advancement, permits the exploitation of digital technologies in the energy sector, so as to improve management and real-time control of electricity provision [60].

## 2.2 Distributed Generation

### 2.2.1 Concept definition

As seen in the previous chapters, the traditional pathways, based on grid extension, implies geographical and technical difficulties in the case of electrification of rural areas. Therefore, the solution, to extend the number of areas covered by electricity provision, must be sought by exploiting innovative possible solutions based on the concept of distributed generation (DG). This topic can be defined as: small-scale electricity generation, near to the place of consumption [61]. The distributed generation unit can be integrated into the grid or independent from it. This latter configuration can be defined as "stand-alone" or "Off-grid", is the distributed systems that better fits the context of developing countries. In this scenario, the application of DG concept, permits to locate the power generation technology in proximity of the load, preventing the costly process of centralized grid extension. DG allow also to reduce transmission and distribution losses. Moreover, this paradigm allows to generate electricity in rural areas relying on the kind of renewable resources which are locally available, decreasing the dependence from traditional fossil fuel which has a negative impact on the limited budget of rural areas [62].

### 2.2.2 Driver for Distributed Generation

Distributed generation of electricity is gaining more and more interest in both developing and developed country. However, this is not a totally new concept. As a matter of fact, at the beginning of the diffusion of electrical systems, there was a very scattered electric system with generation points placed close to the few industrial cities. After, thanks to technological improvement in production and transmission technology, it turned possible to organize electricity system in centralized way. Through centralization, it has been possible to exploit scale economies and keep large power plants far from the cities, warding off pollution. The centralized electricity network was owned and managed by a national utility company, which oversaw all the supply chain steps, generation, transmission and final users' distribution. The trend towards centralization was followed by developed and developing countries, even if the latter ones failed in achieve a complete electrification rate. Afterwards, starting from the 1990s, it began the liberalization process in developed countries. This decision was taken in order to pursue efficiency improvement and attract new private investments to reduce the need of public budget [63]. In the period post reform introducing competition in the electricity sector, the DG regained new interest [61]. This novel concern on distributed generation is due to different factors:

- Economical: save the expenditures for electricity transmission and distribution [3]; reduce the risk related with investment in very large power plant.
- Environmental: increasing interest towards the necessity of reduce pollutant emissions; knowledge of the negative environmental impact caused by large, traditional power plant working with fossil fuel [64].
- Social: progressive change of society mindset with regard to energy and sustainability issue. People and companies are more and more looking for "green" solutions in order to satisfy their energy needs. For this reason, firm are often investing in small scale renewable plant, so as to reduce the environmental impact of their production activities and achieve a series of benefits in term of image and marketing [65]. Other times, the investment in small power generation plants, is undertaken by citizens which aim to become "prosumers": active player into the electricity systems that try to reach a certain degree of autonomy from the national grid [66].
- Political: DG with renewable is the opportunity to decrease dependence from importing traditional fossil fuels from foreign countries. DG allow to satisfy part of the domestic demand with internal generation resources, thus, increasing energy security [67].

- Technical: technological improvement is bringing small scale power plant to a high level of maturity, reliability and to a sensible cost reduction. Democratization of smart technologies, like meter, enable production sources control and management.

The above factors can be related in principle to both developing and developed countries. However, the relevance of these factors, is stronger in developed country. In these countries, DG is seen as an opportunity to enhance the performance of an already well-functioning electric system. On the other hand, in developing country the main driver for the interest towards distributed generation is related to the enhancement of electricity access [46]. Thus, in a developing context, DG coupled with renewable resources, represent a great opportunity to shorten the gap towards complete electrification of rural areas [29]. In particular, off-grid small scale application, according to the forecast of International Energy Agency, represents in the 70% of the cases the optimal solution in order to cover the gap towards a universal electricity access. Conversely, in the remaining 30%, the optimal strategy to address lack of electricity issue, is to extend centralized grid [3].

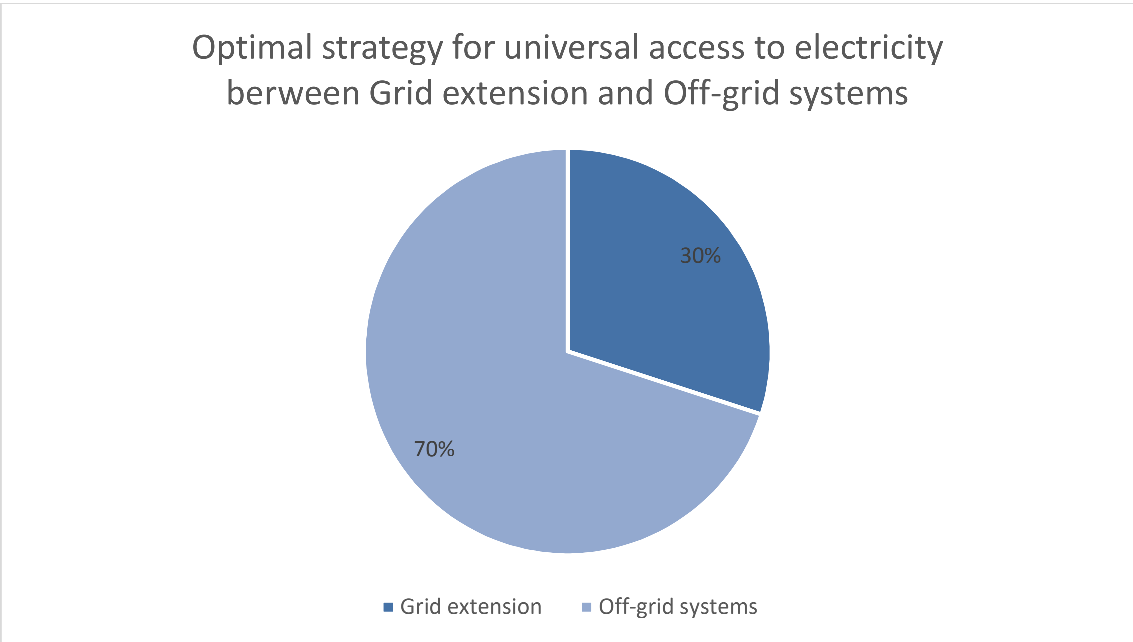


*Figure 10,Optimal strategy to reach universal electricity access grid extension and Off-grid systems*

According to the same source, within the off-grid share, in the 65% of the cases, the optimal solution would be to install an isolated microgrid. Conversely, in the remaining

35% of the cases, the most cost-efficient off-grid electrification strategy are the stand-alone systems [3]. In the following of the work, these technologies will be analyzed in detail.

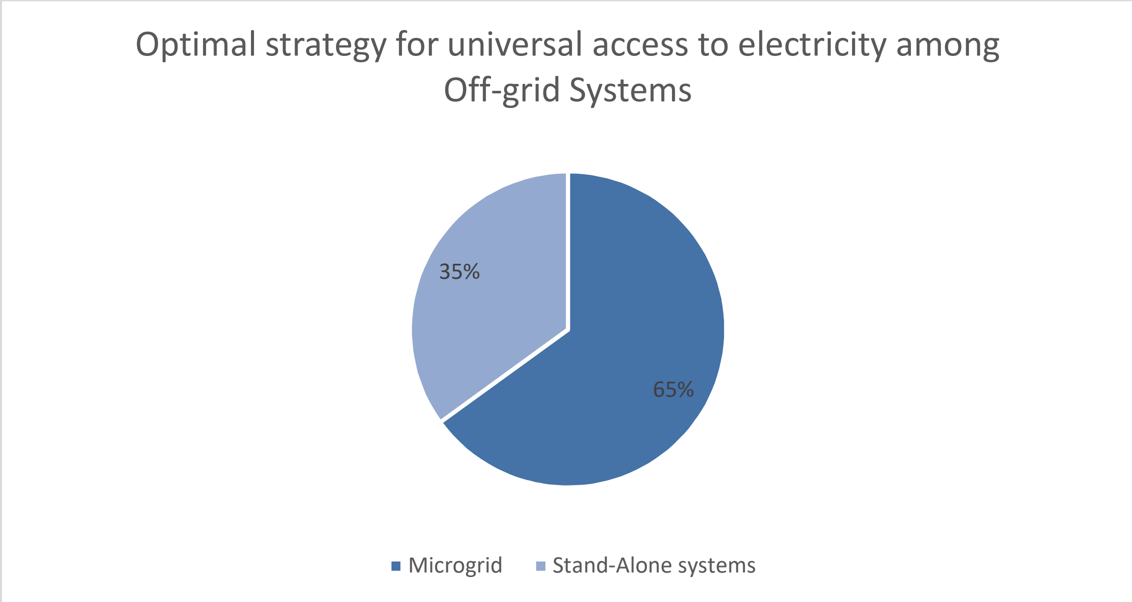


*Figure 11, Optimal strategy to reach universal electricity access among Off-grid systems*

### 2.2.3 Classifications of electric systems

The typical arrangement of electric systems is evolving, embracing new configurations based on the concept of distributed power generation and off-grid electricity systems. Thus, it is needed to introduce new classification of electric systems, that considers new trend. These classifications may be helpful to describe electrification projects in rural area of developing countries. From the analysis of the literature emerges two principal classifications [62] [67].

The first classification analyzed, include the difference between centralized electric system and other electric systems based on the concept of distributed generation. According to Alanne et al. electric systems can be classified in: centralized, distributed or decentralized [67]. The subdivision is performed according to how electricity is generated, transmitted and distributed within the network. Centralized systems are articulated into a group of big power producers which, through transmission and distribution network, supply electricity to the final users. Final users are, usually, placed at long distance from the generating units. Conversely, the other two categories of electric system defined by Alanne, are grounded on the application of distribute generation concept. Hence, are included small-scale power plants located close to final consumers. Decentralized systems are formed by different subsystem, composed by: a single unit of generation, a distribution network and one or more consumption nodes. The subsystems do not have any connection among each other and it is not contemplated interconnection with centralized grid. Basically, a single unit of the system, is composed by only one production plant which deliver power to one or more load. Finally, distributed systems, integrate different power generation sources within the same distribution network. The single subsystems, as defined in the previous category, are interconnected and may also be connected to the centralized grid. Moreover, in distributed systems, it is present a control point which analyze data related to internal production and manage the exchange of power with the centralized grid, in case it is present. In the figure below, are presents the main features of this classification.

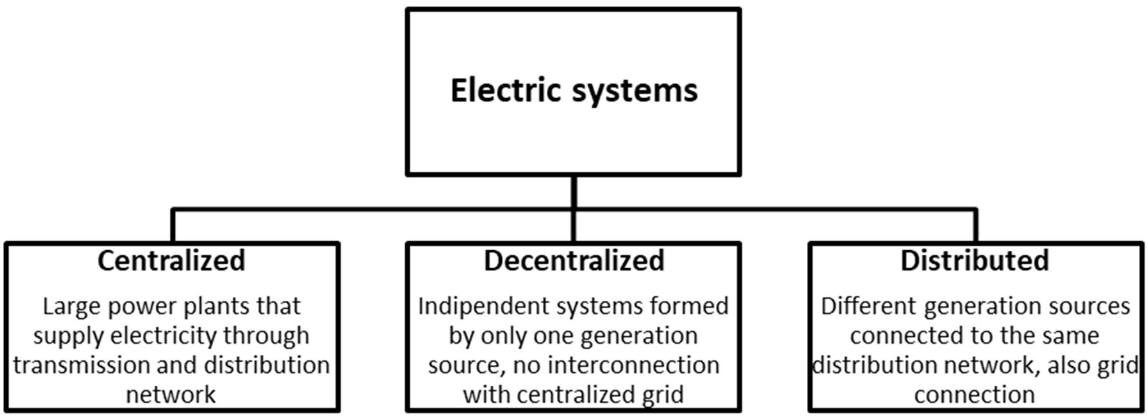


*Figure 12. Classification of electric systems according to Alanne.*

The second classification analyzed is, basically, an extension of the previous one performed by Mandelli et al. [62]. In this case are only considered off-grid application. This assumption is justified from the need to take into account electric systems configurations typical of developing countries. Thus, the centralized grid does not enter in this classification. Moreover, from the “distributed system” case of the previous classification, is not engaged the possibility that can be also present connection to the centralized grid. This study, in the first level, distinguish between off-grid decentralized systems and off-grid distributed electric systems. Then, subdivide decentralized systems category in three sublevels: Home based systems, community or small and medium enterprise systems and centralized microgrid. The firsts two subcategories imply the presence of one electricity producers that deliver energy to only one consumer. The system is detached from other ones, hence can be defined as stand-alone electric system. The user can be a householder, in the first case, or a small local firm in the second case. The centralized microgrid, instead, is structured in one generation unit connected to different consumers. Considering the distributed systems side, there are different electric subsystems interconnected among each other. The element composing this category is the hybrid microgrid. Differently from the centralized microgrid, is made by different production plant, which may use various generation resources and supply electricity to a certain number of users. This work places also an upper limit on the installed capacity value for be defined as microgrid: 5 $MW_{el}$. This limitation on the capacity it is useful to consider only small-scale application. Without this limit, from a physical point of view, a large capacity and geographically extended microgrid, would be equal to a centralized electric system.

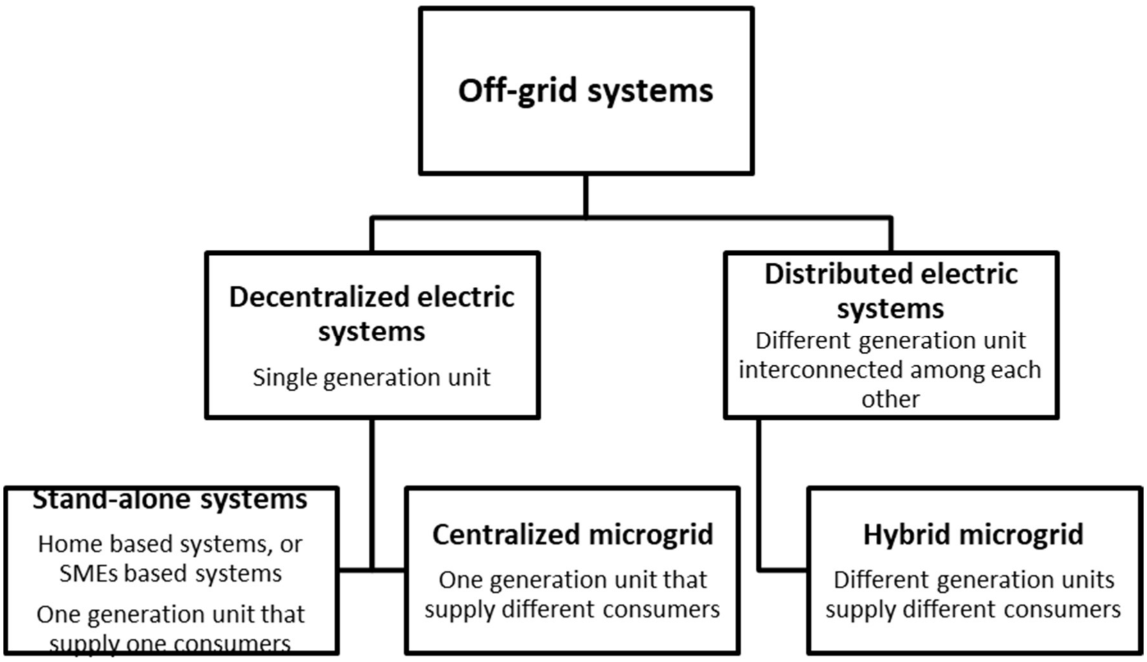


*Figure 13, Classification off-grid systems according to Mandelli.*

According to the classifications of electric system investigated, in the following of the thesis will be analysed the main options for rural electrification: extension of the centralized grid, stand-alone systems and microgrids (hybrid or not).

## 2.3 Renewable energy's role in rural electrification

As said before, off-grid small scale applications represent, in the majority of cases, the optimal solution in order to attain electricity access to people belonging to rural areas of developing countries, who currently cannot benefit of power provision [3]. However, achieve the energy access, is not the only concern for developing country: the objective to be accomplished is an energy furniture which is sustainable from an economic and environmental perspective [68]. In order to grow into an environmentally sustainable direction, the developing countries energy sectors needs to replace conventional fossil fuel which cause pollutant emission during their combustion. Moreover, decreasing costs of renewable technologies, are driving frequently RES based business models towards financial sustainability. According to the estimation of IEA, from 2000 to 2016, almost all the people that received new electricity access, achieved it thanks to power generation based on fossil fuel. However, in the last years, the landscape is changing with an increased penetration of renewable energy sources. The projection for 2030 shows that, new electricity access, will be based for the 60% on RES plants. Moreover, the off-grid energy systems will represent, in the 70% of the cases, the most cost-effective strategy to provide electricity access [7]. Hence, off-grid applications based on renewable, like microgrid and stand-alone systems, can be, now and in future, a competitive alternative to grid extension and fossil fuel small-generator, which are the traditional solution for rural electrification [69], [70].

### 2.3.1 Diesel generator

Ahead of analyse the benefits stemming from the exploitation of RES plant (in particular PV systems), in rural electrification projects, it is worth to mention also diesel generators. As a matter of fact, this system is the most common non-renewable source of electricity in off-grid application [1], [2]. Thus, it is interesting to compare the economic and environmental implication related to the utilization of PV systems respect to diesel generator. Moreover, diesel generator can also be employed together with PV plant in rural electrification project, going to form a Hybrid microgrid system [26], [71]. In this case, the fossil fuel production is used to offset period without solar irradiation, thus as source of back-up power. Additionally, in case of hybrid systems, diesel generator can be used in order to mitigate battery degradation process. In this case, fossil fuel gensets is activated when battery state of charge goes below a specific level, called deep of discharge (DOD). In this case, the electricity generated by the generator is used to satisfy demand and for charge the battery [26].

#### Technology

A diesel generator is composed by a diesel motor coupled with an alternator, that convert mechanical energy in electricity. The diesel generator is usually composed by different components: the diesel engine, the alternator, the fuel system (composed by the tank and the pumping system that bring the fuel towards the engine), the voltage regulator (needed to stabilize the power output), the cooling system (an heat exchangers that reduce the impact of heat on the system), the battery system (needed to start the operations). The fuel consumption needed to operate the generator is function of the model considered. On average, the most recent technologies, operated with an optimal load of the 60-70%, consume 0,3/0,4 liter of fuel per kWh of electricity produced [72]. Diesel generators output is alternating current (AC), thus, can be directly used from largely diffused appliances. However, in case of diesel generators employed in hybrid systems with PV panels, it is needed a bidirectional inverter capable of working as rectifier: transforming AC in DC so as to charge the battery [26]. The useful life of a diesel generator continuously operated is typically between 3-5 years. Of course, in hybrid systems, or when generator is used only as source of back power, the duration depends on the utilization rate which is variable [73].

## Benefits and drawbacks of diesel generators

Diesel generators have been traditionally largely diffused in off grid application thanks to their lower investment cost per kW installed respect to renewable power plant [51], [74]. However, the decreasing costs of renewable are progressively shortening the cost advantage of fossil fuel generators. Another advantage is that, diesel generators, have a short time needed for the installation, since are not needed preventive intervention for the preparation of the site, as in the case of renewable plant [75]. Furthermore, diesel generators have flexibility in facing the variable demand of rural areas [51]. On the other hand, a diesel generator, entails frequent intervention of maintenance, determined by the presence of moving components. For the activities of maintenance, like parts substitution, are required skilled engineers, who may not be locally available [76]. The maintenance operation, in absence of any other source of energy, cause temporal stop to the provision of electricity. Moreover, fuel cost and transportation cost of diesel, negatively impact on the operating cost of a diesel generator [2], [77], [26]. Usually, village inhabitants, have also to sustain the expenses to build adequate storage infrastructure for diesel fuel. As a matter of fact, in some periods, the transportation is not possible for adverse weather conditions or it is too costly for shortages in production. In some cases, in order to minimize the impact of fuel cost, the diesel generators may function only in some hours, normally from 6 to 10 pm [78]. Moreover, diesel generators, have a low capacity factor, it means that there is a significative loss in efficiency when are operated in load conditions lower than the nominal one [25]. Considered the typical instable load of rural areas, operating below nominal condition is a frequent issue. Respect to PV plant, diesel gensets are characterized by a lower useful life [79]. Hence, the need for more frequent replacement, is one of the factors that contribute to raise life cycle cost, adopting a long-term horizon [74]. Finally, the most obvious disadvantages regard environmental pollution and an elevated noise level caused by diesel generator operations that can disturb villagers [80].

A case study on Ivory Coast rural electrification, shows the different life cycle cost between PV and diesel generator. According to the result, in the medium-long term, PV has a lower life cycle cost than diesel generator, even if the initial investment results lower for the fossil fuel-based solution. The reasons for this result are the high operating costs of the diesel generator. The study individuates fuel transportation cost as one of the drivers that mostly raises operating costs, together with the import of spare components and the need of frequent maintenance intervention undertaken by skilled workers [81]. The economic convenience of diesel generator or PV systems can be evaluated through supply-side models [82]. These types of models are based on the calculation of costs for supplying electricity taking into account: renewable resources availability, geographic characteristics, costs of technologies and fuel costs. Szabo et al. carried out this typology of evaluation in African rural areas. In each geographical location, the paper compares, PV systems and diesel generator analysing the cost of the three option in function of distance from the road infrastructures, travel cost for fuel, cost of fuel and average solar irradiation [2].

| **BENEFITS** | **Sources** |
|---|---|
| Low investment cost | [74] |
| Short time for installation | [75] |
| Flexibility in face variability in demand | [51] |
| Alternating current output | [51] |
| **DRAWBACKS** | **Sources** |
| Frequent maintenance intervention | [76] |
| Impact of fuel cost | [2] |
| Transportation cost in rural areas | [77] |
| Loss in efficiency at partial load | [25] |
| Noise and environmental pollution | [80] |
| Short lifecycle | [79] |

*Figure 14,Benefits and drawbacks in using diesel generators for rural electrification.*

## 2.3.2 Photovoltaic technology-overview

As said in the Methodology, the focus of this study is on the utilization of PV technology as source of electricity for rural electrification. With this technology, the solar energy that arrive on hearth surface is converted in direct current thanks to the properties of some material, the semiconductor. The semiconductor material used is typically silicon, which is properly doped by introducing in the crystalline structure atom of boron and phosphorous. When the sunlight hit these materials, is generated electric current thanks to the "photovoltaic effect". The components of a photovoltaic plants are:

- PV modules, where the main elements are the photovoltaic cells. The cells contain the semiconductor material, that allow the energy conversion process.

The key parameter for a PV cell is the power conversion efficiency. That is to say, how much electricity is produced respect to energy input that irradiate the cell. The efficiency is function of the materials employed to form the cell. The PV cells can be classified in three categories. 1st generation, make usage of Silicon, single crystalline (efficiency of 20-24%) or multi-crystalline (14-18%). This category has already reached a consolidated market position. 2nd generation, instead, is in the early phase of the market and it is based on other materials that ensure thinness: amorphous Silicon (efficiency of 6-8%), Cadmium Telluride (8-10%) and Copper-Indium-Gallium-Diselenide (CIGS) (10-12%). Finally, the 3rd generation, already under development, include concentrating PV (36-41%) and organic cells (8%) [83].

- The supporting structure: to protect and sustain the PV panels.
- The electric wires, to transmit electricity produced by PV panels.
- Can be present an energy storage system: in order to cope with the mismatch between energy production and consumption. Electricity can be stored in period of high generation and low demand, then, can be reused when needed and production is not available.
- Charge controller is usually present in system with batteries. The aim of this device is to regulate the energy coming inside and outside the battery. The energy is managed in order to prevent overcharge and the discharge under a certain state of charge which are detrimental for battery.
- Can be present the inverter, in order to convert electricity from DC (as generated by the plant) in AC, used by the majority of modern appliances. Inverter is defined by a proper efficiency which define the measure of AC current output respect to the DC input. The conversion efficiency, on average, range from 85% to 90%.

The amount of electricity that the PV systems can generate depends on: efficiency of the cells, the position of the modules (is preferred an orientation towards south), solar irradiation, surface of the plant and operating temperature. The power output of a PV systems can be estimated through the following formulation [56], [14]:

$$P_{out} = P_r\, D_r\, N_m \left(\frac{G}{G_{ref}}\right) \times [1 + k(t_c - t_{ref})]$$

Where $P_{out}$ is the power output of a single module, $P_r$ is the rated power of the PV module, $D_r$ is the derating factor, $N_m$ is the number of PV module, *G* is the solar radiation (W/m$^2$), $G_{ref}$ is the solar irradiation at standard temperature condition, *K* is the temperature coefficient, $t_c$ is the module temperature that is function of ambient temperature, $t_{ref}$ is the temperature of the module at standard condition.

The global market of PV is growing at high pace. In 2017 the total installed capacity was of 401 GW, with an increase of 100 GW only during the last year [84]. The drivers for this rapid expansion are: the huge drop of module prices [85], [86] (see figure below), the policy which aim to reduce greenhouse gas emission and the incentives for increase electrification rate in developing countries. China, in recent years, is becoming the country with the highest installed capacity, reaching 131 GW in 2017 [87].

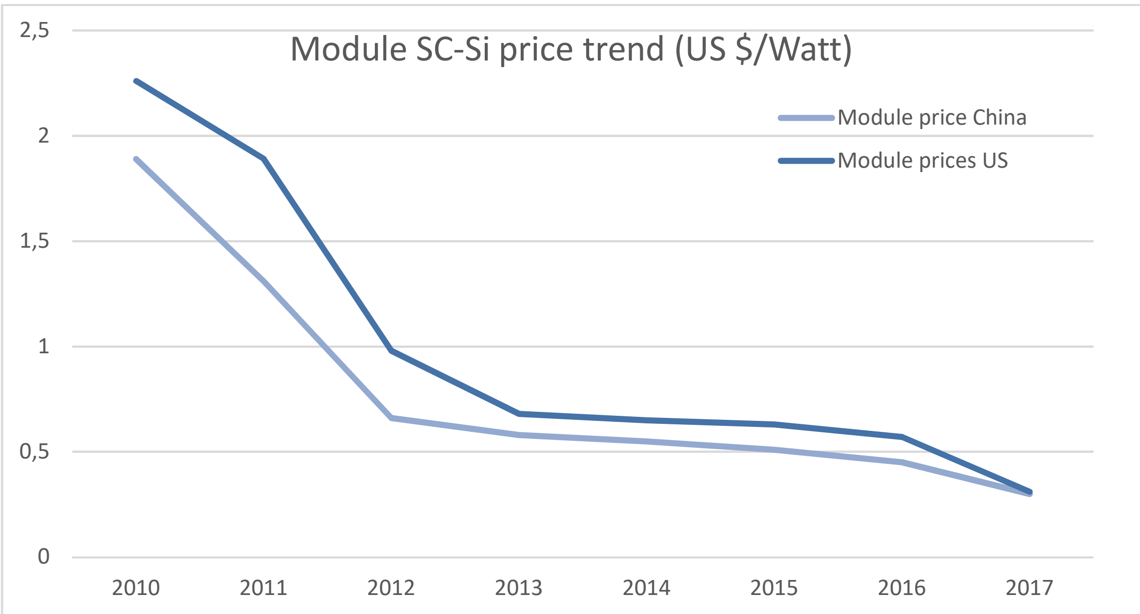


*Figure 15, Trend of PV module (silicon single crystalline) prices.*

## Benefits of PV in decentralized application

Coupling small scale, off-grid applications with production units based on renewable energy exploitation represent the best strategy to fight energy poverty when grid extension is not economically or technically feasible [88]. Having already discussed of the benefits of the small-scale decentralized solutions, in this paragraph the aim is to understand the benefits that can be achieved leveraging on Photovoltaic technology as source of electricity.

### *Curtailment of fuel cost and transportation cost*

An advantages which, electrification through PV systems have respect to conventional generation sources, regard the curtailment of fuel cost and fuel transportation costs [2], [77], [26]. The Renewable energy sources represent the opportunity to rely on resources which are largely available and, in the case of PV, do not imply any fuel cost [47]. Conversely, when the decentralized power production is based on fossil fuel, the cost of fuel itself, plus the shipment cost has a negative impact on the economic balance of remote communities [89].

As regards fuel cost, it oscillates at worldwide level according to variation in demand and supply. When fuel price hits peak value is particularly detrimental especially for low-income communities, which cannot afford to pay more than the average price. Moreover, prices of imported fossil fuel can be raised by opportunistic behaviors of supplier. For these reasons, power generation based on fossil fuels, cannot be considered the ideal solution to pursue energy security in rural areas [90], [77].

As far as concern transportation cost, the situation gets worst in case of zone difficult to be reach for geographical reasons. For instance, there are plenty of rural region without a well-developed road infrastructure. Or else, there are areas that become completely inaccessible during rainy season and so is needed to store large amount of fuels leading to a further increase of operating costs [91]. Another critical situation regards small island. Weisser studied power generation costs on small island of developing countries. The study points out that small islands suffer of diseconomies of scale when importing fuels, since are characterized by a limited electricity demand. Moreover, the remoteness of some islands, make the transportation of fuels more difficult. This aspect reduces the number of suppliers which are capable of provide the transportation service, minimizing competition [92]. In order to have a quantitative idea of the impact of fuel transportation costs it is possible to make reference to the work of Schmid. Studying the feasibility of diesel generator in Brazil, he quantified the impact of fuel transportation costs. The result is an increase on diesel wholesale price between the 15% and 45%, in function of the remoteness of location [93].

### *Environmental benefits*

Off-grid power production based on RES provide to the rural ecosystem also significative environmental benefits respect to the utilization of fossil fuel-based generator [26]. Environmental benefits can be categorized in reduced air pollution, mitigate climate change, avoid damages on ecosystem and reduce noise level.

PV power production imply zero emission of $NO_X$ and $CO_2$. Diesel generators have, instead, an emission factor of 0,074 ton $CO_2$ per GJ [77]. This reduction of emission help to contribute to fight climate change phenomena. Poorer rural communities should be particularly aware of this issue, since are the most negatively affected by climate change effects. Indeed, it causes extreme meteorological events like storms, floods jointly and extreme temperature [69]. These events have a more severe impact in developing countries which are less equipped with advanced infrastructure. As example can be considered, all the island communities which risk to disappear after rise of sea level. Or else damages to agriculture caused by heavy rainfall which eliminate, for a certain period, one of the main sources of income of rural areas.

A cleaner air has also positive impact on the health of rural areas inhabitants. In villages not electrified, the introduction of PV production is likely to substitute kerosene lamps as lighting sources. As said before, these lamps, causes several respiratory diseases since the emission are directly discharged within the houses. In case of remote areas electrified through diesel generator, shift to solar power means reduce outdoor pollution. Rehman studied the variation of emission level in a remote village after the introduction of solar energy. The village was previously powered only through diesel generator. Then it has been transformed into a Hybrid one, by replacing part of the diesel production with PV. The only diesel scenario used to generate an emission level of 15878 tons of $CO_2$ per year. Instead, with a PV penetration of the 40% on the total capacity, it is calculated a reduction till 10347 tons of $CO_2$ per year, bringing positive benefits to the health of the inhabitants [20].

### *Low maintenance costs*

PV technology is characterized by low need of maintenance activities [94]. Usually, O&M, can be estimated to account for less than the 1% of investment cost per year. The absence of frequent maintenance is an advantage stressed in remote areas. Hence, in these areas, may be not present the adequate competences needed to undertake technical maintenance and can be difficult to gather external technicians due to the remoteness of the area. Furthermore, PV panels are light and thus easy to be transported also in location difficult to be reached for topographical reasons [51].

### *Scalability and modularity*

PV applications are characterized by a high degree of scalability given by their modularity. This feature means the ability of a system to face efficiently an enlarged workload. A perfectly scalable system is able to improve the performance when operated with a more elevated demand [95], [96]. Scalability is a key parameter in order to be competitive in providing energy to rural areas: this peculiarity means, in this context, that can be easily increased the electricity quantity produced by the generation technology utilized. Solar PV technology, thanks to their modularity, guarantee flexibility in increase the generation quantity, since it only last to add further units of PV modules to produce more electricity [97]. Furthermore, production capacity can be enhanced without stopping the productive units already in operation. Fossil fuel power plant, instead, don't show off great expansion flexibility. As a matter of fact, once are built with a certain capacity, it is difficult to increase that value without modify the existing plant from a physical point of view. Thus, would be required long period in shut down in order to repower a fossil fuel plant, enlarging the production capacity. Scalability is fundamental in rural areas which, usually, have low budget availability for the initial investment. Moreover, rural areas electrification projects suffer, at least in the first step of the electrification process, of a poor demand from the users' side. A valuable solution, thus, could be to gradually increase the production capacity in PV plant when the economic growth of the area generates revenues that allows to sustain new investment. [22]. The economic growth, as a matter of fact, contribute to create new demand from user's side. Hence, it important that the energy production can be adjusted according to the growing needs of rural areas inhabitants [98].

| **BENEFITS** | **Sources** |
|---|---|
| Curtailment of fuel cost and transportation cost | [47] |
| Reduced air pollution | [77] |
| Modularity, scalability, expansion flexibility | [97] |
| Low need of frequent maintenance | [94] |
| Easy to be transported in remote areas | [51] |
| **DRAWBACKS** | **Sources** |
| High investment cost for low-income segment | [94] |
| Need of storage system, to cope with intermittency | [5] |
| Need of an inverter to convert from DC to AC | [82] |

*Figure 16, Benefit and drawbacks of PV technologies.*

# Chapter 3: Microgrid for rural electrification

**Definitions, technology, classification, operating models and revenues models for rural microgrid systems**

As said in the Methodology, the microgrid topic is analysed more in-depth respect to the other options for rural electrification. Thus, in this chapter will be considered, first of all, the definition of the microgrid configuration, then will be investigated two possible classification: one in function of the level of service provided to user and the connection or not to the centralized grid; another one in function of the microgrid operating models. Moreover, are analysed possible revenues model for microgrid systems.

## 3.1 Microgrid definition

In the table below are summarized the most important definitions of microgrid, according to research software like *Scopus and Google Scholars.* The definitions are selected in function of the most relevant and the most cited results. Summarizing the results, microgrid are systems that bundle together the following set of elements: small-scale energy production units, energy loads and energy storage systems. This units are connected thanks to a low-voltage distribution network and are present technologies that enables the control and the management of the energy flows within the system. All the definitions stress that microgrid imply a small-scale system. The system can be built and operated in both off-grid mode or connected with national, centralized grid. In the latter case, when dictated from technical or economic reasons, can exchange, in a bidirectional way, power with the macro grid. The capability to operate independently from the central grid (also called "islanded mode") it is a necessary peculiarity in order to define an electric systems as micro grid [99]. This aspect is fundamental in remote areas where the centralized grid is not present or unreliable. Regarding the size there is not a universally accepted range of installed capacity in order to be defined as micro grid [100]. Moreover, does not emerge from literature review a unanimous definition that permit to distinguish between "microgrid" and "mini-grid". In the majority of the publications, the two terms are utilized as synonymous. In this work is used the term microgrid.

| Microgrid Definition | Sources |
|---|---|
| *Microgrid comprises a variety of distributed generators, energy storage, loads and power electronic interfaces* | [101] |
| *Microgrid is a Low-Voltage network plus its loads and several small modular generation systems connected to it* | [102] |
| *Micro Grid could be defined as a low voltage distribution network with distributed energy sources (micro turbines, fuel cells, PV, diesel, etc.) altogether with storage devices (flywheel, batteries, etc.) and loads* | [103] |
| *Microgrids (MGs) are tiny power systems which embed various components such as controlled and uncontrolled loads, DG units and storage devices operating together in a coordinated manner with controlled power electronic devices* | [104] |
| *Microgrid are a localized group of energy loads, generation sources and storage systems. The main tasks performed within the microgrid system are energy production, storage, control, management and consumption* | [8] |
| *Microgrids are defined as interconnected networks of distributed energy systems (loads and resources) that can function whether they are connected to or separate from the electricity grid* | [105] |

*Figure 17, Microgrid definition according to the most cited and most relevant literature.*

## 3.2 Microgrid enabling technologies

According to the definitions considered, the enabling technologies for micro grid can be subdivided in the following categories:

- **Energy production technology:** this category is composed by technologies that permit decentralized and small-scale production of electricity.
- **Technologies for energy storage:** technologies that allows to store energy within the microgrid systems.
- **Technology for energy distribution and consumption:** set of technology enabling local power distribution and consumption units.

- **Technology for management, control and monitoring of energy flows into microgrid systems**; the technologies which make possible the remote control of production/distribution/accumulation assets, so as to supervise energy flows within the micro grid system and optimize the energy delivery to final users.

### 3.2.1 Energy production

The first cluster includes small-scale electric power plants. The electricity can be generated using conventional sources (fossil fuels), non-conventional (renewable sources) or Hybrid generation sources [62]. The first category foresees the usage of natural gas or steam microturbines and synchronous generator usually powered with diesel or petroleum. On the other hand, renewable energy sources are mainly solar energy, wind, biomass, hydropower and geothermal [56], [106]. Hybrid microgrid are instead based on the combination of both conventional and renewable generation. Hybrid generation sources permit to have dispatchability over all the hours, overcoming RES unpredictability. Obviously, a hybrid arrangement raises initial investment costs respect to a conventional one. The choice of the generation sources determines whether is produced AC or DC current within microgrid.

### 3.2.2 Energy storage

In order to cope with the unpredictability of RES, maintaining the balance between generation and consumption, in renewable or hybrid microgrid are employed energy storage systems (ESS) [107]. ESSs are characterized by a certain value of storage capacity. It is the amount of energy (kWh) that can be extracted from a storage system, can be also expressed in term of hours that can be covered operating a load at nameplate power with the electricity provided by the ESS. Another key parameter is the roundtrip efficiency, which is the ratio between the energy received from the storage system on the energy injected into the ESS. Hence, it is a sort of measure of the losses associated to energy storage [108]. Moreover, storage systems can be defined in function of power and energy density. In function of this characteristic it is possible to select the most suitable applications for an ESS. Power intensive applications are implemented when is needed to provide a high amount of power for a relatively short period of time. This imply that are used for applications whereby an enhancement of power quality is required, like voltage quality regulation and ancillary services provision. Energy intensive application, instead, are characterized by an exchange of short amount of energy for a long time. Energy density and power density are usually in trade-off [99]. In function of these properties, Storage can be important for microgrid systems for different applications. Foremost, ESSs allow the maximization of the self-consumption from RES plants, since the electricity can be stored when the production overcome the energy needed by the users connected to the micro grid. For example, during daytime, in case of residential load profile. Afterwards, during on-peak periods, the energy can be discharged from the ESS to the system. In this way, in case of islanded microgrid can be guaranteed basic service to users or, in case of interconnected microgrid, can be avoided the withdrawal of electricity from the centralized grid. This function is called time-shift [109]. Then, ESS can be used to stabilize the output of variable RES, facing voltage fluctuation, an application called capacity firming [110]. Moreover, in case of a micro grid connected to the centralized grid, storage systems can be used to mitigate the inconveniences like outages, generated by failures of transmission/distribution grids. At this regard, it is important to remind that the grid of developing country usually suffers of shortages of low reliability, given by: natural gas shortages, low frequency of maintenance operation and it is an aged network [29]. Thus, in order to increase reliability. RES micro grid coupled with ESS are a valuable solution.

The storage technology currently available can be subdivided in: electrochemical, (rechargeable batteries, the most known are lead-acid and lithium-ion) mechanical (hydro-pump, flywheel), electric (supercapacitator), chemical (hydrogen) and thermal (molten salts). Nowadays, batteries have the highest level of technological maturity, are largely available on the market and ensure reliability [107]. Among batteries, Lead-Acid are usually used in off-grid application coupled with renewable since has lower cost than Lithium-ion [111]. However, Lithium-ion batteries are the technology that ensure the best performance in term of both energy density and power density [99].

### 3.2.3 Energy distribution and consumption

The low-voltage distribution network permits the distribution of electricity from generating units to consumers. The voltage of the network ranges from 12 V to 48 V, in case of small size microgrid placed in villages where are not present productive load and distribute DC to satisfy basic needs of householders. In case there is presence of productive load and the microgrid is characterized by a larger size, is usually distributed AC power thanks to a 230 V/50 Hz or 120 V/60 Hz network [112]. The wires employed are becoming thinner, and thus cheaper, thanks to the improvement in energy efficiency. However, a "skinny grid" imply higher transmission losses. The microgrid can operate interconnected from the grid or isolated. In case of interconnected microgrid, the microgrid distribution network is connected to the grid through the point of common coupling (PCC) [106]. According to the power form that characterize energy production, distribution and consumption, microgrids can be subdivided in AC and DC microgrid. AC microgrids are the most implemented and are composed by AC energy production, distribution and loads. In AC microgrid are needed inverter in order to integrate DC electricity generation sources (like PV or fuel cells), and to exchange energy with batteries. Inverters implies conversion losses and higher investment costs. AC microgrid can be easily connected to the grid without using converter [110]. In case of DC production, electricity can be used by DC loads and stored without be converted. Thus, reducing efficiency losses which account for the 10-25% converting from AC to DC. Moreover, DC transmission is characterized by a lower amount of copper losses with an equal resistance respect to AC case. In addition, in DC microgrid, stability and voltage regulation are easier than AC microgrid [99]. DC electricity can be supplied through thinner and less expensive wires than AC power [113]. As far as concern loads, since centralized electric grid distribute AC power, consumption items are more available in AC form. However, DC loads can become more diffused in future since digital devices like computers, routers or lead lights are suitable to be fed with DC [114].

### 3.2.4 Management, control and monitoring of energy flows into distribution network

This category is composed by the technologies that enable to optimize and manage the power flow between generating units and consumption units, across the microgrid distribution network. The objective of an effective control system is to ensure safety of operations considering that voltage and frequency have to be maintained at nominal condition [106]. Hence, the control system has to deliver or absorb the eventual difference between energy generated and power consumed by loads [110]. Demand and supply have to be balanced in real-time, hence, the control systems need to act in an automatic way regulating power injection and withdrawal. For example, in case of PV based microgrid, injections have to be curtailed by the control systems when the production overcome consumption and the storage system is completely charged [107]. The remote monitoring of the microgrid is possible thanks to the interaction of software, communication systems and physical control systems. Thus, a monitoring system is composed by: tools installed on site, a way for transferring data and a central data center. The equipment installed within the microgrid are sensor that collect data related to power production, storage state of charge, system temperature and ambient temperature [115]. Transfer of data is performed through mobile networks or satellite. Mobile network is preferred when signal is available, since it is less costly than satellite. Satellite network is, instead, more expensive but it is the only opportunity in highly remote location [116]. Data can be stored locally and then transferred periodically or can be implemented a continuous transfer. Center for data storage and elaboration are composed by server which collect incoming data which are then analyzed by operators. Data can be collected with smart meter, a device that can be placed close to each consumption units with the aim of records data on electricity withdrawal and transfer it to the operators. As will be seen in the part related to microgrid revenues model, this tool can be helpful in control payments from users [117].

## 3.3 LCOE Microgrid

The LCOE (Levelized cost of electricity) is an indicator that allow to identify the main cost stream, adopting a lifecycle perspective. More detail on LCOE main features can be find in the Appendix B. For a solar microgrid the investment costs are: the cost for PV panel, the cost for energy storage system and the cost for construct the low-voltage distribution network. The nominator is completed by yearly operation and maintenance cost. The electricity at the denominator, instead, is function of the installed capacity ($W_p$), the utilization rate ($h_n$) and the percentage of losses. In this case, there are both losses associated to the local distribution (s, as in the calculation of grid extension scenario) and losses in production over time determined by the degradation of PV modules (d, as in the calculation of stand-alone solar systems) [24].

$$LCOE_{MG} = \frac{\sum_{n=0}^{N}[\left( I(PV)_n + I(ESS)_n + x_{lv}C_{lv(n)} + OM_n\right) \times (1+i)^{-n}]}{\sum_{n=0}^{N}[(W_p h_n(1-d)(1-s) \times (1+i)^{-n}]}$$

$I(PV)_n$, $I(ESS)_n$,$x_{lv}C_{lv(n)}$ represent the investment costs for, respectively, the PV panels, the energy storage system and the distribution network. Theoretically speaking have to be considered yearly cost. However, as far as concern PV panel and distribution network, it is likely that, adopting a project horizon of 25 years, will be purchased only at the beginning. Thus, can also be brought away from the summation. Conversely, energy storage systems, will incur in replacement during project duration.

## 3.4 Micro grid classification

### In function of service level and presence of connection with the grid

An interesting classification of microgrid is proposed by IRENA and it is based on the subdivision of the micro grid according to two variables [8]:

1. The connection to the centralized grid can be available or not. A micro grid which is built so as to be able to operate in both islanded mode and connected to the centralized grid is called "interconnected", while a micro grid which work only in off grid condition is denominated in this classification as "autonomous".
2. The level of services that the mini grid is able to offer to the load connected to it. In particular, the electricity service level is ordered according to the Multi-tier framework proposed by SE4ALL which selects different possible tier of service in function of the characteristic of the power available at single user level [30].

According to the two variables afore mentioned can be identified four types of micro grid:

1. **Autonomous basic services**: this category work specifically off- grid and provide a service level belonging to the 3$^{rd}$ or 4$^{th}$ tier of table 1. The target for this kind of micro grid are communities of rural areas with very low purchasing power. Hence, the scope is to guarantee to dwellers basic energy services while minimizing service costs. The system is so designed to satisfy needs like lighting and radio or TV utilization, with limited interest towards motor and larger loads. The idea is that, even with a low value of performance and reliability, the rural communities can enhance their quality of life. The production sources used are renewable like PV, small hydro and biomass plant. In this case, the microgrid, cannot provide power for all the 24 hours, when there is no renewable resource availability the system may be turned off. These systems are characterized by a limited or null availability of storage technologies since, otherwise, the presence of these tools, would increase investment costs. The ideal target for this category is small villages without consolidated industrial activity.
2. **Autonomous full services**: Also, this typology of micro grid functions exclusively not connected to the centralized grid but, differently from the first one, is able to ensure a level of service equal to 5. This improved result is achieved mainly thanks to the abundant presence of energy storage systems which allow to

store energy when the RES can produce electricity and make it available for all the 24 hours. Alternatively, to guarantee continuity of supply, can be used diesel generators. The targets of this systems are remote communities or island, where there is enough development of commercial or industrial activities but are not covered by central grid. In these zones, inhabitants have an income level that permit them to pay for a more reliable power supply. A common example of this microgrid application is a touristic resort placed in a remote location. Concerning the generation sources used, commonly there are PV plant, Hydro and Wind and provide basic power and energy for productive uses.

3. **Interconnected community application**: in this 3rd case there is connection to the central grid, so the microgrid can work or on-grid or in islanded mode. The production typically exploits renewable (PV, wind, biomass) and CHP plant. The electricity generated by the microgrid can be the primary source of energy for the community, while the centralized grid provides back-up power when the internal demand is higher than generation. In this first case, the application mainly regards large electricity users that, for economic or sustainability reasons, aim to increase the share of energy coming from cleaner sources. Conversely, the electricity utilized can be mainly the one coming from the centralized grid and the electricity auto-generated is used to cover outages or to support exceptional load. This kind of micro grid is applied when the aim of the communities is to raise the reliability of the systems. For example, to guarantee power quality to priority loads in hospitals in case of high frequency of outages from the traditional grid. In both the applications, the microgrid is used, together with the main grid in order to increase the availability of electricity needed to deliver community services. The lower the reliability of the central grid, the higher the value provided by the microgrid. The tier of service that this categories guarantee is 5.
4. **Interconnected large industrial application**: This category is the case of industrial application located in areas where the grid cannot ensure the total absence of outages. Thus, they can decide to support the electricity provision with a microgrid relying on renewable resources (PV and wind) coupled with diesel generator or storage system. The example for this application is firm for which

the absence of power would means a relevant loss in quality of the output, like precise manufacturing. The level of services is defined as 5+.

In this thesis will be considered autonomous microgrid since are more suitable to the context of rural areas of developing countries. Thus, the focus is on the first row of the table below: autonomous basic services and autonomous full services microgrid.

| Microgrid Typology | Lower tier of service | Higher tier of service |
|---|---|---|
| **Autonomous from centralized grid** | Autonomous basic services | Autonomous full services |
| **Interconnected to centralized grid** | Interconnected community application | Interconnected large industrial application |

*Figure 18, Microgrid classification in function of service level provided and interconnection from centralized grid*

## 3.5 Micro grid operational model

Microgrid can be classified according to the actor who perform the operator role. The main tasks of a microgrid operator are: ensuring the correct functioning of electric system, from generation to distribution, undertaking operation and maintenance of the equipment when necessary and collecting the payment of the fees from final consumers. According to the literature considered are typically defined four possible operational models. There is no "one size fits all" operating model which is universally adopted. The inclination for a configuration rather than another is influenced by factors of different nature, proper of the country considered: environmental, regulatory, economic and social. The operational methods are explained above, according to an analysis of different literature sources. [118], [119], [120], [121], [122].

### 3.5.1 Utility operated

In this case is the national public utility which owns and operate the microgrid. The strength of this model is that utilities can benefit of different resources: technical, financial and legal [121]. The technical competences are given by the experience gained in energy production and distribution activities. Utilities can exploit economies of scale and economies of scope, in relation to both skilled workforce and energy technologies.

The financial advantages are determined by the simplicity that utilities have on gathering public funds for the initial investment [119]. To promote a fair treatment of the final consumers, the policy maker, can enforce the utility to charge, to microgrid customers, a similar tariff to the one applied to users connected to the centralized grid. In order to reach this objective, the government can directly subsidize the tariff of microgrid users, or else, utility can cross-subsidize the micro grid user's whit the fees charged to large consumers connected to the centralized grid [120]. Thanks to the collaboration with government, utilities can count also on legal resources. Legal advantages might be useful, for example, in order to reduce the administrative lead time (period required to receive the necessary permits to start the building operations). On the other hand, the utility operated model, has also some setbacks. First of all, there are evidences in the literature that public owned utility fails in maintaining, over the long run, quality of the service and efficiency in operations [63]. The reasons, for this loss in performance, are typically: an excessive reliance on limited public funds lead to financial losses when these funds become absent or lower; low physical presence of the microgrid operators in the rural areas and rare maintenance of the infrastructures. Furthermore, utilities competences regard large scale energy project. Thus, small-scale off-grid systems, may be far from their core competences.

### 3.5.2 Private sector operated

Traditionally, private sector has been not willing to invest in rural electrification for clear reasons related to the riskiness of the investment which implies difficulties to gather upfront capital. However, in the last years, technological innovation and the spreading of alternative forms of finance (investments which has, as primary objective, the creation of a positive social impact for local communities), are helping the private sector to partially overcome the issue of low capital availability. In this operating model, an entity belonging to the private sectors build and operate the microgrid. The main challenges for private investors are: to gather the capital for undertake the initial investment and ensure that the business model is economically sustainable. In absence of public support, capital invested may come from equity of the firm or loan from banks. Or else, government, recognizing the positive impact that the project generate, can offer grants or capital subsides to private investors. However, the absence of government intervention, can turn out to be an advantage in the operating phase. As a matter of fact, private investors are free to negotiate with the local community a cost-reflective tariff [119]. Thus, achieving commercial sustainability, operators can guarantee quality of the service in the long-term and plan to scale-up the size of the business when needed. On the other hand, after the intervention of the government with subsides, it is likely that is imposed to the operators the obligation to apply a regulated tariff. Respect to the utility operating model, private entrepreneur, being the owner of the systems, are usually more present in site and are likely to have higher attention towards maintenance operation [121]. Considering the disadvantages, it may emerge tensions between the consumers and the private investors in relation the tariff setting process. Moreover, it is important to remark that, private sector, respect to the utility, may have fewer information on the future plans of the government regarding grid extension.

### 3.5.3 Community based model

In this model, a group of users is entitled to set up, manage and operate the micro grid. This solution may be pursued in case that an area is not economically attractive for the private sector and utilities. In order to receive the necessary funds, this model, rely on grants by the government and the communities can offer, in exchange, some non-monetary contribution, like land or labor [118]. In any case, the installation and the design phases, are undertaken by a third parties since the competences needed are not present among the local community [120]. There is positive evidence that, when management responsibilities are left to rural communities, they develop technological competences and decision-making capabilities [122]. Moreover, this arrangement, can be the chance for the population of rural areas to increase the rate of employment considering the new opportunities, in operation and maintenance activities, that microgrid creates. In general, this model, has positive social consequences since, the shared ownership among the community members, contribute to create a positive sense of belonging and collaboration. Moreover, being coincident the energy users with the operators, there is a strong incentive to try to achieve the highest performance possible. Another success factor of this configuration is the capability to cover operating costs thanks to a cost-reflective tariff [38]. Typically, maintenance is outsourced to an external team of technicians [112]. Therefore, the presence of external assistance for the community is a necessary driver for the success of this model. Another pitfall is that it is likely to happen the phenomena known as “tragedy of commons”. It refers to potential abuse of consumption of a public good from some users, can be avoided installing individual meters [121]. Furthermore, conflict may emerge even in the phase of tariff collection. Hence, it is fundamental that a consolidated leadership is established, within the communities, to make the rules respected.

### 3.5.4 Hybrid model

In this case there is a combination of some of the aspects belonging to the previous models. The player who make the initial investments, the legal owner of the micro grid and the operator can result to be different actors. The aim is to mix together the advantages of the others operating models and minimize the negative aspects. These entities stipulate a specific contractual arrangement or set up a joint venture in order to clearly split up roles and responsibilities among each other. Without a proper identification of the roles and tasks among the actors of the systems there is a clear risk of failure [119]. The contractual agreement can be a public-private partnership. For example, it is frequent that the public sector invests and constructs the infrastructure, which are then given in concession to an entity of the private sector that will be in charge of run operation and maintenance activities. For example, the private sector firm can be a RESCO (“Renewable energy service company”), which rely on consolidated technical know-how in the management of the systems but may lack the necessary funds to own and install a microgrid [120]. Another example, of hybrid operating model, is when it is left the “Symbolic ownership” to the local community. As a matter of fact, non-profit sector or public sector may invest into a rural microgrid and entrust the responsibilities for operations to a local committee [112].

In the techno-economic analysis will be considered a private sector operational model. Indeed, as will be also stressed in the next chapter, the role of private sector, to boost rural electrification rate, is recognized as fundamental. In the table below, it is provided a summary of which are the advantages and the drawbacks of each operating models.

| **Operating Model** | **Advantages** | **Limitations** |
|---|---|---|
| **Utility** | -Availability of public funds<br>-Technical competences in energy sector<br>-Economies of scale and scope for technicians, maintenance, procurement, technologies<br>-Legal advantage given by the government | -Public budget is limited<br>-Political pressure for apply a low tariff<br>-Low interest from operators<br>-Scarce maintenance<br>-Distance from utility core business (large scale projects) |
| **Private sector** | -Low pressure from the government, can enforce a cost-reflective tariff<br>-Financial sustainability create the condition for long term planning and scale up | -Difficulties to gather capital from commercial banks<br>-Threat of grid extension that mitigate microgrid utility<br>-Revenues are too low since consumers are low demanding |
| **Community** | -The shared ownership contributes to foster collaboration within the community<br>-Interest from the operators in achieve the highest possible service level | -Technical skills can be not enough in the community<br>-Can be not clearly defined roles and responsibilities<br>- “tragedy of commons”, abuse of the service by some users |
| **Hybrid** | -Interaction among different categories of actor<br>-Combine the advantages of the previous operating models | -Risks of role ambiguity among the actor that operate the system<br>-The default of one actor, expose to risk all the system |

*Figure 19,Advantages and drawbacks of different operating models for microgrid*

## 3.6 Microgrid revenues model

In order to develop a successful business model for rural microgrid, it is important to define how cash inflows are realized by operators. In few words, which revenues model is implemented. It is interesting to understand the difficulties related to realizing revenues in rural areas and how, smart technologies and new methods of payment collection, can overcome these challenges. According to IEA "Energy access report" of 2017, the rise of new business models, based on exploitation of digital technologies and mobile platform can help to increase the electricity access in poorer areas [7]. It is important to bear in mind that, in rural areas, not all the potential demand is automatically translated in revenues for the microgrid operators. This assumption is usually true for business models operating in developed countries, where all the users are generally able to pay for electricity provision. On the other hand, in poorer zones, it is of primary importance to select a revenues model tailored on the context conditions. In this way, inhabitants are able to purchase electricity and the potential demand turns in real revenues. The key issue in operating a microgrid system is to a set an appropriate tariff for the users. More in detail, the problem is that, the fee has to be sufficiently high to let producers benefitting of a certain remuneration and, at the same time, has to be affordable for users which, usually, has a low purchasing power. In order to permit the consumption of low-income consumers, often tariff is regulated by imposing a cap on the price for the final users. Or else, the tariff can be set in a way that privilege energy producers: through a cost-plus method. Usually, the aim of regulation on the electricity tariff for rural microgrid, is to charge the inhabitants of rural area of a fee equal, or a little bit higher, to the one applied to the citizens connected to the centralized grid. However, it is very likely that the cost-reflective tariff is higher than the price paid by main grid users. Thus, in this case, in order to be sustainable, the microgrid operator need to receive payment from the government which can be in form of incentives or subsides [120] .The definition of the revenue model imply the selection of: a way to collect payments and of a method in which the tariff is designed. In the table below it is present a classification of the main method described in the literature analyzed [123], [89], [124], [125], [126].

| MICRO GRID REVENUE MODELS | | | |
|---|---|---|---|
| **COLLECTION MODEL** | **Description** | **Comments** | **Sources** |
| Pre-paid | Electricity is purchased in advance through mobile phone payment, then can be consumed until the credit is exhausted | -Easy for user to not exceed budget<br>-Operators avoid risk of late payment and decrease operating cost for revenue collection | [127]<br>[125]<br>[126] |
| Post-paid | Electricity is billed after the consumption phase | -Not suitable for low-income segment<br>-Risk for energy sellers | [89] |
| 3rd party retailer | Electricity produced by the microgrid is sold to a retailer which manage payments from users | -Microgrid operators avoid carrying out customers relations<br>-PPA guarantees stability of revenues in the long-term | [89]<br>[128] |
| **TARIFF MODEL** | **Description** | **Comments** | **Sources** |
| Consumption based tariff | The electricity bill is proportional to the consumption | -Fair respects to users that withdraw less<br>-Suitable for fossil fuel micro grid (high variable costs) | [119] |
| Fixed Fee | The payment is not function of the consumption but is fixed | -Suitable for PV microgrid (high fixed cost)<br>-Adapt in off-grid application, when there is limited capacity | [125] |
| Hybrid tariff | Implies a fee which is composed by both a fixed component and a variable one | -Fixed parts should cover fixed costs<br>-Fair respects to users that withdraw less | [89] |
| Fee for service | Payment is linked to the provision of a service: like charging mobile or batteries | -Delivered at energy kiosks in non-electrified<br>-Payment is ex ante defined but imply transportation cost and time | [120]<br>[126] |

*Figure 20, Overview of microgrid revenues model*

### 3.6.1 Tariff models

#### Consumption-based tariff

This tariff is based on the effective energy consumption of the users and it is the closest way respect to traditional electricity billing. According to this method the electricity bill is proportional to the kWh of energy withdrawn from the microgrid [119]. At first sight, this method, appears to be fair toward consumers since, the ones who use more electricity, will pay more at the end of the period considered. The consumption-based tariff may also be applied in the time-based modality. In this case, the unitary fee, changes according to the time frame in which the energy is consumed. The mechanism aims to disincentivize electricity consumption in hours with the largest demand, so as to prevent that load overcome supply.

#### Fixed charge tariff

Consumption-based tariff has some limitations when it comes to rural microgrid application: limited electricity production; important share of fixed cost; cost for electric meters, necessary for consumption-based tariff, enhance investment costs [125]. Explaining more in detail, foremost, the amount of electricity that the system is able to produce is limited by the size of the plant and, in case of intermittent renewable source, generated quantity can be function of weather conditions and seasonality. Thus, it is needed a billing system which place a cap on the amount of electricity that it is possible to receive from the microgrid. Moreover, in case of RES technologies, there are high fixed costs and low variable cost, since there is no impact of fuel cost and lower impact of maintenance costs (especially for PV). For instance, fixed costs, are determined by the loan cost for financing the initial investment which is typically high. Basically, it is possible that, the costs (being fixed) generated during a period by a RES plant, do not reflect the real earnings of electricity sold by the microgrid. Conversely, the energy consumption-based tariff, can be more appropriate for a diesel powered microgrid, where it is more relevant the share of variable costs (fuel cost and maintenance cost) and these costs are directly linked to the amount of electricity produced. To overcome the negative aspects of consumption-based tariff related to microgrid, can be applied a fixed fee to be paid by users in each period. In this way, the expenses for the users, can be tailored to cover part or the totality of fixed costs allocated in a period. The fixed fee may be calculated on expected energy needed to power a certain set of appliances [89]. Furthermore, the fixed tariff, can be set according to the value of the maximum quantity of electricity that each consumer can withdraw, to prevent overconsumption. When the electricity taken from the grid exceed the established quantity, the users may be charged with a penalty. Another advantage of fixed tariff model is that it seems easier, even from consumers point of view, to monitor electricity expenses.

### Hybrid tariff

An intermediate solution between energy based and fixed fee tariff is the hybrid tariff. It works by defining a fixed fee which permit to users' consumption a certain amount of kWh. Then, after this threshold, the electricity is exchanged according to an energy-based tariff. The fixed fee has the objective of covering fixed costs and, at the same time, the users who withdrawn less electricity do not subsidize the higher consumers [89].

### Fee for service tariff

Finally, fee for service tariff, it is based on the payment from the users of a sum, ex-ante defined, in exchange of a service, which can be, for example, the charging of a mobile device or of a portable battery [120], The service is delivered in some points, the charging stations, also called energy kiosks. Energy kiosks business model is similar to a retailer where are provided energy services. Hence, are an in the middle between having no electricity at all and having the houses interconnected to the grid (centralized or decentralized). In energy kiosks it is possible to charge large batteries that can provide lighting service to a householder for different days. However, the travel to the kiosks can be a time-consuming activities and lead to additional costs for transportation. The load profile of the charging stations is different to the typical one of householders. Indeed, kiosks require electricity availability during working hours (typically from 9 to 17 h). Hence, are optimal to exploit PV technology. The payment is generally undertaken with cash, after the charging service. The fee-for service tariff is defined through ex-ante established criteria, different from the energy consumption. Some examples of criteria are the size of the battery or the charging time [126].

### Break-even and profitable tariff

Regardless of being energy based, fixed, fee-for service or hybrid, tariff can also be classified according to the economic objective in: break-even tariff or profitable tariff. The first does not foresee any positive return from the operations, but only to recover costs. It is usually employed in community operated microgrid, where there is a very flat and collaborative organization, without business purpose. The profitable tariff, instead, is set in order to ensure remuneration to investors. Thus, it is applied in case of private sector operated microgrid [119].

## 3.6.2 Collection models

Independently on how the tariff is set, the revenues models are described even in function on how the collection of the fees from users take place. This process can turn out to be very tricky in rural areas: the difficulties are due to economic factors, related to the low income of consumers, and logistic factors, which derive from the low level of development of infrastructures [89]. The payment can be collected ex-post respect to the consumption phase or ex-ante in case of pre-paid collection model. The former mechanism is the commonly employed in developed countries, where, the electricity bill of certain period, is paid by the users after having consumed the electricity itself. On the other hand, it is always more frequent in literature concerning sales of electricity in rural areas, the pre-paid collection models. The electricity is purchased in advance, and then can be consumed by the users until the credit is pulled off [127]. Thus, the principle is similar to the one of pre-paid cards for mobile phones. This method is enabled by pre-paid meter, which are more costly than conventional one but reduce operating cost, reducing the effort needed for revenues collection and monitoring consumers [125]. As a matter of fact, pre-paid meters, enable the microgrid operators to perform remote control of the payment thanks to the telecommunication network. Thus, the operators are not forced to travel to the microgrid location on a regular base. More in detail, this method works with the users that purchase a scratch card. The card provides a code which has to be send, through SMS, to the central server that activate, sending a signal to the meter, consumption of electricity for the householder. Then, when the credit is almost exhausted, the software automatically advises the consumers through an SMS. In this way, the users can purchase additional kWh, or reduce at the minimum the usage [124]. The advantages are both for users and microgrid operators. As a matter of fact, the firsts are able to manage their expenses in a better way, undertaking the purchasing only when funds are available and being sure of do not consume more than the budget [123], [126]. For example, this method is particularly suited to face irregular income linked to agricultural production. The sellers, instead, are protected from the risk that consumers fail or delay in making the payment. Moreover, by ex-ante managing the sales, microgrid operator can set a certain load limit to each user, avoiding of incur in brownout when consumption exceed capacity [123].

### Sale to 3rd party retailer

The payment of the users can be collected by the microgrid operator into an indirect way. The collection model which mostly reduce the risk for micro grid operator is based on the sale of electricity to an independent retailer. Then, this entity, is entitled to retail energy to final consumers. In most of the case the retailer is financed by government funds for electrification programs. The contract, stipulated between the retailer and the micro grid operator, is a long-term contract called power purchasing agreement (PPA). This typology of contract works by defining in advance a fixed price, or a fixed algorithm to set the price at which the electricity is remunerated to the producers. This contract is used by the state in order to incentivize generation of electricity by privately owned microgrid. Indeed, the microgrid operators enjoy a premium price and are not in charge of collect fees from final users. Moreover, a PPA contract established with state, increase the willingness of banks of finance further investment into microgrid generation plant. The PPA contract may protect microgrid developers also towards the risk of low demand, in order to cope with the typical low load of rural areas. For this purpose, the contract has to ensure that a minimum quantity for each period is bought by the retailer [89]. There is evidence of this mechanism in the policy of African state. For example, Kenya introduced in 2010 a feed-in-tariff remuneration of 0,20 USD/kWh for a duration of 20 years, in order to incentivize off-grid power producers leveraging on PV [128].

# Chapter 4: Private sector investment in rural microgrid

## Analysis of barriers and opportunities to boost private sector penetration

After having introduced, in the previous chapter, the different possible operating models, the focus here is directed to the role of the private sector investment in rural areas electrification. From literature review, it emerged that the role of private sector investors is considered necessary in order to pursue higher share of rural electrification [59], [89], [55], [129]. As a matter of fact, the public sector has been able only in part to realize small scale off-grid project, since government of developing countries are subject to rigorous budget constraints. Moreover, as said in a previous paragraph on the utility operating model, public sector fails in guarantee elevated performances in the long term. Private capital, instead, can be the solution for finance capital intensive electrification project. Thus, the aim for entity promoting rural electrification (institution, rural electrification agency, international organizations) should be to mitigate the barriers that prevent private investments.

## 4.1 Barrier for private investment

Barrier for private investment in rural microgrid can be subdivided in three categories, according to Williams et al. [89]: Financial, technical and regulatory.

### 4.1.1 Financial barriers

Every decision-making process regarding a private investment imply a balance between the risk and potential return. To reduce the risks, it is important to secure a stable revenues stream to cover operating costs, repay debt capital and guarantee positive return to investors. However, rural areas inhabitants have typically low ability to pay for the service. Indeed, the income level is very low or null and, if present, may be subject to seasonal variability according to the cycle of agricultural production [130]. In synthesis, demand for electricity can be variable, and moreover, it is also difficult for project developers to estimate the electricity demand for communities that have never had energy provision. A correct demand assessment is important otherwise, if the demand is overestimated, the microgrid is likely to generate losses while, if it is underestimated, the result is a poor service level for users. For all these difficulties, may be needed years in order to reach the break-even point and many projects reach the bankrupt before starting to generate positive profits. Other uncertainties derive from the context, in developing countries it is usually turbulent, with high level of political instability [131]. The consequences of riskiness and uncertainties in these projects are that gathering third parties financing is typically tricky for developers. Commercial banks are not willing to accept to finance investment which has an elevated riskiness [132]. When they accept, they fix very high interest rate that are not feasible for developers. Banks, usually, struggle to accept to finance micro grid in the early phase of the project, when the uncertainty is higher. More frequently can accept to provide capital for further development in a second moment, only when the business model is consolidated and generating positive returns.

Project developers may try to gather funds from foreign banks rather than local one. However, in this case it is interesting to analyze the issues related to the difference between local currency and hard currency. The revenues realized by micro grid are in the currency of the local areas while the larger part of the funds is received in hard currency [133]. The capital received is in foreign currency since, the local bank institutions, as said before, or do not offer loans at all or can pose very hard requirements in terms of collateral and interest rate. The immediate implication of this unbalance is that the micro grid may lose value if the local currency is devalued respect to the hard currency. If this happen, the micro grid owner may be unable to repay the hard currency loan. Moreover, is typically not possible to face this problem with an increase of the tariff charged to the final users. Indeed, the users could be not able to pay an augmented price and, in case of regulated tariff, the government may not tolerate a higher tariff for the users. One possible solution to this issue could be the natural currency hedge. For example, a micro grid that realize large revenues in a country, can achieve a natural edge on this currency in case the micro grid operator also undertakes operating costs in this specific country. An alternative, for the micro grid developers, could be to take capital in hard currency and acquire a hedge product in order to cover the risk of local currency value loss [134].

### 4.1.2 Regulatory barrier

The role of local authorities for stimulate private investment is fundamental [100], [129]. According to a survey analysis carried out by Rodriguez, the 70% of the sample pointed out that “support from institutions” and a “favorable regulatory framework” are among the main driver to increase private investment in rural electrification projects [135]. Policy maker must consider the need of the investors and foster social impact creations for householders. The firsts aim to set a cost-reflective tariff plus remuneration, while the latter, require that the electricity is affordable and hence, that the tariff is regulated. Thus, policy maker must find a trade-off between the exigence of the private sector and the ones of the rural communities [134]. Relationship between tariff law and private investment has been studied by Marandu et al. [136]. Another barrier that discourage private investment for electrification is the time and the effort needed to receive the necessary permits and concessions. Policy maker should try to speed up preliminary administrative procedure to mitigate investor hidden costs. Furthermore, another threat for investors is related to the risk of sudden policy change. Rules can be modified and become less favorable for the investment profitability. This is the case of incentive mechanism for renewable production, which are very important to reach financial sustainability, but can be reduced or eliminated by government [137]. Thus, a clear and stable in the long-term regulatory framework seems necessary to promote private investment [56].

### 4.1.3 Technical barriers

The project design phase for rural microgrid is extremely complicated. In isolated system the impact of demand variability is higher than in centralized electric system. Moreover, the eventual presence of RES in microgrid generation resources, additionally increase the unpredictability of operations. Thus, in design step, it is not easy to find the right combination between the provision of a high-quality service level and the costs for generation capacity. Many projects failed since in project design phase lack to consider worst-case scenario. For example, in sizing a PV microgrid most of the estimation are based on dry season irradiation value which are higher than the average ones [56]. The building phase also implies difficulties in searching for quality materials, that cannot be available on local market of developing countries. Another technical barrier regards the low densities of houses in rural area. For this aspect, the unitary distribution cost is elevated and entrepreneur willingness to invest is reduced [138]. After the installation phase, technical difficulties arise also in the operation phase. Many off-grid projects suffered the absence of frequent maintenance [139]. Private entrepreneurs may find tough to gather technical skills in rural and developing areas. Lead times for receiving maintenance services or parts replacement can be long and cause stoppage of the energy generation for a while [55].

| Barrier for private investment in rural electrification projects | | | | | |
|---|---|---|---|---|---|
| **Financial** | | **Regulatory** | | **Technical** | |
| Barriers | Sources | Barriers | Sources | Barriers | Sources |
| Low income of potential users, low revenues | [130] | Regulated tariff is not cost reflective | [134] | Low population density | [138] |
| Commercial banks are not willing to take risks, lack of capital | [132] | Regulatory framework perceived unclear and unstable | [56] [135] | Difficulties in project design: variable load and RES production | [56] |
| Revenues can be realized in local currency while loan are in hard currency | [133] | Sudden policy change (incentive support) | [137] | Absence of technical skills for maintenance | [139] |

*Figure 21, Summary of financial, regulatory and technical barriers preventing private investment in rural microgrid*

## 4.2 Solution to promote private sector investment in microgrid

In the following paragraphs, starting from the barrier defined in the previous paragraph, are analyzed which are the opportunities that can permit to overcome these challenges and, thus, attract private investment in microgrid rural electrification project. The opportunities are subdivided in three categories. First of all, are listed the mechanism used by the government in order to incentivize private investment. Then, are taken into account the new opportunities delivered by the social impact investing. Finally, are listed strategic opportunities for microgrid business models.

### 4.2.1 Public mechanism to incentivize private sector investment

In this part are explained the main tools employed by local government to help investors to overcome barriers. These mechanisms are mainly directed to face financial barriers like lack of capital and low revenues. Are analyzed: subsides (capital and operating), tax incentives, loan guarantee, preferential lending and concession from government.

#### Subsides

Local authorities are likely to directly provide capital, in the form of grants or subsides, to project developers helping them to overcome financial barriers and promoting the competitiveness of clean generation technologies [140]. Source of grants and subsides are local government and international organization for development. There are different typologies of subsides. Capital subsides are more appropriate for financing microgrid based on RES. For this kind of plants, the investment cost is the main financial hurdle, while fuel costs are absent and maintenance cost are typically low [121]. However, the full coverage of the investment costs from the government is rare, since developing countries lack of public funds. A case of capital subsidy program is "*Luz para todos*", promoted by Brazil in 2003, with an objective of reduce the 12 million people who, in that period, was without electricity provision. The project was ground mainly on grid extension, however, for 250000 householders the extension of the grid was judged economically or technically unfeasible. Thus, for these people was arranged capital subsides for microgrid projects. The government offered the coverage of the 85% of the initial investment as subside for microgrid based on RES [141]. Subsides on operating costs, instead, are suitable for microgrid which work with fossil fuel generation, like diesel. The cost of fuel procurement may be sustained in part by the state. In this way, the impact of fuel cost on total operating cost is minimized, and the tariff become more affordable for users [1]. Subsides on diesel, are largely used in Indonesian islands which make use of diesel generator for electricity. The drawbacks of fuel subside is, obviously, that do not incentivize the switch to cleaner source of generation [129]. Another form of operating subside act directly on the tariff, rather than on fuel cost. Subsidization of the tariff is implemented introducing a state financed retailer. This entity purchases the electricity from the microgrid owner and, then, resale it to final consumers at a lower price [142].

It is important to remark also the negative aspects induced by subsides. Foremost, an excessive capital aid to the private investors, may induce less care in pursuing efficiency and innovation in project design phase. Furthermore, if the subside is allocated only to specific technologies, it may lead to prevent the diffusion of other ones. This happened in Nepal, where an excess of subsides on PV and Hydropower, caused that wind market has been penalized, even if there is a good wind potential in the country [140]. Another problem with subsides financing mechanism, is that entail high transaction costs for receive the funds. A frequent issue is the delay in capital outlay by the funders, especially in case of governmental grants. Difficulties arise since, between project developers and authorities in charge of distribute subsides, is made a contractual agreement which has low level of flexibility. Instead, the development of a microgrid, is likely to face technical unforeseen events which can slow down the development or require an unexpected amount of money and, so, it is not possible to respect the contractual duties with the authorities [134].

### Tax incentives

Policy maker can use fiscal incentives to provide financial support to microgrid project. It is a less direct support means than subsides which aim to reduce financial burden on microgrid investors. Taxes paid by developers may be subject to exemption or reduction. Frequent incentives in developing countries act on import duties for microgrid technologies since there aren't internal producers able to supply these specific tools [143]. If not reduced, import duties account on average for the 21%, considering a PV system [13]. An example from literature of this technique concern the island Comoros, where the government guaranteed 3 years without import duties on PV component, so as to boost installation [144]. Other solutions are: the abatement of VAT on microgrid technologies or on the electricity sales. The first solution reduces investment costs for developers, while the second decrease final tariff for users. China and India are examples of countries which reduced VAT in order to promote rural electrification with RES plant [145]. One of the pitfalls with tax deduction scheme is that it is not easy to monitor if, the equipment which benefits of the incentives, is employed in an electrification project or is used for other purposes. For example, electrochemical storage systems can be used for different applications [89]. Another incentive related to the fiscal dimension is the accelerated depreciation. It works by allocating a larger quantity of the investment cost in the first accounting periods, and then a smaller fraction to late periods. Hence, the aim is to boost profit in the first years after the investment (paying taxes in a lower extent), shortening payback time [146].

### Preferential lending and loan guarantee

Considering the difficulties perceived by private investors in receiving capital from banks, other solutions that government or development banks can implement, are the direct provision of preferential lending and loan guarantee [134]. Preferential lending works by offering capital to project developers at an interest rate lower than the market one and allowing them to repay back the debt in a longer period than usual. In the past, Chinese government strongly adopt this technique in order to finance rural electrification project for areas close to Tibet [40]. This kind of loan is suitable when the project promises high return, economic and social, but it is considered too risky from commercial banks [89]. As far as concern loan guarantee, it is a warranty offered by guarantor to private borrower to repay part of the debt capital in case of borrower default. The presence of a guarantee, by a third party like government or international organizations, may increase the bankability of the project [78]. Partial risk guarantee provided by The Word Bank for simplify the financing of rural power producers in Kenya and Nepal [147], [148].

### Concession from the government

Concessions to distribute electricity to a specific rural area is a non-monetary measure which can be used to reduce the risks and incentivize private sector investment. Once received the concession, the private company can benefit of a monopoly position over a defined geographic area. In exchange the private company, owner of the permit, must respect some contractual rules, like the provision of a non-discriminatory connection to the grid of all the householders belonging to the area. However, the demand for concession can be low in particularly unprofitable areas, for all the difficulties stemming from the implementation of successful business models in these places. In this case, the solution could be to bundle together the concession to distribute electricity to urban areas, densely populated, with the obligation to serve rural area through off-grid project. Or else, the concession can be assigned to group of villages, close to each other in other to develop project that can profit of scale economies [54]. A successful example of this strategy is the PAEPRA program for rural electrification promoted by Argentine government. It was based on the subdivision of the users of each province in: concentrated (urban), grid connected and dispersed off-grid costumers. When the permission to distribute electricity to a province was assigned to a company, it took the task to serve all the category of consumers [144].

| Mechanism | Strength | Weakness | Case studies | Sources |
|---|---|---|---|---|
| **Capital Subsides** | Reduce upfront investment, ideal for renewable off-grid plant | Are not an incentive to pursue efficiency, risk of market distortion | "*Luz para todos*" project in Brazil,85% subsides on capital cost | [121] [141] |
| **Operating subsides** | Reduce operating costs, tariff become affordable for users | Risk that subsides may be removed over time | Diesel subsides in Indonesian islands | [1] [129] |
| **Tax incentives** | Decrease financial burden on project developers reducing import tax or VAT | Reduced revenues for government | Island Comoros reduced import taxes on PV foe 3 years | [143] [144] |
| **Preferential lending** | Loan at lower interest rate and higher repayment time than market | Additional costs of financing by third party provider | Chinese government to promote off grid project in Tibet | [40] [134] |
| **Loan guarantee** | Warranty on loan in case of receiver default, increase bankability | Government bear risk and costs of project | World Bank secure loan for in Nepal and Kenya | [147] [148] |
| **Concession from government** | Monopoly position on a given area | Remain low interest of investors towards rural areas | PAEPRA program in rural Argentina | [54] [144] |

*Figure 22, Mechanism useful to incentivize private investment in rural electrification project*

### 4.2.2 New opportunities for finance micro grid: social impact investing

In order to cope with the barriers described in the previous paragraphs, are becoming available for developing countries new models of finance that can simplify the task of gathering capital for micro grid developers. Moreover, mechanism like microfinance, can also promote the growth of demand, allowing low-income users to acquire energy services. These new models of financing are based on the concept of social finance. Social finance encompasses to invest economical resources in order to pursue, as first objective, the environmental and social impact and, in some cases, even financial return. A subset of the social finance is the social impact investing. The idea on which is grounded the concept of impact investing is that can be achieved financial return while, at the same time, generating a positive social and environmental impact. Thus, it is a strongest form of social finance. This trend come from the match between the traditional finance, purely profit driven, and the philanthropy, which instead is purely social impact oriented [149] . The mindset of the traditional philanthropist is changed: just donate money is not perceived anymore as economically sustainable and valuable in term of generation of the intended social impact. As a matter of fact, donation effects are destroyed in few years if the money are not invested in creating a replicable and scalable business model, which is capable to provide benefit to the communities, while operating with financial discipline [150].

The ideas of social finance and social impact investing are practically applied using the following innovative means of financing: social impact bond, crowdfunding and microfinance.

#### Social impact bond

Social impact bond (SIB) is an instrument which aim to finance interventions trusting on a performance-based contract. The contract is stipulated between the government and investors into a project aiming to provide social or environmental benefits to a certain part of the population. SIB, thus, rely on concept of "Paying by result". According to this method, the capital disbursement by the founder is linked to the achievement of some specific project objectives, ex-ante defined. In this way, the risk of failure, shifts from the financers to the actor who receive the capital for implementing the project [151]. The latter, would be highly incentivized in pursuing the project goal, looking for the exploitation of innovative and efficient solutions. The idea behind the concept of SIB, is to attract private sector to invest in activities which are traditionally managed by public sector. Indeed, private sector has less capital constraint than government budget and will pursue cost efficiency and innovation in trying to achieve the objective [152]. The functioning of the SIB mechanism is the following. It is stipulated an agreement between the government and an intermediary, who is in charge of collect capital from private investors and offering in exchange bonds. The money will serve to finance a social impact project which the government judge as relevant, like for example a rural electrification intervention. To the project is associated an expected outcome. If this objective is realized, the government repay back the investors plus a certain positive rate of return [153]. Considering rural electrification programs, this mechanism, allow the government to mitigate the risk of finance unsuccessful projects. The private investors, instead, can be interested by the opportunity to fully recover the upfront capital in case the project turn out to be successful. An example to link the deployment of SIB to rural electrification regard "Uneme Ltd", an electricity distribution company operating in Uganda which received, with this mechanism, 20 million US $ in order to extend the grid and increase electricity access [154].

### Microfinance

Microfinance represent a win-win solution to, at the same time, fight poverty and develop financial institutions. The aim is to provide access to finance to the people which generally do not have possibility to request a traditional loan, since are not able to offer collateral and do not have a credit history. The micro finance instead of using collateral, is based on the formation of groups of credit receiver, which are commonly called "group-lending". Thus, the lenders pool a group of borrowers together that co-sign the loan. Financial institutions (NGO, saving banks and commercial banks), by setting up the group, reduce transaction cost which, instead, are high when lending to a single customer [155]. Since the positive outcome of the group program is achieved if everyone repays back the loan, is created a form of peer to peer collaboration to reach the common objective [156]. In order to have access to the micro loans, usually is required that the recipient attend some classes in which are explained the basic principles regarding interest rates functioning and economics. The microfinance projects turn out as a success in different countries: in literature emerges repayment ratios between 95% and 99%, which are similar to the average value of traditional banks sector. As far as concern the quantity, Micro loans has an average size of 288$ in Africa, 495$ in Asia and 888$ in Latin America [157].

Microfinance can be helpful to increase energy access in developing countries. Low income inhabitants of rural areas can collect the needed money for purchasing a solar home system, to cover the costs for micro grid connection (where available) and purchasing electrical equipment. In particular, the energy products may be offered jointly with the microcredit. In this case the player which offer micro credit establish a partnership with the energy service providers in order to provide a complete supply of both financing and energy technologies. Thus, microfinance is a way to pull demand, allowing low-income users to purchase energy services. The energy service provider also offers technical support and education on the function of the devices [158]. This collaboration has been implemented in India by SELCO, an energy supplier which commercialize solar home systems, solar lantern, solar battery charging and efficient cookstoves, and SEWA, a microfinance organization [159].

### Crowd funding

Crowd funding is a financing method which works by collecting small amount of money from a large number of people, instead of gathering the capital from a small number of wealthy funders [160]. The money collection process is enabled by internet platform, where project developers describe their objectives and the amount of capital that aim to gather. This mechanism differs from traditional fundraising methods: there is, usually, an active engagement of the crowd of capital provider into the project and the emotional factor is an important driver for the funders. Investors, thanks to the internet platform, can monitor the ongoing progress of the project and, in some cases, even provide suggestion and sharing information with developers [161]. The crowdfunding mechanism can be implemented in four different models. According to reward-based crowd funding, the funders are provided with an award in exchange of the capital granted to the project. The reward can be a physical product, that it is possible to produce relying on the capital of the donors. The equity-based models, instead, is based on the provision of shares of a start-up to the financers. The donation-based methodology, in which money are transferred from the funders as a result of a charitable action, hence without receiving anything as return. Finally, the peer to peer lending model is a loan among individuals with an interest rate lower than the market one [162]. Micro grid developers can see in crowd funding an opportunity for gathering low interest capital. Moreover, thanks to the utilization of an internet platform, transaction costs, which arise usually from the research of funds from banks, are minimized. As a matter of fact, through the online platform, are removed the intermediaries between investors and entrepreneur. Furthermore, the individuals voluntarily donate their money when feel engaged with the project's mission [146]. Crowdfunding is used by "Sun Funder" to finance small scale, off-grid solar projects in remote areas of Africa [163].

In the table below are listed the main features of crowdfunding, social impact bond and microfinance.

| **Mechanism** | **Strength** | **Case studies linked to rural electrification** | **Sources** |
|---|---|---|---|
| **Social impact bond** | -Payment by results: government pays only if the outcome is achieved<br>-Stimulate innovation in achieve the objective | Uneme electricity distribution company in Uganda | [151] [152] |
| **Crowdfunding** | -Low transaction cost thanks to internet platform<br>-Emotional engagement of the funders<br>-Low interest rate capital | SunFunder in rural Africa to finance off-grid solar project | [160] [161] |
| **Microfinance** | -No usage of collateral<br>-No credit history is required<br>-Peer to peer collaboration | Selco and Sewa in India offering SHS jointly with microfinance to low income users | [155] [156] |

*Figure 23, Overview of new financial mechanism that can facilitate rural electrification project*

### 4.2.3 Strategic opportunities for micro grid business models

As said in the chapter on the barriers, private investors in microgrid, find difficult to scale up the activities due to the low level of cash inflow respect to the amount of the operating costs. However, the following strategy can be helpful in order to pursue or a reduction of operating costs (franchise and clusters approach), or an enhancement and stabilization of revenues (anchor load model).

#### Anchor load model

One of the barriers that, usually, prevent to develop an economically sustainable business models for rural microgrid is the lowness and variability of demand of these areas. Without a consolidated demand it is difficult to recover the investment and cannot be made plan for future expansions. Thus, the aim of this model is to couple one microgrid serving a village of householders with a large consumer, like a telecommunication tower, a gas station or a small rural firm [164]. In this way, it is possible to ensure a stable demand to the operator allowing to recover the investment cost. Moreover, the presence of an anchor load increases the possibility to collect funds from banks and can be a source of employment and local economic development [29], [165]. An ideal anchor load consumes electricity during all day. Hence, contribute to enhance the average load of the system. The householders load profile is, instead, concentrated usually in the evening timeframe. In these hours is determined the peak load of the system. Supposing a generic load curve (graph expressing the electricity demand (W) for each hours of the day, so that the area below the curve give the total amount of electricity consumed in kWh) can be introduced the concept of load factor as [166], [167]:

$$Load\ factor(LF) = \frac{Average\ load\ (W)}{Peak\ load\ (W)}$$

Where the average load is defined as [166]:

$$Average\ load = \frac{Area\ \ under\ daily\ load\ curve\ (kWh)}{24\ (hours)}$$

The electric grids are usually designed in order to deliver electricity in correspondence of peak load hours. Thus, it is cheaper to distribute energy to system with a high load factor since electricity unit cost is lower [168]. The closer LF is to 1, the higher the economic convenience. Since the anchor load improve the load factor, by enhancing the average load, it brings economic advantages to the energy firm. According to Robert et al. the LCOE can be reduced of the 48%, in a PV based microgrid, where the anchor load account for the 30% of the total load, [21]. Moreover, anchor loads, contribute also to reduce energy wastage. Without anchor customers, the energy wasted is almost equal to the useful energy, despite of large investment in storage system. To the player which set the contract with the microgrid operators can be offered fiscal incentives to become anchor load. Furthermore, the anchor load can receive a reliable source of energy that, in some areas, the centralized grid cannot guarantee. The other side of the coin, with this model, is that for the dwellers will be available only the residual power not consumed by the anchor load. The role of anchor load, in developing a microgrid business model, will be analyzed later on in techno-economic analysis.

### Franchise approach

The objective of this method is to reduce the operating costs sustained by microgrid operators. As a matter of fact, according to this method, the management costs of a rural electrification projects are borne by a central company, the franchiser, that is able to sustain these expenses at a lower marginal cost exploiting scale economy. The tasks sustained by a revenue franchiser, as defined in India [54], on behalf of a small power distributor are: billing, payment collection, management of complaint and monitoring of the distribution network. The franchisor is remunerated with a certain share of the earnings. This method was previously only applied for distribution companies operating in urban areas. Afterwards, having recognized evidence that this method enhances distribution effectiveness and quality of the service, has been also applied to rural areas [169]. Franchise approach has been implemented mainly in India where currently can be estimated 37000 franchisors to which can be linked 200000 villages as franchisee [120]. An example of the implementation of this method is Husk Power Systems. This company offers to local private entrepreneurs in microgrid contract called BM (Build and maintain), which foresee that the central company support the project in the phase of project design and operations [170].

### Clustering approach

Clustering approach is similar to franchise approach. Even in this case the aim is to exploit synergies and economies of scale in order to face the usual small-scale of rural microgrid projects. The idea in this case is the collaboration, sharing some costs stream, among different villages located close to each other. The advantage can be achieved in term of maintenance cost having, for example, just one technician working across different villages of the cluster. The approach can also have advantages for what concern transaction costs linked to the process of achieving incentives from government or funds from banks [171], [170]. Other advantages are that the cluster can attract the interest of investors for further development and can negotiate better deal with suppliers [169]. On the other hand, this method, cause also an increase of the organization costs for the coordination among different microgrid operators belonging to the cluster. In order to be economically convenient, the benefit stemming from the decrease of the operating costs must overcome the additional coordination costs [120]. An interesting application of this business model regard a cluster of microgrid that take advantage of geographic characteristic: the cluster is formed by 9 run of the river hydro power plants which are located along the same river in Zambia [172]. The formation of cluster has been successfully implemented by the agency for Indian rural electrification, CREDA, which exploit a model called “Cluster based service delivery model”. According to this method, the cluster technician visits each plant on a regular basis, supervising the operation and reporting results to the agency [170].

| Strategic opportunities | Strength | Case studies | Sources |
|---|---|---|---|
| **Anchor load model** | -Ensure stability of demand<br>-Enhance LF, reduce unitary cost of electricity<br>-Minimize energy wastage shifting consumption during daylight hours | Study on the introduction of telecommunication tower representing the 30% of the load in an Indian rural microgrid | [164], [21] |
| **Franchise approach** | -Decrease operating costs of a microgrid<br>-The franchiser performs: billing, payment collection, management of complaint and monitoring of the distribution network | Husk Power system provide “build and maintain” contract to franchisee, which are local investors in microgrid | [54], [120] |
| **Clustering approach** | -Collaboration between close villages<br>-Scale economies exploitation<br>-Benefits in negotiating with government and suppliers | CREDA, Indian rural agency delivers O&M services to plant belonging to the cluster | [171], [169] |

*Figure 24, Overview of strategic opportunities that can be useful for microgrid developers in order to reach financial sustainability*

# Chapter 5: Other Options for Rural electrification

**Analysis of grid extension and stand-alone solar systems.**

Microgrid are not the only way to extend electricity access towards rural areas. The extension of the centralized grid and the installation of stand-alone systems remains two valuable options. In this chapter, the aim is to analyze these two opportunities, trying to compare them with a microgrid project and fixing which are the driver that determines the choice for an option rather than another.

## 5.1 Centralized grid extension

Although the rapid diffusion of stand-alone and microgrid solutions for rural areas electrification, one of the options considered by the policy maker remain the extension of the centralized grid. A centralized electric system is characterized by large power producers, which delivery electricity to a wide number of consumers through a branched network. The production is based mainly on fossil fuel plants, large hydropower plants and, more rarely, also nuclear power plants in developed countries. The electricity network is articulated in two different levels: transmission and distribution. In the first tier, the electricity flows, through high-voltage lines (more than 115 kV), from injection points (importing nodes or generation site) to substations or towards eligible consumers, that withdrawn the energy directly from transmission network. The second level, instead, transport electricity from substations to final consumers through a medium voltage network (ranging from 4 kV to 35 kV) and, finally, a low-voltage network (120-240 V) [173]. Centralized, large-scale production enable to produce electricity at lowest marginal cost, thanks to advantages given by scale economies. Obviously, this is true comparing costs of centralized and distributed generation applications that leverage on the same energy source.  Moreover, centralized solution has the highest capability to face an increase in electricity demand [82]. Grid extension in rural areas may be enabled by the diffusion of the so called “skinny-grids”. This typology of distribution network is based on the exploitation of thinner and less expensive wires. This possibility has been enabled by gaining in energy efficiency. As a matter of fact, the amount of power required to provide householder basic services is drastically reduced in the last years. For example, modern LED lights account for only 5 W, while traditional fluorescent lamps have power equal to 100 W. Thus, basic services can be satisfied with few watts that can be transported across cheaper (1-2 $/m) transmission lines. Obviously, the reduced thinness increases the energy losses. Hence, has to be find a trade-off between the two dimensions, energy losses and cheaper wires [174].

Nevertheless, the centralized systems lead to some inefficiencies especially when it comes in relation to developing countries. Foremost, transmit electricity over long distances, imply significative losses that impact on the total cost of electricity. For instance, in USA the value of transmission losses is equal to 8%, while in developing countries this percentage is usually much higher: 37% in Venezuela, 20% in India and 23% in Ghana are some examples [4]. In developing countries, the overall value of energy losses, it is raised also by a more frequent presence of non-technical losses. This typology of losses is due to thefts and frauds, that is to say, energy which is illegally withdrawn from the network or users which own equipment able to register lower level of consumption than actual one (practice also known as "tampering") [175]. One weakness of centralized grid in developing countries regard the reliability which is often low. The causes of low reliability are the presence of aged infrastructure, infrequent predictive maintenance operation and not enough network capacity to face a growing demand [45]. Especially in Sub-Saharan Africa, the high frequency of power outages reduces the utility of the central network for commercial and industrial purposes [82]. Moreover, since are necessary large investments for transmission network, centralized model is not cost-efficient in area with low demand and when long distances must be covered in order to reach a specific group of loads [51].

### 5.1.1 Cost for grid extension

The possibility of extending centralized grid to currently unelectrified areas has to be pondered through an analysis of the necessary costs and the expected benefits. The costs to be sustained for expand the grid is function of the distance of the load from the closest point of the existing grid and the nature of the terrain to be crossed , the cost of distribution transformer and operation and maintenance costs (function of the local cost of labor) of the new part of the grid [29], [176]. In order to calculate the LCOE for electricity delivered through the centralized grid, is needed to sum three different components: electricity generation LCOE, electricity transmission LCOE and electricity distribution LCOE [24], [177], [176], [178]. However, it is important to make an important accounting consideration. The larger share of cost considered in the case of generation and transmission LCOE calculation are operating and maintenance cost. As a matter of fact, the energy production plant and transmission network are supposed to be already present in the moment in which grid extension is evaluated. Thus, in the initial investment for transmission and generation is not "differential" respect to the grid extension scenario. On the other hand, the investment for construct a new part of the distribution grid, in order to reach the rural area, is assumed to be undertaken at the beginning of the period under analysis.

### Power generation LCOE

This part of the total cost is function of the generation source used in the central power plant [24].

$$LCOE_g = \sum_{i=1}^{m} S_i \times LCOE_i$$

$S_i$ is the share of the energy sources *i* on the total generation mix utilized, m is the number of generation sources composing the mix and $LCOE_i$ is the power generation LCOE defined for all the *m* sources employed (for example: coal, wind, hydroelectric, gas etc.). LCO$E_i$ for each generation technology can be calculated as [177]:

$$LCOE_i = \sum_{n=1}^{N} \frac{CC_n + E_n\, \mu_i\, FC_i + CC_n\, \beta_i}{(1+r)^n} \Bigg/ \sum_{n=1}^{N} \frac{W_i h_n}{(1+r)^n}$$

$$\forall\ production\ plant\ i\ of\ the\ generation\ mix$$

Where $CC_n$ are the eventual costs needed for install new capacity of the technology $i$ in the year *n*. $\beta_i$ is the percentage, for the technology $i$, on capital cost for the operation and maintenance costs. $E_n$ is the annual electricity output which can be calculated as the product between the installed capacity $W_i$ of the technology $i$, and the plant utilization rate $h_n$. Then, $\mu_i$ is the conversion rate in MJ/kWh, that express for each unit of fuel the quantity of electricity produced. Multiplying the conversion rate with the total energy output is achieved the total fuel consumed. F$C_i$ is the fuel cost for each MJ. Finally, *r* is the discounting rate and N is the project duration.

### Power transmission LCOE

The costs for electricity transmission are given by: eventual new investment in new transmission capacity needed for transport the electricity to rural area, operation and maintenance costs. Moreover, it is relevant the impact of transmission losses at the denominator. In the transmission network LCOE, it is considered the cost for the transformers that separate the high voltage network to the medium voltage one [24].

$$LCOE_t = \sum_{n=1}^{N} \frac{CG_n + CT_n + OM_n}{(1+r)^n} \Big/ \sum_{n=1}^{N} \frac{ET_n(1-z)}{(1+r)^n}$$

N is the length of the period under analysis. At the numerator there are all the cost stream for each year n. $CG_n$ represents new investment for the grid in the year n, $CT_n$ are the cost for intervention on the transformers, $OM_n$ are the operating and maintenance costs. On the denominator it is present the amount of electricity $ET_n$ transported by the high voltage grid each year, decreased by the share of losses thanks to the factor $(1-z)$. Both the terms are actualized with the discounting factor *r*.

### Power distribution LCOE

The third component is related to the cost for the investment in the new lines and substation transformers needed to distribute electricity to the rural area under analysis. The electricity will flow through the medium and low voltage network in order to arrive to final consumers [177].

$$LCOE_d = \sum_{n=1}^{N} \frac{x_{mv}C_{mv} + x_{lv}C_{lv} + \frac{C_t L}{P_f} + OM_n}{(1+r)^n} \Big/ \sum_{n=1}^{N} \frac{L \times LF_n \times (1-s)}{(1+r)^n}$$

$x_{mv}C_{mv}$ and $x_{lv}C_{lv}$ are the investment cost for the distribution network. The costs are calculated multiplying the distances between the existing transmission grid and the rural area for the unitary cost of medium voltage lines, plus the distance of the lines within the rural are for the cost of low voltage grid. $C_t L/P_f$ represent instead the cost for distribution transformers, that lower the voltage at level utilized by the users. It is composed by the unitary cost of transformer $C_t$, the peak load of the area $L$ and the power factor of the transformer $P_f$. At the denominator, the energy distributed is calculated thanks to the product between the peak load and the average load factor $LF$. Finally, $s$ are the distribution losses.

**Total LCOE grid extension**

Hence, the total levelized cost of electricity delivered through grid extension mode is given by the sum of the previous three component [176], [177]:

$$LCOE_{g.ext.} = LCOE_g + LCOE_t + LCOE_d$$

From the formulation above mentioned is possible to explain, also from an analytical point of view, the critical success factor of grid extension model. As underlined also by Nguyen, the $LCOE_{g.ext.}$ is influenced by the number of householders of the areas. According to this source, the number of householders is the attribute that mostly impact on LCOE. Fixing the other parameters and making oscillate the number of householders from 50 to 1000, the LCOE reduce of the 464% [25]. As a matter of fact, the higher the number of users, the higher the load and hence, the denominator of the LCOE calculation. Another important parameter is the distance from existing grid, the shorter this distance the lower the needs for undertake new investment in distribution network. This is highlighted in the studies of Nguyen and Nassén [179]. In order to minimize the costs for the building of the low-voltage network is also important that there is a high load density. Otherwise, in case of scattered distribution of population, the costs for the final connection of the users, would strongly impact on investment costs [25], [179], [140].

## 5.2 Stand-alone systems

One of the options for rural electrification are home based systems. These systems are characterized by the production of electricity to satisfy the needs of only one householder. Considering the hypothesis made: the focus is on the utilization of photovoltaic as energy generation source. The solar home-based systems can be further subdivided in Pico PV, Solar home systems (SHS) and large SHS according to the size of the systems [180], [181]. Regardless of the capacity, stand-alone solar systems are gaining importance among the off-grid opportunities. There are three macro trend driving the success of solar home-based systems. Foremost, the decreasing cost of the technologies composing the system (PV, battery, LED light) make the system more affordable for rural householders.

In the second place, the expenditure needed for acquire kerosene is increasing. The outlay for householders was 67.8 $/year in 2012, while in 2020 the projection foresees an expected price of 93.1 $/year, an increment of the 40%. Finally, the third driver is the increased rate of penetration of mobile phones within low-income segment, especially in Africa. This trend generates the need for off-grid householders to have access to basic electricity provision so as to be able to charge their mobile device [181]. In the table below, it is present a classification of the stand-alone solar systems, according to systems size, the tier of service which is possible to deliver to users and average system price.

| Category | Size (W) | Tier of service | Price ($) | Sources |
|---|---|---|---|---|
| **Pico PV** | W<10 | 1 | 10-40 | [180] [181] [182] |
| **SHS** | 10<W<1000 | 2 | 50-200 | [181] [5] [183] |
| **Large SHS** | W>200 | 3 | P>200 | [180] [181] |

*Figure 25, Classification of Solar stand-alone systems*

## 5.2.1 Pico PV systems

The system is composed, typically, by the PV panel, a small battery and a Lamp. Pico PV, considering their low cost, are targeting users with low purchasing power, that cannot afford to buy a larger solar home system. The price needed to purchase this small PV systems range, on average, between 10 and 40 $ [181]. It is operated by very low-income householders in rural areas as lighting source. By mentioning the tier of services defined by SE4All, Pico PV can be positioned in the first tier. Thus, are generally suitable for lighting and mobile phone charging purposes [180]. Pico PV represent an alternatives source of energy to kerosene lamps and candle, which are traditionally used in rural areas for lighting purpose [184]. This category of PV systems differs from larger solar individual systems since it is usually single light output, due to the limited capacity of the system. Rarely, due to a dramatic increase in energy efficiency of small appliances, Pico PV may also be employed to power radios, and very small TVs [185]. The Pico PV technology refers to panels with low capacity: according to the literature consulted, below 10 W [182]. The battery typology which is more frequent in Pico PV systems is the Li-ion, with lead-acid used sometimes in the biggest systems of this category. Regarding the lighting technology employed, it is typically a heavily efficient LED lamp. This lamp guarantees high performance in term of durability (hours of light), lighting efficiency (lumen/watt) and energy efficiency (watt). As a matter of fact, with the old incandescent bulbs of 60 watts, would have not been possible use PV panel of small capacity. The diffusion of low energy consumption lamps has allowed the technical feasibility of this model. Pico PV need a very limited area to be installed, hence, are very flexible and easy to be transported. In this way, the maintenance operations are simplified and less costly since the panel can be easily brought to shops able to deliver technical assistance, without requiring of door to door assistance. For example, considering a multi crystalline cells, with 100 W/m$^2$ and an efficiency of the 10%, in order to have 10W of installed capacity are needed just 0,1 square meters [185]. Hence, one of the key features of this systems, is that they are portable. This peculiarity is implemented in a sub-models of Pico PV systems: the solar portable lights or solar lanterns. Solar lanterns can be used where needed and are designed to provide just lighting to users, without mobile phone charging [186].

### 5.2.2 Solar home systems

Solar home systems (SHS) are stand-alone photovoltaic systems that are used for satisfying basic energy needs of householders in rural areas. This size of systems can provide electricity for lighting and small appliances (fan, TV, etc.). The typical size ranges between 10 and 100W. This range of capacity allow to power multiple lights. Considering the service level that SHS are able to deliver, can be classified in the 2$^{nd}$ tier of the multi-tier framework. The price is higher than Pico PV systems, it ranges from 50$ to 200$ [181]. The systems generate direct current (DC), which is usually fed into a battery in order to be stored and reused when needed. The battery is coupled with a charge controller that regulate the electricity coming in and out the battery. Battery is commonly designed to cover 2 or 3 days of energy requirement, ensuring reliability even in case that solar irradiation is not sufficient [5]. SHS represent an alternatives source of energy to kerosene lamps and candle, as the Pico PV systems. Moreover, considering the higher range of capacity of SHSs respect to Pico PVs, it can also be considered an alternative to portable dry-cell batteries, which are used in non-electrified areas to power small appliances [183]. When coupled with battery, SHS reliability is high. However, the amount of electricity that can be generated is limited. Thus, this system, is suitable to cope only with small demand. For this reason, SHS are not indicated for productive uses of electricity and for the provision of community services [5]. Moreover, without inverter, electricity produced can only be supplied to DC appliances which are costly and less diffused AC ones [82].

### 5.2.3 Large solar home systems

Large solar home systems are the largest category for individual solar home systems. From a physical point of view, they are similar with SHS, but being in a range of capacity over 200W, guarantee a higher service level. Considering the usual classification, this system is in the 3rd tier or services. As a matter of fact, they permit, as the SHS: multi lighting source application, the functioning of radio and fan. Moreover, additionally to SHS, they allow to power small refrigerator and larger TVs [180], [181]. Obviously, the price is higher than the previous category: on average it starts from 200 $. Thus, are affordable only for householders with a relevant income.

### 5.2.4 LCOE of solar stand-alone systems

The LCOE of a PV stand-alone system can be calculated, as usual, through the ratio between the present value of life cycle costs and the electricity generated. The life cycle cost is given by the cost of the component of the system (PV modules, battery and charge controller), plus annual maintenance costs. The electricity generated, instead is function of the peak capacity of the module, the average solar irradiation hours and the losses determined by degradation of the modules [187], [5].

$$LCOE_{SHS} = \frac{\sum_{n=0}^{N}[( I(mod)_n + I(batt)_n + I(con)_n + OM_n) \times (1+i)^{-n}]}{\sum_{n=0}^{N}[(W_p h_n(1-d) \times (1+i)^{-n}]}$$

Where I(mod), I(batt) and I(con) represent the investment respectively for the PV modules, the battery and the charge controller. It is important to point out that the investment in technologies is likely to happen only in the year zero, short of unexpected replacement. $OM_n$ are eventual cash outflow paid to technician for maintenance activities in year n. Then, $i$ is the interest rate. Shifting to denominator, it is present the yearly energy output of the system. The output is given by the product between the rated capacity $W_p$, the yearly utilization rate $h_n$ (which depend on the yearly irradiation hours) and the term *(1-d)* that take into account modules degradation. In the formula above are not considered interest expenses since it is assumed that, due to the limited initial investment, no debt capital is involved.

### 5.2.5 Solar lighting against traditional lighting, evidence from literature

Considering lighting application, the availability of electricity provided by solar systems is beneficial for the householders in term of quality of the service provided. Moreover, also considering the financial dimension, the traditional method for lighting, based on fuel combustion, represent an inefficient way to satisfy this need. Thus, electricity from PV, is also a cost-effective means to achieve lighting service. This is demonstrated in different studies. ESMAP declares that, electricity from solar systems, guarantees to users a 10 times more affordable services in terms of cost per lumen per hour, respect to lighting sources working with fuel [31]. According to Mills, off-grid users spend almost 40 billion $ per year on polluting, fuel-based mechanisms for lighting services. However, they benefit of only the 0,1% of the light quantity used by on-grid consumers [188].

A study analyzes, from 2012 to 2015, the expenditures for lighting of a householder's sample in absence of grid connection and without PV panels, from Malawi, Tanzania, Uganda and Zambia. They used to spend on average 1.20 $ per week, equivalent to the 9%-10% of their income, for only 4 hours per day of lighting. The main source of lighting was kerosene (69% of the sample), while other alternatives were candle or torch. Although the high share of income paid for lighting, the quality of the service guaranteed was low. Considering brightness, a kerosene lamp can provide at maximum 20 lumens, while a candle just 10 lumens. As far as concern reliability of lighting, with kerosene, the provision of the fuel can be reduced in some countries for problem related to the import. After the introduction of the SHS, the 71% of the families decreased the amount of money paid for lighting. Shifting to solar energy for lighting, householders saved 60$ year, passing to spend just the 2% of their income for lighting. Moreover, most of them, totally cut out kerosene (the 69%). Considering the lighting performance, solar lights can provide up to 100 lumens as brightness and increase the total hour of light per day, that shift, from an average of 4 h with kerosene, to 5.1 hours. Finally, the 92% of the householders, have declared that PV systems are judged as reliable source of electricity [180].

### 5.2.6 Example of Stand-alone solar system Business model: M-KOPA

Decreasing cost of PV technologies opened the possibility for the emergence of new business models, specialized in the provision of these equipment to low-income consumers of rural areas. The most famous company in this sector is M-KOPA Solar, born in 2012 with the mission of supply reliable and affordable energy to poor householders in area without centralized grid. M-KOPA's basic offer is composed by: 8W PV panel, 3.3 Ah battery, four LED lights, LED torch, mobile phone charger and radio. Hence, according to the classification proposed, it is a Pico PV system offering tier 1 services. On the other hand, customers with higher willingness to pay, can choose advanced offer which foresee a panel of 20W, a TV and a small refrigerator [189]. Thus, this second model is a SHS, offering second tier service to user. The payments are organized in order to target the low-income segment: users are charged of 35 US$ as down payment, and then 50 cents/day for one year. After one year, users become the owner of the equipment. The payment is usually carried out through mobile platform, selling pre-paid scratch card in small local retailer and establishing partnership with telecommunication operators. This method of payment is enabled by the large diffusion of mobile phones in Africa. In Uganda M-KOPA collaborate with Safaricom, which offer reduced price for mobile payments to PV users [181]. The daily electricity price is higher than the one paid by householders served by the centralized grid, however, the cost of connection to the grid is significantly lower than the down payment necessary to activate the home-based solar system [82].

## 5.3 Comparison of Microgrid with Stand-alone systems and grid extension

Summing up, the options analyzed in this work for rural electrification are: centralized grid extension, solar microgrid and solar stand-alone systems. The aim in this paragraph understand which variables determine, for a specific location, the best strategy for rural electrification.

### 5.3.1 Decision making process for rural electrification project

In the figure below, it is schematized a possible decision-making process useful to decide the best option for rural electrification as schematized by The World Bank [190]. There are two main decision to be taken: foremost, the choice between central grid extension and off-grid systems. Then, in case of off-grid systems, it is necessary to choose between stand-alone system and microgrid. Thus, according to the scheme below, it is interesting to compare a microgrid system with both SHS and grid extension, explaining the variable that determine the choice.

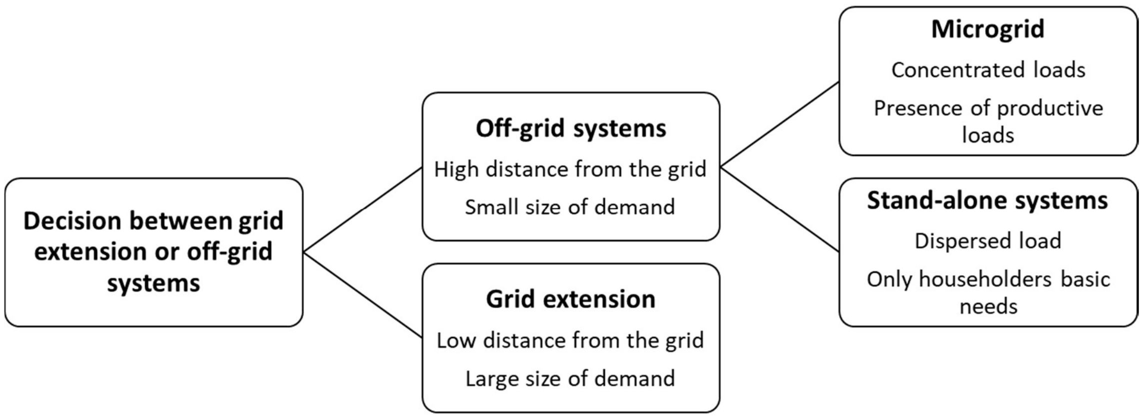


*Figure 26, Decision making process for rural electrification according to The World Bank.*

### 5.3.2 Comparison between grid extension and microgrid

The first evaluation regard the choice between an off-grid project or an extension of the centralized grid. The variable that impact on this selection are: the distance from the existing transmission network and the size of demand of the rural area under analysis [190]. As a matter of fact, if must be covered long distances to reach a remote area, the investment cost for the new lines prevent the economic feasibility of grid extension. A long transmission grid implies also significant transmission losses and the enhancement of operation and maintenance cost along the lines. At the same time, for small size of demand, the costs for extend the grid, are not justified since have to be allocated on a short quantity of kWh consumed. Instead, in areas when demand is high and the distance to be covered is limited, grid extension can be feasible option that permit to exploit the scale advantages of centralized generation [190].

#### Economic distance limit

In order to define the least cost option between an off-grid systems and grid extension it is worth to define the concept of economic distance limit (EDL). Which is sometimes also called break-even distance. Fixing all the other variable, the EDL is defined as the distance, from the transformer of the existing transmission network, where it is equal the cost of supply electricity through grid extension or off-grid system [176]. For location placed at a distance higher than the EDL, the best strategy in term of costs, is to set up a decentralized system. For distances lower than the breakeven, it is worth to expand the existing grid. From an analytical point of view, the EDL can be calculated equalizing the LCOE of grid extension with the LCOE related to the off-grid systems. Then, since only $\mathrm{LCO}E_{g.ext}$ depends on the distance $x$ of the area from transmission network, the distance can be isolated, and the results will coincide with the EDL [177].

$$\mathrm{LCO}E_{g.ext}(x) = LCOE_{off-grid}$$

Supposing to consider the microgrid as option for off-grid electric systems, and reminding that levelized cost of electricity in the case of grid extension is calculated as the sum of three parts:

$$LCOE_g + LCOE_t + LCOE_d = LCOE_{MG}$$

Then, substituting the levelized cost of electricity for the distribution part as defined before:

$$LCOE_g + LCOE_t + \sum_{n=1}^{N} \frac{xC_{dg} + \frac{C_t L}{P_f} + OM_n}{(1+r)^n} \Big/ \sum_{n=1}^{N} \frac{E_n(1-s)}{(1+r)^n} = LCOE_{MG}$$

Assuming for simplicity that the investment cost for the grid is undertaken only in n=0, Hence, the term $xC_{dg}$ (cost of distribution grid for the line length), can be taken out of the summation.

$$\text{EDL} = \frac{\left[(LCOE_{MG} - LCOE_g - LCOE_t) \times \sum_{n=1}^{N} \frac{E_n(1-s)}{(1+r)^n}\right] - \sum_{n=1}^{N} \frac{\frac{C_t L}{P_f} + OM_n}{(1+r)^n}}{C_{dg}}$$

This formula points out that, the EDL, increase when grows the electricity delivered to the location $E_n$. Conversely, EDL, decrease increasing the unitary cost of distribution network $C_{dg}$ .

### 5.3.3 Comparison between Solar home systems and micro grid

Before of digging into the analysis that determine which configuration better suits the external condition between SHS and microgrid, it is worth to make some considerations on difference in term of design, operation and maintenance and possible application related to SHS and microgrid [5].

Starting from design, when sizing the battery of a SHS, it is usually considered a capacity able to cover 2 or 3 days of absence of sun, guaranteeing no shortages in peak-load hours. On the other hand, in case of microgrid it is possible to take advantages sizing the battery on the average loads rather than peak one. This characteristic can be explained with the concept of diversity factor. The diversity factor (DF) is defined as [166]:

$$DF = \frac{\sum_{i=1}^{N} Peak\ Load_i}{Average\ load\ of\ the\ systems} > 1$$

Where at the numerator is present the summation of individual peak demand from the users of the systems *i.* The diversity factor is always greater than one, since the user's maximum consumption of electricity will not occur simultaneously. The diversity increases when the number of users connected to the system grow. The higher the diversity, the lower the cost for producing electricity, since decrease the investment cost for generation capacity [6].

As far as concern implication on operation and maintenance, it is important to remark that SHSs are usually owned by the users. For this reasons, O&M costs are sustained by the householders. For them may be difficult to gather the necessary experts for maintenance service. Moreover, maintenance service may have a high cost for householder since SHS are distributed in remote and dispersed location. On the other hand, microgrid maintenance is undertaken by the electricity service provider (utility or private operator), with a non-additional cost included in the energy price. Furthermore, unitary cost for maintenance operation is lower than in the case of SHS since production unit are geographically concentrated and more easily accessible [5].

Finally, considering the implication on possible application, SHSs have usually a limited scope for income generating activities. The electricity generated is directed to satisfy basic need of householders. On the other hand, microgrid exploiting scale advantages in energy generation and storage, usually permit to power productive activities like water pumping, agriculture activities and so forth.

### Variable driving the choice between SHSs and microgrid

In area where grid extension is not feasible, the choice for electrification fall on one between solar stand-alone system or microgrid. The decision must to be taken pondering two variable: the level of dispersion and the typology of the load. The distance between singular loads impact on the cost of the low-voltage distribution network. When loads are dispersed, the length of the line raise investment cost and enhance electricity losses during distribution phase [177]. Hence, the unitary cost of connection would be too elevated in order to set up a microgrid. Instead, when loads are geographically concentrated the conditions are theoretically feasible for microgrid implementation. As far as concern the typology of loads, it is worth to distinguish between two situations: in the area are presents some productive loads or in the area there only householders with basic needs. When there is presence of income-generating activities, electricity demand is higher and stable, thus can be feasible the microgrid configuration. As a matter of fact, productive activities decrease the LCOE, enhancing the load factor and shifting consumption during daylight hours, minimizing solar energy wastage. Moreover, productive loads have a higher willingness to pay for electricity respect to householders. Indeed, local entrepreneurs see in a stable provision of electricity the opportunities to increment the productivity of their business.  Conversely, for a similar reasoning, when there isn't productive load, the revenues gathered risk to be not enough to justify the investment into a microgrid. In order to satisfy basic energy needs of householders, like lighting and power small appliances, solar stand-alone system may be enough and less expensive, considering the low purchasing power of dwellers [190].

# Techno-economic analysis

As said in the methodology, the second part of the work is based on the analysis of a case study based on real data. In the specific, the location considered is a rural village of Nigerian country.

# Chapter 6: Country overview, Nigeria

**Context definition and analysis of Nigerian Power sector with focus on regulatory framework for rural electrification projects.**

## 6.1 Context analysis

Federal Republic of Nigeria, shortly Nigeria, is located in West Africa and confines with Niger in the north, Chad in northeast, Cameroon in southeast, Benin in the west and has coasts on the Atlantic Ocean. Nigeria has a surface of 923768 $Km^2$ [191]. In the following paragraph it is present an overview of the country in order to figure out the context of the location under investigation.

### 6.1.1 Population and society

Nigeria has a population of nearly 190 million. This quantity makes Nigeria as the 7$^{th}$ most populated country in the world, the 1$^{st}$ among African countries [191]. In the last decades, the country has faced an outstanding increase of population, doubling the number of inhabitants from 1990 to nowadays. As a result of this demographic boom, nowadays almost the 50% of the population is below 18 years old. Hence, has one of the youngest populations in the world. Continuing with this grow rate, Nigerian population would reach 700 million people by 2100. The population is distributed for the 52% in urban areas, while for the 48% in rural areas. The most important urban center in Nigeria are Abuja, the capital, and Lagos, which is one of the most important commercial point of Africa and the most populated cities of the continent.

The Nigerian population is composed by a multitude of ethnic groups which has different languages and culture. The larger groups are the Hausa, Yoruba, Igbo and Fulani that, jointly, account for the 70% of the population. Since is the one of the most advanced economies in Africa, in Nigeria, are also present small minorities of immigrants from other African countries which lives in the neighbourhood of larger Nigerian cities. Moreover, are present minorities from United States, Great Britain, China, Japan, Greek and Cuba [192].

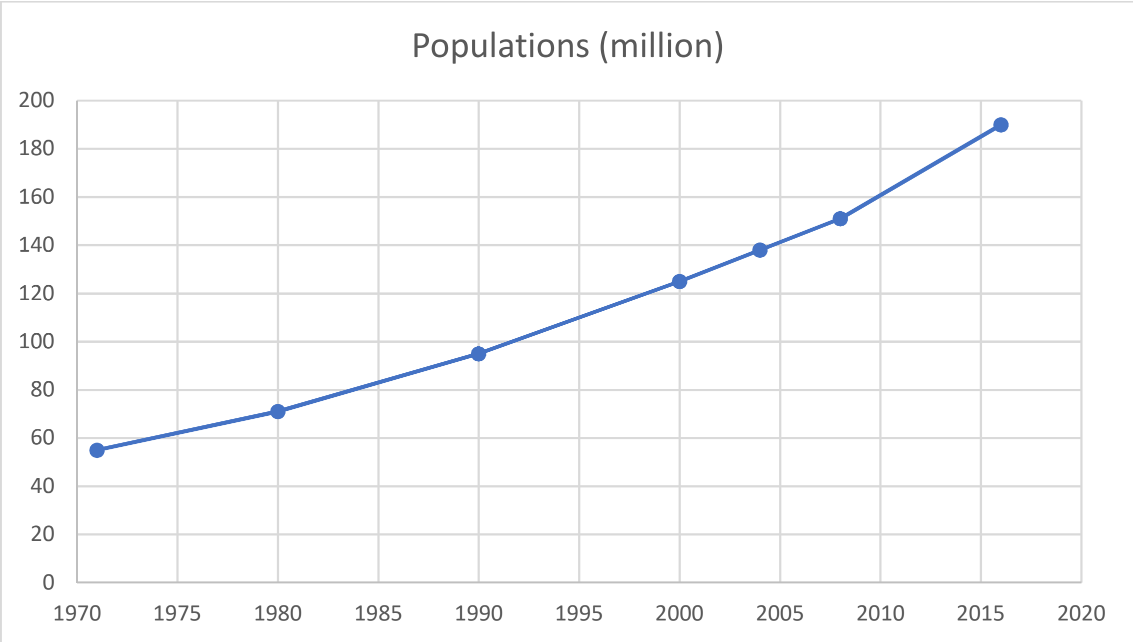


*Figure 27, Nigerian population growth between 1970 and 2016*

As a result of the different ethnics that lives in the country, even the language spoken is not uniform. The official language is English, which has been chosen in order to promote integration and unification of the state. English is mainly used in main commercial hub of the country, to facilitate trade and for children education. It is also relevant the share of inhabitants that speaks French, mainly dictated by the facts that many confining countries adopt this language as the official. On the other hand, in rural areas are spoken African languages characteristic of the ethnic group: Igbo, Hausa and Yoruba. Despite a recent growth, Human Development Index of Nigeria remains low if compared with world average and other African countries. The HDI in 2017 was equal to 0.532, the 157$^{th}$ in the world [193].

### 6.1.2 Government and politics

Nowadays Nigeria is a federal republic where the president has executive power. President is voted by the population and can govern for a period of 4 years. The system is based on the division of the territory in 36 states which form the federal state [194]. The Democracy in Nigeria has been established in 1999. Before democracy, Nigeria has been for a long time a British colony. The nationalism movement has acquired momentum after second World War and independence has been achieved in 1960. From 1960 to 1999, Nigeria has faced a tough period of civil war and dictature caused by ethnic differences present within the country [192]. One of the main challenges for Nigerian government is to fight corruption, which has always been largely diffused as means to gain power. In Nigeria are valid three different low systems. The common low, inherited from colonialism period. The Customary low, which born from traditions and habits of indigenous inhabitants. The Sharia law used in the northern Muslim part of the country. These differences contribute to generate arguments and tensions among Nigerian inhabitants and politicians.

### 6.1.3 Economy

Nigeria economy is rapidly growing in the last years. In 2014 has become the largest African economy for GDP, reaching the 21$^{st}$ position at worldwide level in 2017 with a GDP equal to 1125 billion of dollars (considering purchasing power parity, PPP) [194]. The process of growth started with the democracy period since, previously, economic growth was prevented by a high degree of corruption and internal conflict. Despite the huge economic growth faced by the country in the last years, remain present in the country a high level of poverty. According to CIA, the 62% of Nigerian people lives in condition of extreme poverty. The currency used is the Naira and in 2018 can be exchanged with 0.0028 US dollars according to Central bank of Nigeria (CBN) [195].

In the figure can be seen the huge growth of Nigerian GDP in the lasts years.

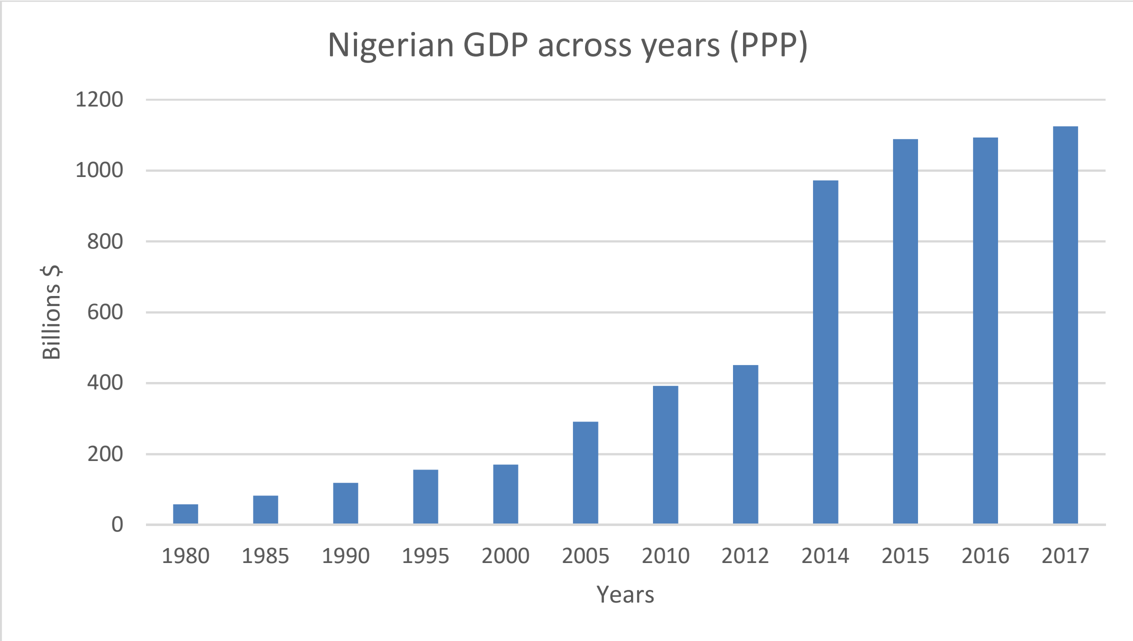


*Figure 28, Trend of Nigerian GDP in billions of dollars and considering PPP.*

Agriculture has always been largely developed in Nigeria. Currently, Nigeria is the 6th country for agricultural output in the world and the first one in Africa. Agriculture generates the 21.6% of GDP and is one of the main sources of employment for inhabitants. As a matter of fact, the 70% of the labour force is employed in the agricultural sector. Despite this large agricultural output, Nigeria is not anymore one of the biggest exporters since have to satisfy the internal demand which has steeply increased in the last years. The main agricultural products cultivated are cocoa, peanuts, rubber and palm oil. Nigeria underground is full of oil resources; thus, the country has always based its economic growth on production and export of oil. Nigeria belong to OPEC from 1971 and nowadays is among the first ten countries for proven reserves in the world. Internal demand is 425000 barrel per day, while production is 1535000 barrel per day [191]. Thus, Nigeria is a net exporter of crude oil and these revenues guarantee most of government sales. Government revenues from oil export has been traditionally used in order to finance manufacturing sector. The main manufacturing output is provided by food, beverage and tobacco production, followed by the textile sector output. Manufacturing companies, together with oil production and sales are aggregated into the Industry item of GDP and accounts for the 18,6% in Nigeria.  Service sector in Nigeria contribute for the 60% of the GDP and is the most developed in Africa [194]. As far as concern tourism, Nigeria has a good potential which derive from its seaboard. However, the frequent events of violence occurred in the country during the period before democracy, discourage many tourists from travelling to Nigeria. Transportation sector in Nigeria suffer of insufficient and aged infrastructure that prevent flow of resources from and to rural areas [192]. The problem suffered by both railways and road network is the absence of frequent maintenance operations. Government is trying, trough privatization, to enhance the quality of transportation sector to favour trade to remote areas.

In the graph below can be seen the breakdown of Nigerian GDP in services, agricultural and industrial sector according to CIA World Factbook of 2017 [194].

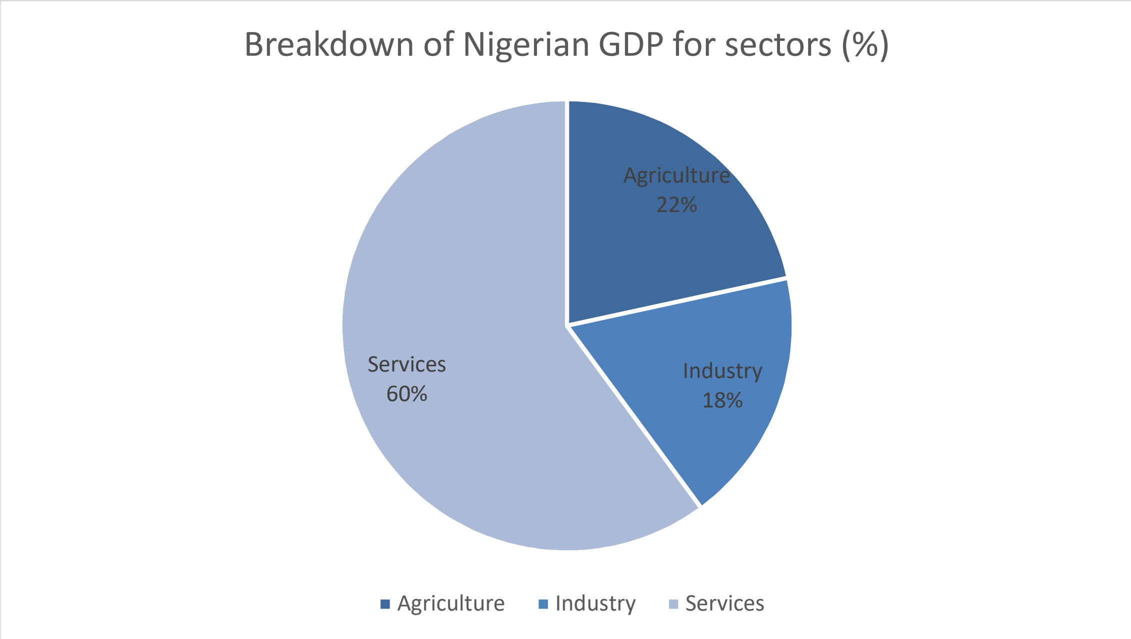


*Figure 29,Breakdown of Nigerian GDP, CIA World Factbook.*

## 6.2 Energy sector overview

Nigerian territory has a good energy potential, considering both conventional sources and renewable ones.

### 6.2.1 Conventional energy resources

Nigeria has abundance of traditional energy sources [196]. As already said, is among the largest producers and owner of reserves of oil. The last estimation of proved reserves is equal to 37.06 billion of barrel [194]. Oil production is mainly concentrated in proximity of the Niger delta. As a result of this, the area is suffering of extreme level of pollution which causes damages to heath of inhabitants.  Nigeria also owns the biggest reserve of natural gas of the whole African continent, with proved reserves of 5.28 trillion of cubic meter [194]. Considering the production of natural gas, Nigeria with 45.15 $m^3$ in 2015, was the $18^{th}$ larger producer in the world. Even natural gas production is located close to the Delta of Niger. Indeed, this region has been strongly polluted by gas flaring activity which has been only recently mitigated, through strong government measures [197]. As far as concern coal, Nigeria is not among the largest owner of reserves. The proven reserves of coal are assessed to be 639 million tons.  The interest towards this source of energy has decreased after the discoveries of oil and natural gas resources. Looking ahead of fossil fuel, there is no presence of nuclear energy exploitation in Nigeria [194].

### 6.2.2 Renewable energy resources

Nigeria is also rich of renewable energy resources. Nevertheless, the exploitation of this resources has been low until now, due to inadequate government measures and low capability to attract foreign private investments [198]. Starting from biomass, the potential is estimated to be 8800 MJ. The mostly available resource is wood with 13 million hectares of forest [199]. Moreover, are used in a lower extent, shrubs, forage and animal waste. Biomass are utilized in order to satisfy heating and cooking needs of householders or as fuel for process heating in rural firms. The utilization of biogas is minimal and constrained by costs barriers [197]. Hydropower potential is given by the presence of large rivers and basin and, in Nigeria, is estimated to be equal to 11250 MW for large plant, while 3500 MW for small plant [199]. However, it has been estimated that only a small part of the hydropower potential is currently exploited. The penetration in recent years of Small Hydro power (SHP) plants is increasing the total diffusion of this energy source. As a matter of fact, SHP, contribute for the 23% on the total electricity generated through hydropower [197]. Wind energy diffusion in Nigeria is minimal since government has always preferred to count on fossil fuel electricity production. Nevertheless, recent studies show that wind potential of the country is high especially in hilly regions and in proximity of sea coasts [200]. The average value for wind intensity ranges from 2 to 9.5 m/s [196]. As far as concern solar energy, Nigeria is placed in area characterized by high solar irradiation. The average values range from 3.5 kWh/$m^2$ per day along the coastline, to 7 kWh/$m^2$ per day in arid regions located in the North of the country. These values result in an average energy received from sun equal 19.8 MJ/$m^2$ per day [199]. Moreover, due to the latitude close to equator, there is low degree of seasonal variability for solar irradiation. Thus, even in light of the high degree of technological maturity reached by PV plant, solar energy is considered one of the main opportunities for rural area electrification in Nigeria [198].

## 6.3 Nigeria power sector

From 1962 to 2001 electricity production, transmission and distribution in Nigeria were managed by national utility. This entity used to operate benefitting of a monopoly position. This public entity was previously called Electricity Corporation of Nigeria (ECN) and turned in National Electric Power Authority (NEPA) from 1972. Then, from 2001 to 2005, took place the process of liberalization of the power sector with the aim of attract private investors and enhance quality of the service for final users. After privatization, NEPA has been subdivided in NESI, TCN and DISCOS which manage the different three level of electricity supply chain.

### 6.3.1 Electricity production

NESI (Nigerian Electricity Supply Industry) undertake electricity production. It manages 23 plants connected to the grid, with a total installed capacity in 2014 equal to 10.4 GW. However, in Nigeria the available capacity is usually lower than total capacity. In 2014 the available capacity was of 6.1 GW [199]. As a matter of fact, electricity production suffers of low maintenance, aged plants, vandalization of facilities, shortages of natural gas and insufficient equipment and tools [201], [202]. Fossil fuel represent the bulk of the electricity generation mix, with the 80% on the total installed capacity for electricity generation. For this reason, most of power plants are concentrated in the south of the country, where oil and natural gas extraction is performed. Coal instead play a marginal role for electricity production since, as said before, is produced in minimum quantity within the country [201]. The remaining share of electricity generation is through Hydropower plants, with a contribution on the total installed capacity of the 19.5% [194]. Other RES instead has a very limited contribution on the total electricity generation mix, equal to the 0.2%.

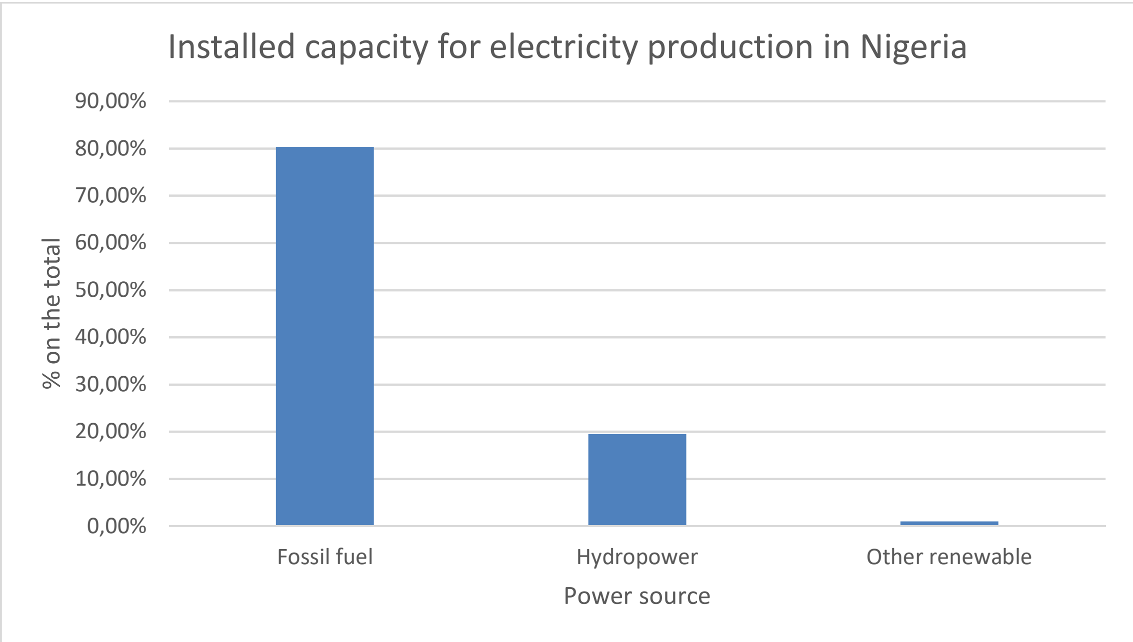


*Figure 30, Installed capacity per source on the total generation mix for power generation.*

### 6.3.2 Electricity transmission and distribution

The electricity transmission is instead carried out by Transmission Company of Nigeria or TCN. The transmission lines have a total capacity of 5524 Km for the 330 KV grid and 6800 Km for the 132 KV grid [199]. The transmission network is also composed by 32 substations 330/132 KV and 105 substations 132/33/11 KV that connect transmission grid to distribution network. The distribution network is managed by 11 operators called DISCOS. The overall length of the network is equal to 224838 km, subdivided in lines of

33 KV, 11 KV (medium voltage) and low-voltage lines [203]. Even in this case the total theoretic capacity is generally larger than the available one. The effective maximum capacity is equal to 4000 MW, which is lower than how much would be needed by the country [202]. The electric grid in Nigeria suffer of extremely low reliability and high transmission losses (higher than 10% of the total electricity transported, [199]). Moreover, the current electric grid is far from cover all the areas of the country. Only the 10% of rural Nigerian householders are connected to the grid [201]. All these inefficiencies result in a poor service level delivered to energy consumers. In 2015, according to ESMAP, the users connected to the grid received an average hours of service per day equal to 9 hours [12]. The causes that determine a low level of development of electricity network are: low public expenditures, low frequency of maintenance provided by under skilled workers, obsolescence of infrastructure, vandalization of the wires and lack of technology for monitoring the systems [202]. The north of the country is the region characterized by lowest electrification rate, as can be seen in the figure below.

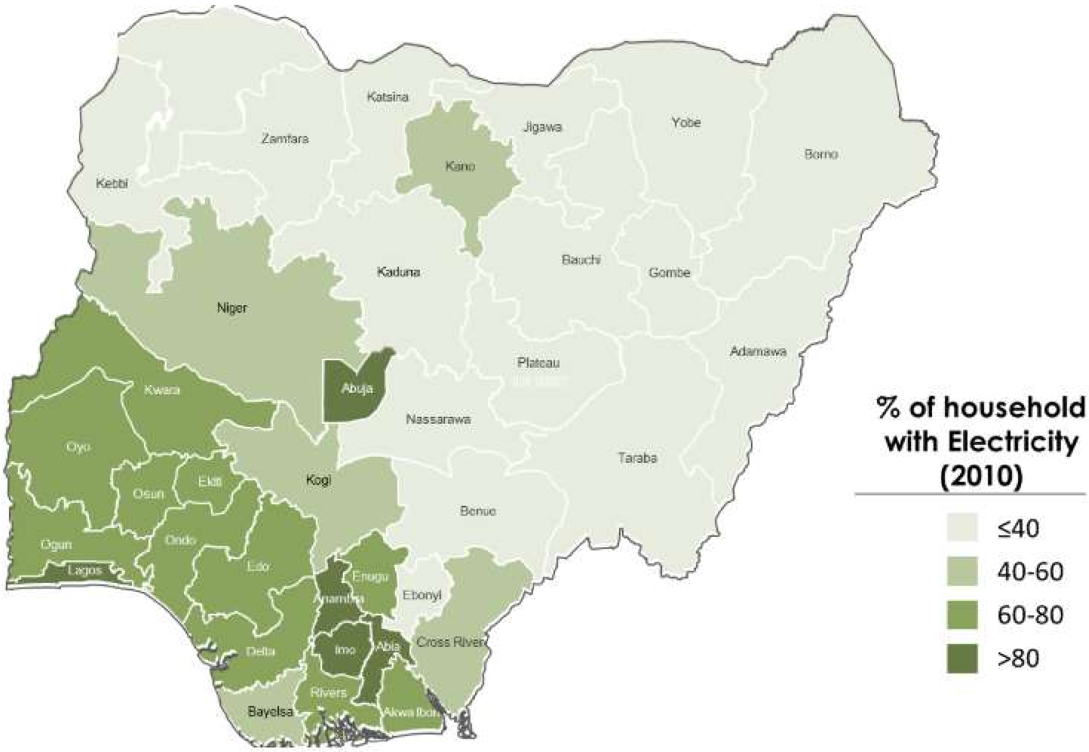


*Figure 31, % of householder with electricity per state*

### 6.3.3 Off-grid and microgrid power sector

Nigeria inhabitants, despite the abundance of potential energy resources, suffer of energy poverty. As a matter of fact, the electrification rate is equal to the 59% on the total (74 million people without access to electricity) and fall to 34% rural areas of the country [10]. When a village is connected to the grid, it does not mean that electricity is effectively available. Indeed, many villages receive power supply for just 4 hours [14]. Hence, many remote communities and rural business are forced to count on other solutions for receiving power supply. It is estimated that, currently, are present in the country 14 GW of capacity through small diesel and petrol generator. The 86% of firm in Nigeria owns and operates fossil fuel small-scale generators, receiving from it the 48% of their electricity needs [204]. These generators provide electricity at a cost for users in the range 0.60-0.80 $/kWh [205]. At the same time, 85 million of rural inhabitants' use to spend almost $ 1.50/kWh for portable batteries, torch and Kerosene to satisfy their basic energy needs [206].

Among off-grid solutions for power supply, Microgrid are becoming important in Nigeria in the last years. Microgrid are usually installed next to rural communities of 300-500 householders on average. According to ESMAP, are present Nowadays in Nigeria 11 microgrid operated by private sector, with a cumulative installed capacity of 236 kW and that serve 9100 people [12]. The totality of the microgrid currently in operation is placed in area previously defined as "unserved", where householders used to satisfy electricity needs through kerosene lamps, portable batteries and candle. The existing microgrid are largely based on solar energy coupled with battery storage, with lower diffusion of hybrid systems, based on the addition of a diesel generator [12]. Existing microgrid project are commonly characterized by a flat electricity tariff charged to all users, while in just one project is active a mechanism of cross-subsidization through anchor load. Average values for microgrid tariff are around 0.578 $/kWh, which is competitive with price needed to power fossil fuel generators [205].

## 6.4 Nigeria power sector regulatory framework

The regulatory entity on Electricity sector in Nigeria is NERC (Nigerian Electricity Regulatory Commission). NERC was set up in 2005, with the aim of control and govern Nigerian electricity sector after liberalization process. NERC main tasks are: to assigns permits for independent power producers and establish market rules and fix operating standard. Moreover, NERC, is in charge of protect final users of electricity, ensuring them fair price (a cost-reflective tariff) and an adequate service level [197]. The underlying objective is to foster penetration of private sector in electricity market, promoting competition among players to enhance quality of the service delivered [201]. In this study will be analysed the regulatory framework related to RES plant and to rural electrification project. Thus, without considering regulatory dynamics of on-grid power sector.

### 6.4.1 Regulatory framework for RES plant

In recent years, one of the main objectives of NERC, has become the stimulation of investment in renewable energy production. The main goals of NERC in promoting RES are: to stimulate renewable self-generation so as to reduce load on transmission and distribution infrastructure; promoting innovation for renewable energy technology to stimulate market growth; reduce greenhouse gas emission shifting to cleaner source of energy to satisfy the growing demand of the country [207]. The policy of 2015 which aim to increase RES penetration is called "National Renewable Energy and Energy Efficiency Policy" (NREEEP) [205]. The regulatory commission fixed a goal of 2 GW of installed capacity from RES by 2020 and of 3 GW for 2030. These values consider both on-grid and off-grid application. In order to achieve this goal, the total objective is spilt in two main obligation imposed to DISCOS and to Nigerian Bulk Electricity Trading Company (NBET). Both the parties are forced to purchase 1 GW of electricity from renewable sources up to 2020 [208]. The electricity is procured from independent power producers through long-term contracts (PPA, Power Purchasing Agreement). To incentivize independent power producers (IPP) using RES are available 3 mechanisms in function of the capacity of the plant [209]:

1. Net metering for small RES plant below 1 MW. This mechanism consists into a remuneration of the electricity injected into the grid.

2. Feed-in tariff (REFIT) for RES plant with, capacities up to 5 MW in case of PV, up to 10 MW in the case of wind and biomass and up to 30 MW in the case of hydropower. This mechanism oversees a favourable remuneration for the electricity produced through RES plant. Off-grid projects are not included in REFIT mechanism. The tariff is calculated in function of long run marginal cost. Hence, should permit to power producers to recover capital cost and operating cost over the duration of the PPA. In 2016 the tariff, corresponded to power producer with PV plant receiving Feed-in tariff incentive, was of 177 $/MWh [208].
3. Competitive auction mechanism for plant over the threshold above indicated in order to access to incentives. For larger plant, in order to receive the incentive on energy produced trough RES, IPP needs to participate to auction based on the lowest-bid criteria.

As far as concern PV technology, the import of PV modules is characterized by the removal of any import duties according to NREEEP of 2015 [204].

### 6.4.2 Nigeria regulatory framework for microgrid

"NERC Mini grid regulation" of 2017 regulate allowed features for electric microgrid systems isolated or interconnected to Discos infrastructure [205]. Interconnected microgrids must make request to NERC to receive the license and must stipulate a contract with both the local community and Disco company (tripartite contract). In case of isolated microgrid, NERC regulate what happens in case of grid extension. When centralized grid arrives in an area covered by an isolated microgrid, the owner of the plant has two opportunities. Or can convert the isolated systems into an interconnected one or transfer all the assets to grid operator receiving a fair remuneration in function of remaining useful life of the plant [210], [12]. The need of a permit for microgrid is function of the system size:

- Isolated microgrid with installed capacity less than 100 kW can operate without receiving the permit. However, if they receive the permit, are covered from the risk of grid extension, as specified before. In case that microgrid want to operate without the permit, the operator needs just to perform a registration to the authorities.

- Microgrid larger than 100 kW and lower than 1 MW must receive a permit from NERC to start operations.
- Large microgrid, over 1 MW need to achieve a specific license. This category will be recognized as Independent Power Producers regardless of the presence of interconnection to the centralized grid.

Permits for isolated microgrid may be assigned only to area defined as “unserved” (where electricity provision is not available at all). While permit for interconnected microgrid may be assigned only to area defined by the regulator as “underserved” (that receive an amount of power from the grid which is lower than the demand). If a microgrid has a permit or a simple registration has implication in fixing the tariff:

- Microgrid without permits can freely decide the tariff, they usually reach an agreement with local community to set a tariff favourable for both the parties. The proposed tariff has to be approved by, at least, the 60% of the users.
- In case of microgrid that receive a permit, the tariff must be calculated according to MYTO methodology (Multi-Year tariff order). This method implies a regulated tariff that take into account: inflation rate, US $ value respect to Naira, CAPEX and OPEX of the microgrid. The aim of MYTO methodology is to set a cost-reflective tariff ensuring a positive remuneration of invested capital [207]. After calculation of the tariff, regulatory commission has to validate the tariff proposed by developers.

With the starting of NEP project, it has been decided that tariff, in rural microgrid, should allow a higher remuneration than on-grid projects, so as to attract investment [206]. Average tariff for rural microgrid are 0.58 $/kWh [205], while users connected to centralized grid usually pays 0.08 $/kWh [12]. Finally, the obligation for receive permit, influence technical standards which must be respected in microgrid design [12]:

- In case of registered microgrid (no permit), the voltage has to be maintained in a range between +/- 10% of its nominal value at the consumers premises. The frequency has to be kept between +/- 20% of nominal value. Moreover, there is no particular obligation respect management of incidents and power outages.

- In case of microgrid that received a permit, voltage must be between the 94% and the 106% of the nominal values of lines (230 V or 415 V). Frequency must be maintained between 48.5 and 51.75 Hz. In case of planned outages, to users must be communicated 72 hours in advance. Eventual incidents that damages environment or people have to be quickly notified to NERC.

### 6.4.3 Regulatory framework for rural electrification project in Nigeria

Projects for rural electrification are promoted mainly by Rural Electrification Agency (REA). REA is an entity of Nigerian federal government in charge of coordinate and promote projects which aim to enhance electricity access in rural areas of the country. The portfolio of projects promoted includes either grid extension, stand-alone systems or microgrids. The aim is to establish, for any location, which is the most cost-efficient and quick strategy for electrification. Currently, the projects in place is called NEP (Nigeria Electrification Project), it started in April 2018 and will have an expected duration of 5 years. The project is enabled by financial support from The World Bank, that is going to invest $ 350 million in 5 years. The total amount invested is subdivided in $ 150 million in microgrid projects for rural communities, $ 75 million for solar home systems, $ 20 million on technical assistance to investors and $ 105 million for power system aiming to supply hospital and universities. Universities and hospitals currently suffer of unreliability of power supply obtained thanks to fossil fuel self-generation [206], [211]. Moreover, REA pool funds together, from other public and private sources, to generate rural electrification fund (REF). REF funds can be assigned to electrification project having at least 30% of renewable energy penetration if coupled with conventional sources. Another criterion to be classified as eligible for receiving funds, is that the project has to guarantee financial sustainability without need of operating subsides [12]. REA is using these funds to implement NEP, by providing capital subsides to private investors and supporting them with technical assistance [11]. Technical assistance implies supporting investors in the phase of individuation of the site, collecting of the permits and project design. All microgrid projects are eligible to receive technical assistance by REA. Financial aid on the initial investment are fundamental to remove entry barrier and permit project developer to apply a tariff based on reduced costs, rather than real costs [211]. Capital subsides for eligible projects are calculated in function of the number of expected connections per microgrid, and according to the service level (According to Multi-tier framework of SE4ALL) that is possible to guarantee to electricity consumers. Moreover, capital subside must be in the range between 10000$ and 300000$ and can cover maximum the 75% of total capital cost [212]. Thus, it is a sort of performance-based grant delivered in $/new connections [211].

| **Tier** | **Tier 2** | **Tier 3** | **Tier 4** | **Tier 5** |
|---|---|---|---|---|
| **Subside per connection** | 25 US$ | 300 US$ | 500 US$ | 600 US$ |

*Figure 32, Capital subside per connection in function of the service level*

.

It is forecasted that 1200 new microgrids will be installed during NEP project outline. The project objective is to reach 200000 householders and 50000 small rural firms. According to REA the project is likely to have success since there is a market opportunity of 10 billion of dollar per year deriving from the implementation of off-grid projects [206]. Indeed, it is believed that in Nigeria there is large potential electricity demand, currently unsatisfied [13]. Another possible support instrument to reduce initial investment is the split-asset model. According to this method, the state invests in distribution asset for microgrid, using budget for grid extension. Then, lease the asset to a private investor. The investors will be the owner of production assets of the microgrid, while distribution grid remains under ownership of the government [213]. In this way, initial investment is decreased of a relevant share. This mechanism is promoted by GIZ ("Gesellschaft für Internationale Zusammenarbeit"), a German company for international cooperation. The project has finished its first phase in 2017, having supported 6 microgrid projects. It is starting in 2018 the second phase of the project [205]. Another entity that can support private investor is Bank of Industry (BOI). BOI set up Solar Energy fund in 2017, offering concessional loans at a rate of 7% to small and medium enterprise that embrace the utilization of solar energy for productive purposes. Thus it seems not allowed to finance microgrid investors which aim to serve also householders segment [211], [12], [214].

| Mains Support mechanisms | Brief explanation | Support provider | Eligibility criteria | Sources |
|---|---|---|---|---|
| **Technical assistance** | Support investors in site selection, receiving permits and project design | REA (Rural Electrification Agency) | All microgrid projects targeting rural location "unserved" or "underserved" | [211] [12] |
| **Concessional loans** | Debt capital at a favourable interest rate (7%) | BOI (Bank of Industry) | Small and medium enterprises utilizing solar energy for productive purposes | [211] [12] [214] |
| **Capital subsides** | Grant capital on the initial investment in function of the number of expected connection and the service level delivered to users | REF (Rural Electrification Funds) | Microgrid project:<br>-Target rural areas<br>-Renewable penetration> 30%<br>-Do not require operating subsidies for financial sustainability | [211] [12] [212] |
| **Split-asset model** | Public sector owns distribution asset for microgrid while private sector owns generation asset. | GIZ (Gesellschaft für Internationale Zusammenarbeit) | Microgrid targeting rural electrification | [205] [213] |

*Figure 33, Main mechanism to support private investment in Rural microgrid in Nigeria.*

# Chapter 7: Microgrid project simulation

**Techno-economic analysis for a private investment in an existing Nigerian village.**

## 7.1 Input data from a Nigerian village

The REA website provides a geographical map where can be seen all the rural communities unelectrified. Moreover, they subdivided unelectrified communities according to the potential of the area for an off-grid electrification project. Some locations are judged as suitable for a microgrid project or other locations are evaluated adapt just for solar home systems [215]. Thus, starting from this database, has been randomly selected one community, evaluated by REA as adapt for microgrid installation, to carry out the simulation. The selected village is located at latitude 11.79593576 and longitude 5.8675237391, into the state of Zamfara, in the north of the country, and the ward of Gwashi. Zamfara state has a rural electrification rate of 6.9% [203]. According to REA's data, the village has a population of nearly 1100 people. Thus, supposing that on average in each house live 5 people, which is the average value for Nigeria according to United Nations [216] ,the number of householders in the village is assumed to be equal to 200. In the figure below can be seen a satellite-based view of the village under analysis.

*Figure 34, Satellite-based view of the village under analysis.*

Using the tool from *Google Maps* that allows to measure distances and the map developed by REA, that shows the location of transmission grid and substation can be estimated the distance of the village from the existing centralized grid (Gusau transmission substation) which is equal to around 96 km.


*Figure 35, Distance of the village considered from the closest substation*

### 7.1.2 Load assessment

In order to design the microgrid systems, one necessary step is the estimation of the potential daily demand for electricity. Load profile of a rural areas is function of the typology of load present in village. Generally, it is possible to categorize load profile in three categories: residential, commercial and Industrial. The category of load establishes how the consumption is distributed along the hours of the day. In the village considered, are examined two different potential scenarios for the electricity demand. In the first scenario are present only domestic load, the householders. This situation seems coincident with the as-is situation of the village. In fact, according to the REA map [215], are not currently present in the village school, health centre or water points. Thus, it is reasonable to assume that are not yet developed productive activities in the village and dwellers must collect basic resources and services from larger villages in the neighbourhood. In the second scenario, has been assumed a higher electricity consumption assuming that the village has encountered an economic growth. Hence, will be added, to the total load of householders, a small school, an health centre, 5 small shops selling basic products to dwellers and a 2 small rural firm working in the food processing sector and carpentry. The main features of the two-load scenario studied are summarized in the table below.

| **Scenario 1: low-consumption case** | **Scenario 2: high-consumption case** |
|---|---|
| • Only domestic load<br>• No community services (school, health centre)<br>• No productive load<br>• Dwellers rely on other village for procure basic services | • Domestic load<br>• Small school and health centre<br>• Small shops selling basic products<br>• Two rural firm: Food-processing and Carpenter. |

*Figure 36, Two scenario for load assessment of the village.*

The average daily load $E_t$ (kWh/day) can be estimated through the following formulation [18]:

$$E_t = \sum_{i=1}^{n} nP_iT_i = E_1 + E_2 + \cdots + E_n$$

Where $n$ represent the number of consumption units $I$, $P_i$ the power rating of the consumption equipment and $T_i$ is the time of usage (hours/day) of the equipment $i$.

Usually load profile are subject to seasonal variability. However, considering the longitude close to equator of Nigerian country, seasonal variability in electricity consumption can be neglected [127].

## First scenario average load assessment

The table below summarize the calculation of the daily consumption for each householder.

| **Householders average load** | **Number per HH** | **Power (W)** | **Hours/day** | **Consumption/day (kWh/day)** |
|---|---|---|---|---|
| **Light** | 3 | 17 | 7 | 0.357 |
| **TV** | 1 | 80 | 5 | 0.4 |
| **Fan** | 1 | 40 | 3 | 0.12 |
| **Radio** | 1 | 19 | 3 | 0.057 |
| **Phone** | 2 | 8 | 2 | 0.032 |
| **Refrigerator** | 0.2 | 110 | 24 | 0.528 |
| **Total per HH** | | | | 1.494 |
| **Total per Village** | | | | 298.8 |

*Figure 37, Estimation of average consumption per day for householders and the village.*

The average consumption per day for each householder has been calculated considering 6 possible appliances: lights, TV, fan, radio, phone and refrigerator. Each appliance is defined by the number of unit present in each house, the rated power, the average hours of utilization per day and the average consumption per day. The data has been collected considering average value from similar studies on load assessment [6], [14], [18], [217], [218], [94], [9], [23], [23] plus research on the web [219], [220]. The whole calculation for each consumption unit can be seen in the Appendix C. As far as concern the lights are considered 3 CFL (compact fluorescent lamp) units for house, with an average rated power of 17 W, and is supposed that are used 7 hours/day. TV is assumed to be present in each house. Considering a 20”-30”, the average power from literature is 80W and TV is supposed to be used for 5 hours per day. Similar assumptions have been made for the fan and the radio. According to the sources consulted radio and fan has an average rated power of respectively 47W and 19W and are both used for 3 hours per day. The fan is supposed to be operated one hour during the day (during lunch-time) and 2 hours in the evening. As far as concern the mobile phone, is assumed a rate of ownership of 2 devices for house, which seem consistent with the high rate of diffusion that mobile phones are experiencing nowadays in Africa [58]. It is envisaged a rated power of 8W and a charging time of 2 hours. As far as concern refrigerators, it is assumed that this appliance is not owned by all the householders since it is more expensive than other equipment considered. Hence, is supposed an ownership rate of the 20% for refrigerator, according to the sources consulted. For refrigerator is supposed a rated power of 110W, with hour of consumption assumed equal to 24 hours/day. The calculation provides an average daily consumption of 1.494 kWh/day for each house and, thus, a total consumption for the community, achieved multiplying for the number of householders, equal to 298.8 kWh/day. This result has been judged as reliable since it is compatible with the value of daily consumption of tier 3 householder, according to SE4ALL multi-tier framework [30], and with REA estimation on Nigeria [11]. In the figure below can be seen, the load profile for the community, achieved by aggregating average load of the householders. As can be seen from the shape of the curve, the domestic load is quite low during day hours, while has a peak in the night, from 18 to 22 pm. It means that, in this case, the system has a low load factor. This feature will have important consequences in the following of the analysis.

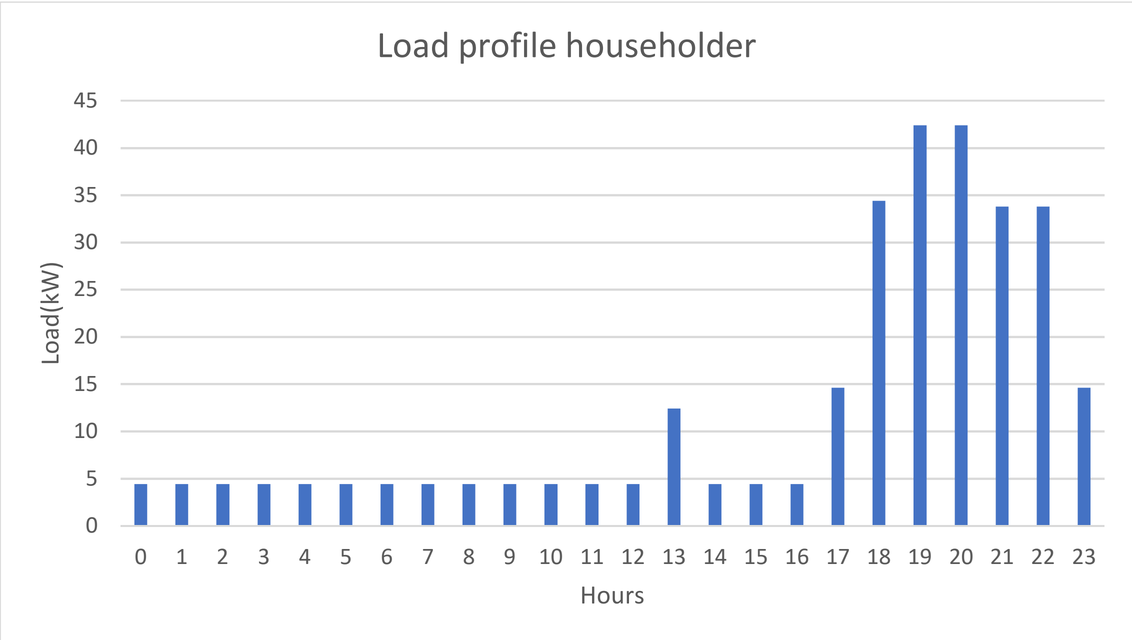


*Figure 38, Load profile of the community of householder.*

## Second scenario average load assessment

Even in the second scenario, are considered for the calculation average data from literature review and recent report.

### Small school

| Average load school | Unit per facility | Power(W) | Hours/day | Consumption/day (kWh/day) |
|---|---|---|---|---|
| **Lights** | 10 | 17 | 8 | 1.36 |
| **Miscellaneous** | 1 | 50 | 24 | 1.2 |
| **Computer** | 2 | 80 | 6 | 0.96 |
| **Fan** | 4 | 80 | 8 | 2.56 |
| **Total** | | | | 6.08 |

*Figure 39, Estimation of average consumption per day for a small school.*

In order to estimate average consumption per day of the small school, are considered 10 lights for the facility (CFLs as in the domestic load case) used for 8 hours/day, which is the typical opening time of school, looking at both lesson time and the time for preparation activities. In addition, is supposed that the school owns 2 computers, with a rated power of 80 W and which are used on overage 6 hours/day. Moreover, are accounted 4 large fans, which are largely diffused in community infrastructure in order to cope with high temperature of Nigeria. Finally, has been added a consumption stream defined as miscellaneous. This voice represents the summation of all the small consumption not due to higher appliances. Miscellaneous load has been considered active for 24 hours and imply a rated power of 50 W, according to average value from similar assessment [19], [14]. The average consumption per day is estimated to be equal to 6.08 kWh/day. The value is believed as trustworthy according to similar estimations for small school of rural areas [19], [221].

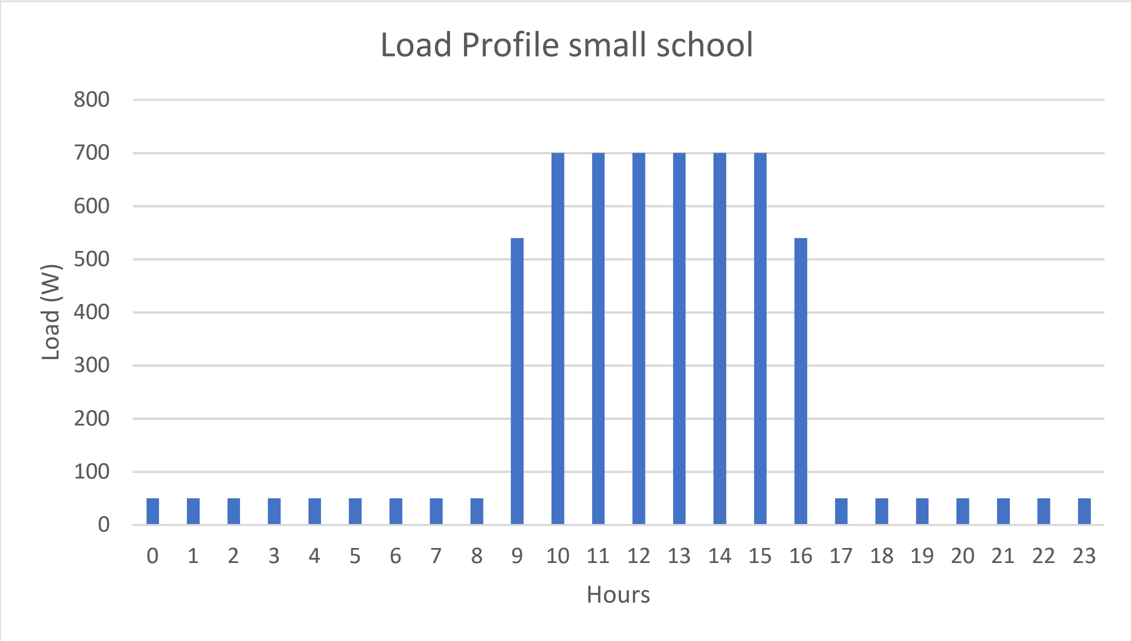


*Figure 40, Average Load profile small school*

## Health centre

| Health centre | Unit per centre | Power (W) | Hours/day | Consumption/day (kWh/day) |
|---|---|---|---|---|
| **Light** | 8 | 17 | 10 | 1.36 |
| **Computer** | 1 | 80 | 8 | 0.64 |
| **Fan** | 2 | 80 | 8 | 1.28 |
| **Refrigerator** | 1 | 350 | 12 | 4.2 |
| **Oxygen concentrator** | 1 | 400 | 2 | 0.8 |
| **Electric sterilizer** | 1 | 1500 | 2 | 3 |
| **Miscellaneous** | 1 | 50 | 24 | 1.2 |
| **Total** | | | | 12.48 |

*Figure 41,Estimation of average consumption per day for basic health centre.*

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The consumption unit of the health centre are lights (CFLs), computer, fan, refrigerator, Oxygen concentrator, electric sterilizer and miscellaneous [23], [19], [14]. Lights are supposed to be present in 8 units, with the usual rated power of 17 W. Lights are considered to be used for the entire operating hours of the centre, 10 hours. The presence of a computer is possible so as to simplify daily operations of the health centre. The PC, as defined in the case of the school, has a power of 80 W, in this case is supposed to be used for 8 hours per day. A similar reasoning can be done for 2 fans, which are used during daylight hours to fight warm climate. The refrigerator is needed in order to enhance shelf life of drugs and similar products. Refrigerator is supposed to be of a larger size respect to the small freezer considered in the case of the householder's load. Thus is accounted a refrigerator of 350 W and is supposed to be on for 12 hours/day, according to average value from literature [14], [6], [18]. Moreover, are commonly used health centre sterilizer and oxygen concentrator. For these units, is assumed an average utilization rate of 2 hours/day [23]. Finally, is considered miscellaneous load as in the case of small school load profile. The total is equal to 12.48 kWh/day. This value has been judged as consistent with reality since is similar to the result of a similar assessment [14].

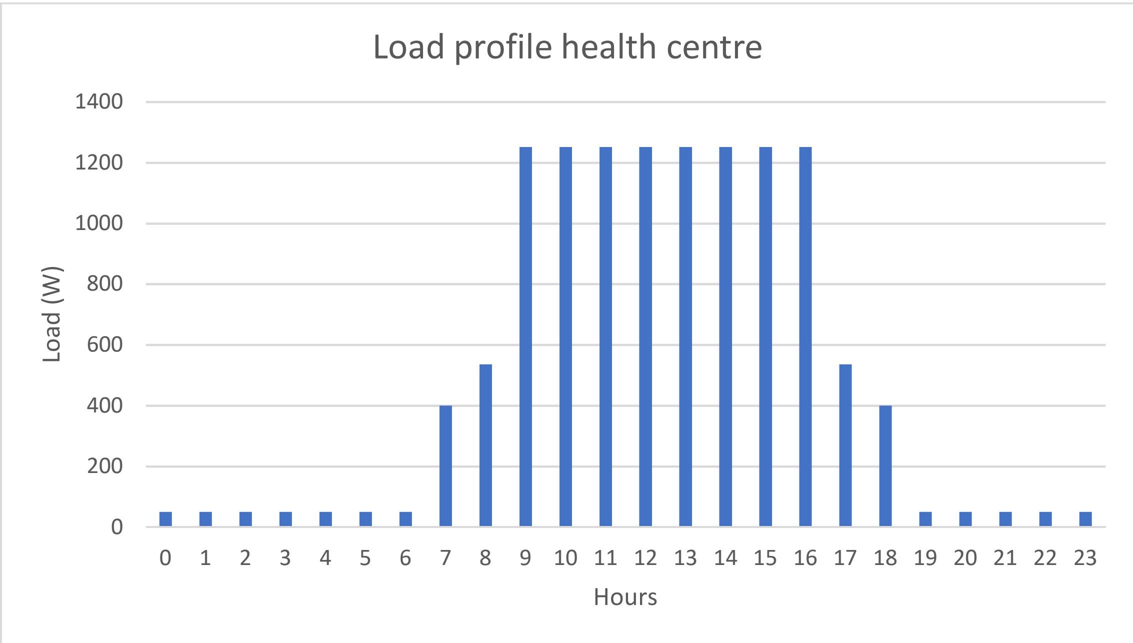



*Figure 42, Average load profile for a basic health centre in rural areas.*

### Small shops

| Small shops | Unit per shops | Power(W) | hours/day | Consumption/day (kWh/day) |
|---|---|---|---|---|
| **Lights** | 6 | 17 | 10 | 1.02 |
| **Fan** | 1 | 80 | 8 | 0.64 |
| **TV** | 1 | 80 | 8 | 0.64 |
| **Total per shops** | | | | 2.3 |
| **Total per village** | | | | 11.5 |

*Figure 43, Calculation average daily consumption for small local shops.*

As said before, are supposed to be present in the villages 5 small shops selling basic products to dwellers. The consumption units are lights, Fan and TV [14]. The operating hours of the shops are 8, from 9 am to 5 pm. Lights are assumed to be on for 2 additional hours, so as to allow preparation activities. The average rated power is considered equal to the calculation for school and health centre. The 5 shops present in the village has together an average daily consumption is equal to 11.5 kWh day. While, for a single shop is equal to 2.3 kWh/day. This value is consistent with the one indicated in the literature [221].

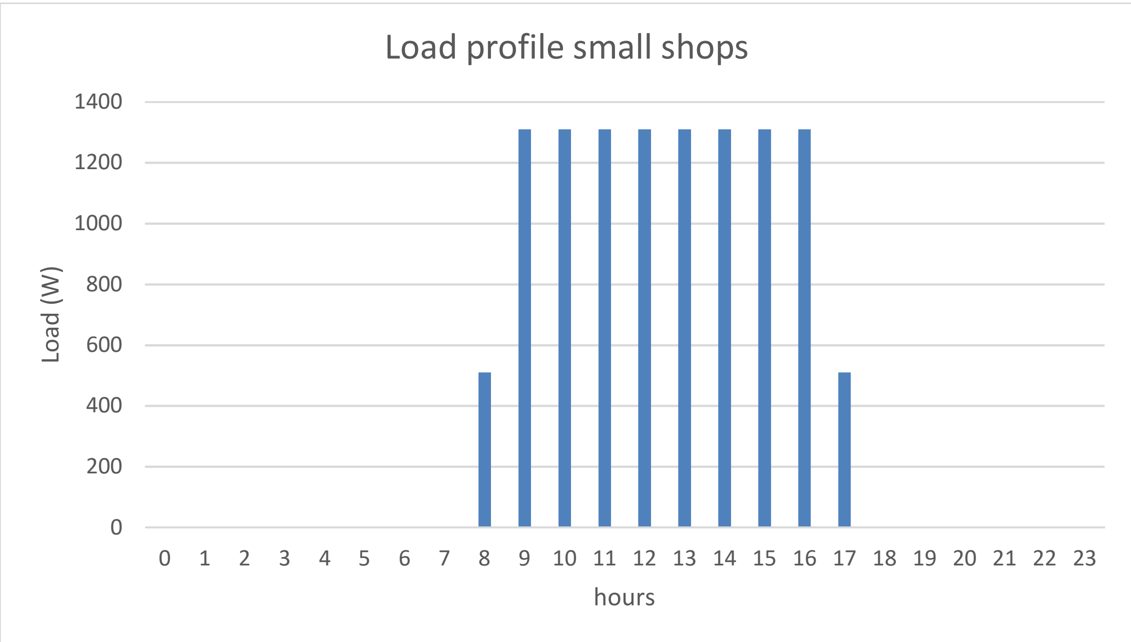



*Figure 44, Load profile small shops.*

### Small rural firm: Food-processing firm (Peanuts milling) plus carpenter

| Food-processing firm | Unit per facility | Power (W) | Hours/day | Consumption/day (kWh/day) |
|---|---|---|---|---|
| **Light** | 4 | 17 | 10 | 0.68 |
| **Miscellaneous** | 1 | 50 | 24 | 1.2 |
| **Milling machine** | 1 | 7500 | 8 | 60 |
| **Carpenter** | **Unit per facility** | **Power (W)** | **Hours/day** | **Consumption/day (kWh/day)** |
| **Light** | 4 | 17 | 10 | 0.68 |
| **Metal grinder** | 1 | 120 | 8 | 0.96 |
| **Drilling** | 1 | 350 | 8 | 2.8 |
| **Circular saw** | 1 | 1500 | 8 | 12 |
| **Planer** | 1 | 450 | 8 | 3.6 |
| **Total** | | | | 81.92 |

*Figure 45, Load assessment for a productive load: Peanuts Processing firm.*

In the second scenario it has been supposed the presence of productive load that receive electricity from the microgrid. In order to select the typology of firm present in the rural areas, it has been considered that Zamfara state is characterized by a frequent presence of agricultural cultivation [222]. Thus, it is a reasonable hypothesis to suppose the presence of a firm that process agricultural production. In particular, in North west on Nigeria there is high production of peanuts (also called groundnuts) [223]. Hence, is considered the presence of a firm which process peanuts. The processing phase is characterized by milling activities. Milling can be subdivided in huller and grinding activities [23]. The rated power for a peanut milling machine is taken from research on the web: for an average output of 0.3-0.5 t/h the rated power is 7.5 kW [224]. The operating hours of the firm are supposed to be 8 hours per day, from 9 am to 5 pm. In the calculation of average consumption for the peanuts processing firm are also accounted lights and miscellaneous loads. Additionally, has been hypnotized the presence of a carpenter. This activity is typically largely diffused in rural areas since can exploit the potential given by the abundance of woody biomass present in the north of Nigeria [199]. The machinery enabling carpentry are metal grinder, drilling machine, circular saw and planer. The rated power and the hour of utilization are supposed according to a similar assessment from Blum et al. [23]. Carpentry and milling have been selected also since are considered, among the activities diffused in rural areas, the ones that can mostly benefit from electricity availability [167].

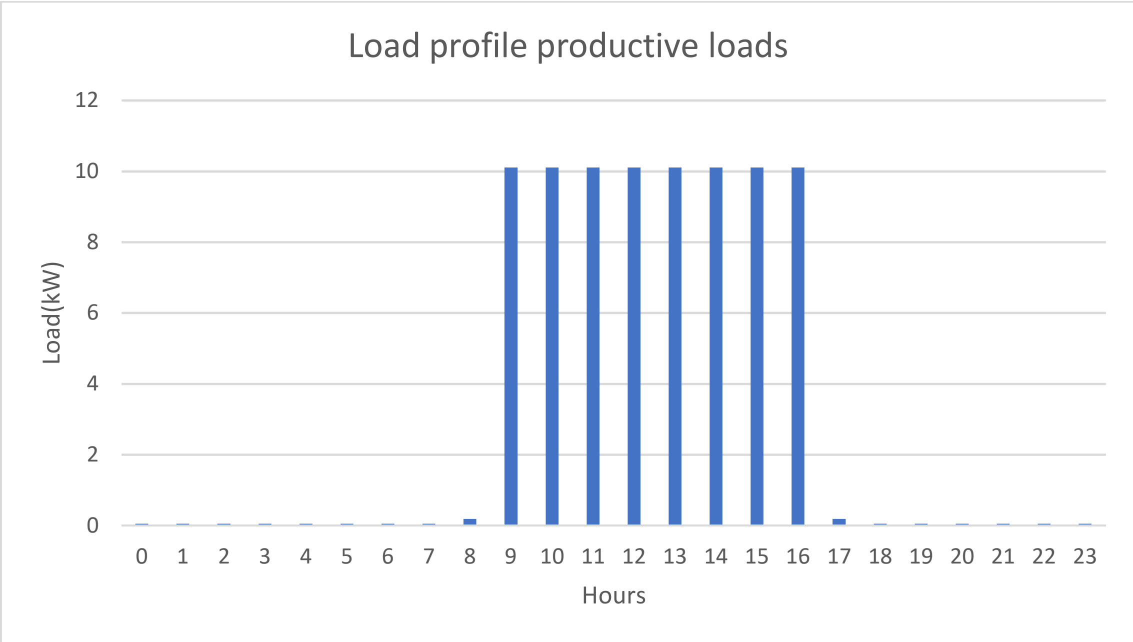



*Figure 46, Average load profile for the agriculture processing firm.*

### Total community second scenario

In order to achieve the overall load profile of the second scenario, it is needed to make the summation with load profile of householders, that represent the load profile of the first scenario. The contribution of the productive load considered (school, health centre, small shops and the two firms) generate a total average consumption per day equal to 410.78 kWh/day. These results have been judged as realistic according to similar case studies that calculate total daily load for rural village [18], [9].

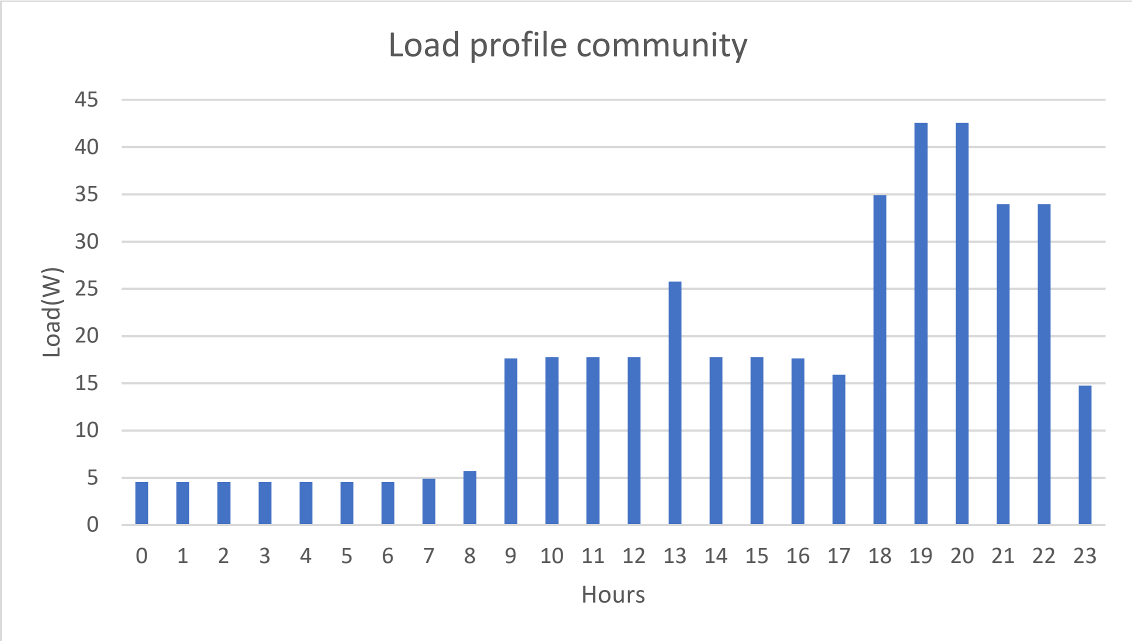



*Figure 47, Load profile of the whole community in the second scenario.*

The main implication of the load applied in the second scenario is that, productive activities, operating during daylight hours, when householder's consumption is low, enhance average load per hour of the village. The average load increase from 12.45 kW to 17.12 kW. The peak load is instead constant, and equal to 42.5 kW, in the two scenarios since is determined by householder's electricity consumption in the night hours (19-20 h). Thus, the second scenario has a higher load factor respect to the first one. Load factor shift from 0.29 in the first scenario, to 0.40, in the second one. The value is consistent with typical load factor for rural village defined by Robert et al. [21].

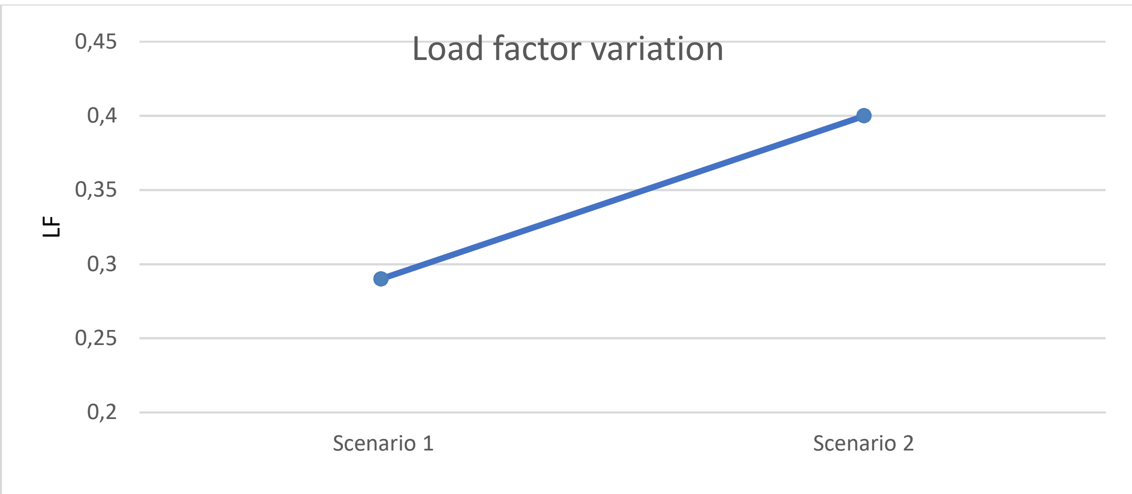



*Figure 48, Load factor in the two different scenarios*

### 7.1.2 Resources state

Another input required by HOMER software is the average daily irradiation per day ($kWh/m^2/day$). For this simulation has been downloaded data from "NASA surface meteorology and solar energy database" which provide average values for a given location analysing measurements from 22 years. For PV installations the value of interest is the Global Horizontal Irradiance (GHI). In the figure below can be seen average value per each month in the Nigerian location considered.

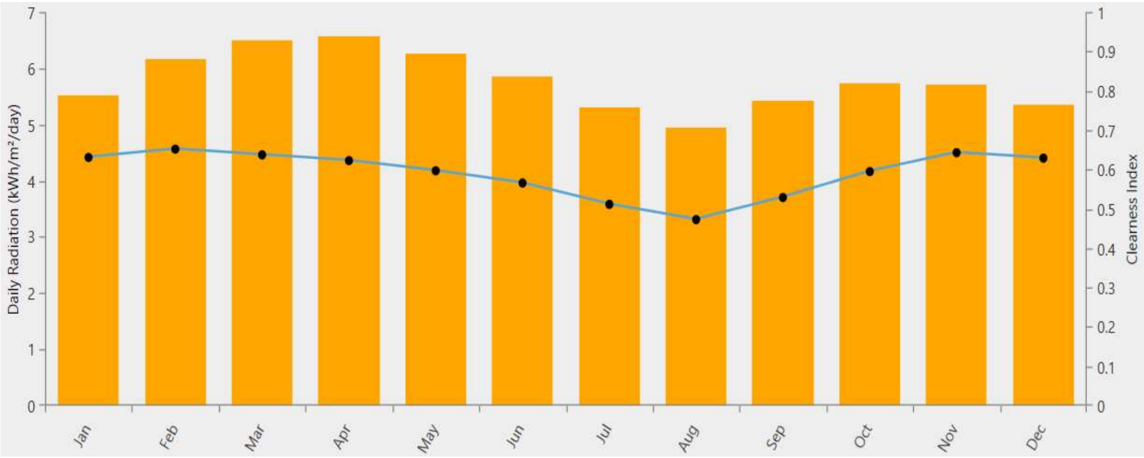



*Figure 49, Average GHI per month in Nigerian village considered.*

To determine PV electricity output, it is important to take into account also ambient temperature. Thus, it has been downloaded through HOMER also average data regarding average temperature per month in the longitude and latitude under analysis. The value are reported in the figure below.

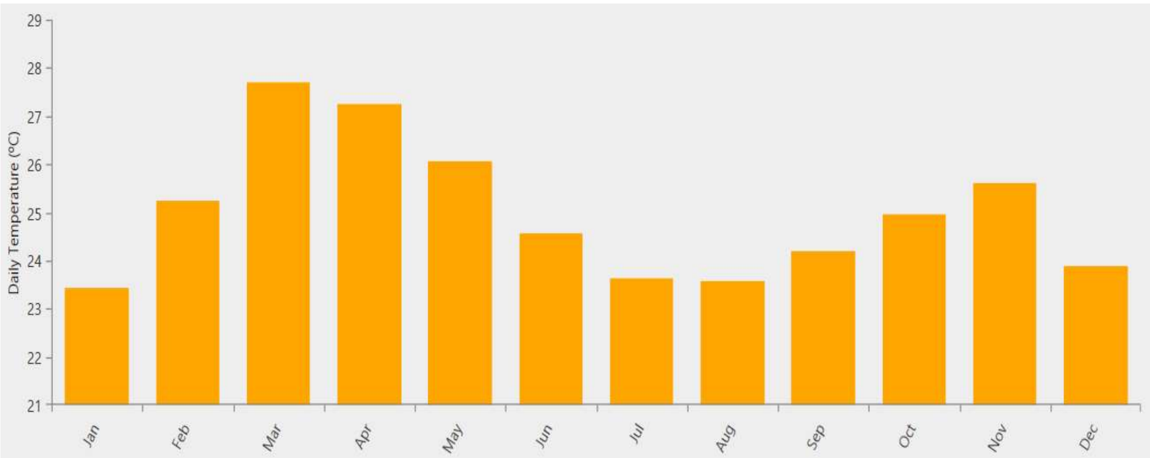



*Figure 50, Average ambient temperature in Nigerian village.*

### 7.1.3 Technological input

In HOMER software can be inserted, as input, the techno-economic assumptions related to the technologies that compose the microgrid. As stated in the methodology, the production technology considered are PV (coupled with ESSs) and diesel generator. Moreover, for transform DC power in AC is needed an inverter. Additionally, in order to evaluate Economical distance limit are needed assumption on grid extension investment cost and operating cost.

As far as concern PV panels, it is assumed to employ a generic flat plate PV. Most of the data are taken from “Enabling PV in Nigeria” since it is recent (2018) and specific of the location [204]. Moreover, for the data are considered average values from similar studies [225], [14], [9] and report [83], [86], [221]. The capital cost of PV panel is assumed equal to 1650 $/kW installed. The replacement cost is instead assumed 1500 $/kW, to take into account technology improvement in future. The maintenance cost is considered to be equal to the 2.5% of capital cost per year. The PV panels has, generally, a useful life of 25 years. It is also considered a derating factor of the 80%. Finally, it is assumed that temperature impact on PV electricity output, with a temperature coefficient of -0.5, and a nominal operating cell temperature of 47°C. The ESS adopted is a generic Lead-Acid battery. This kind of battery is commonly used in off-grid application in developing countries since has a certain initial cost advantage respect to Lithium-ion batteries. Moreover, has reached technological maturity that guarantee high reliability and round-trip efficiency [9], [111]. The technical parameters assumed for the battery are: nominal voltage 12V, nominal capacity 1 kWh, Roundtrip efficiency 80%, maximum charge current 16.7 A and maximum discharge current 24.3 A. Moreover, it is assumed that lifecycle of the batteries is function of both time and energy throughput. Thus, replacement can be due to time (aged battery) or can be caused by an excessive cycling of the battery. The specific cost for Lead-acid batteries is assumed to be 400 $/kWh and replacement cost is assumed to be 350 $/kWh, considering average value from recent sources. [9], [14], [111], [108], [221].

For the diesel generator is assumed an investment cost of 400 $/kW [221]. The technical assumptions for the diesel gensets are: expected lifetime of 15000 hours, operation and maintenance cost equal to 0.030 $ per working hour and minimum load ratio equal to the 25% of total capacity. As far as concern the diesel fuel cost, it has been considered a price of 1.10 $/l. This value has been gathered starting from "Nigerian economic summit group", which points out a unitary price between 0.5 and 0.86 $/l [205]. Then, the fuel price has been enhanced of the 40% in order to take into account transportation cost towards rural area, as indicated by Schmid [93].

For the converter is assumed a capital cost of 500 $/kW and a replacement cost equal to 400 $/kW, considering average value from literature [14], [226], [221]. The efficiency for a system converter is defined by inverter efficiency (converting DC in AC) and rectifier efficiency (converting AC in DC). It has been assumed for inverter efficiency a value of 95% and for rectifier efficiency, 90%. Useful life is considered equal to 10 years [221]. Operation and maintenance cost for the inverter are neglected [226].

Finally, as far as concern cost for grid extensions, it has been considered a unitary cost of 23000 $/km and O&M cost equal to 1.5% of investment cost per year [226], [18], [178].

Main assumptions made for input technologies are summarized in table below.

**Summary of assumptions for PV panels, battery, diesel generator, converter and grid extension**

| PV panel | Assumptions | Sources |
|---|---|---|
| **Capital Cost** | 1650 $/kw | [204], [221], [17] |
| **Replacement cost** | 1500 $/kw | [204], [221] |
| **Maintenance cost** | 2.5% of capital cost/year | [9] |
| **Useful life** | 25 years | [225], [14], [9] |
| **Derating factor** | 80% | [9], [17] |
| **Temperature coefficient** | -0.5 | [221] |

| Lead-Acid Battery | Assumptions | Sources |
|---|---|---|
| **Capital Cost** | 400 $/kWh | [108], [221] |
| **Replacement cost** | 300 $/kWh | [108], [221] |
| **Nominal voltage** | 12 V | [14], [111] |
| **Nominal capacity** | 1 kWh | [120] |
| **Lifecycle (year/throughput)** | 10 years/800 kWh | [221] |
| **Roundtrip efficiency** | 80% | [9] |

| Diesel Generator | Assumptions | Sources |
|---|---|---|
| **Capital Cost** | 400 $/kW | [221], [17] |
| **Replacement cost** | 350 $/kWh | [221], [9] |
| **Fuel cost** | 1.10 $/l | [227], [205] |
| **Maintenance cost** | 0.030 $/operating hour | [9], [23] |
| **% of transportation cost on fuel cost** | Average price+40% | [93] |

| System converter | Assumptions | Sources |
|---|---|---|
| **Capital cost** | 500 $/kW | [14], [226], [221], [17] |
| **Replacement cost** | 400 $/kW | [14], [226], [221], [17] |
| **Operation and maintenance** | 0 | [226] |
| **Inverter efficiency** | 95% | [6], [14] |
| **Rectifier efficiency** | 90% | [6] |
| **Lifetime** | 10 years | [221] |

| Grid extension | Assumptions | Sources |
|---|---|---|
| **Capital cost** | 23000 $/km | [226], [18], [15] |
| **O&M cost** | 1.5% of capital cost per year | [178] |

*Figure 51, Summary of main assumptions for technologies cost and performance.*

### 7.1.4 Financial assumptions

Inflation rate (*f*) and nominal discount rate ($i_n$) determine real discount rate ($i_r$), in function of the following equation:

$$i_r = \frac{i_n - f}{1 + f}$$

The inflation rate in Nigeria is assumed equal to 11.28%, according to "Trading Economics" Website [228]. Weighted average cost of capital (WACC) is usually employed as nominal discount rate in order to consider to what extent an investment is financed through debt and equity.

WACC is defined by the following formula:

$$WACC = k_e \frac{E}{D+E} + k_d\,(1-t)\frac{D}{D+E}$$

For Nigeria, cost of debt is assumed to be equal to 14%, current interest rate in Nigeria [229]. The fraction of debt capital and equity capital are assumed to be: debt capital 70%, equity capital 30%, which is the usual fraction in existing project [205]. Cost of equity has been estimated through capital asset pricing model formula:

$$k_e = r_m + \beta\,(r_m - r_f)$$

Risk free rate is the rate of return a risk-free investment in Nigeria and is assumed equal to 5% [230]. Market risk, $r_m$, reflect average return of Nigeria market and can be assumed equal to 11.20% considering the average return of Nigerian Stock Exchange [231]. Beta takes into account the risk specific of the investment and is assumed equal to 1,2. Thus, cost of equity results 12%. The data gathered generates a WACC equal to 13.5%, and a real discount factor of 1.99%. The project lifetime is assumed to be equal to 25 years, as is usually done in project regarding energy investment.

After the analysis of regulatory framework, have been selected subsides on initial capital as supporting mechanism to be applied in calculation. Thus, in hybrid microgrid, it has been imposed to HOMER simulator a constraint on the minimum percentage of renewable penetration allowed. As a matter of fact, as said before, in order to be judged as eligible party to receive REF aid on capital cost, it is required that RES fraction is equal or higher than the 30% of total production [212]. The subsides for each connection is calculated in function of the tier of service. In the first scenario, it has been used subsides for tier 3, which is equal to 300 $ per user. Indeed, the electricity is used only by householders to satisfy low power appliances. Conversely, in second scenario has been considered subside per connection related to tier 5 (600 $/connection), since electricity is used for commercial and productive purposes [212]. Technical assistance by REA, has also been considered since the beneficiaries of this support are all microgrid projects targeting rural area. This support has been implicitly considered in calculation through an underestimation of initial cost for site selection, project assessment and transaction costs for require permits. Concessional loans from bank of industry are not considered since are assigned only to small and medium enterprises leveraging on solar energy. Thus, it is not clear if community of householders can benefit of this incentive. Finally, split-asset model by GIZ offers a benefit lower than capital subsides from REF.

### 7.1.5 Other generic assumptions

In addition to cost for technologies, it is needed to consider system fixed operating cost which are sustained regardless of the architecture and the size of the microgrid. To this category belong land lease cost, which are estimated equal to 800 $/year [221], [232]. Management cost per year as well have to be considered as fixed cost which are sustained regardless of system size. In this cost stream can be aggregated: costs for customer relations, revenue collection cost and metering cost. Considering estimation of Reber et al. for villages in rural areas of Kenya and Zambia, these costs can be estimated as equal to 3000 $/year [221].

HOMER software considers that generating and consumption unit composing the microgrid are located in the same point. Thus, neglect the impact low-voltage distribution network on total investment cost. In order to take into account also grid cost, have been added to investment cost an estimation of the grid cost. This cost has been calculated through the formula:

$$C_{grid} = c_{LV}\, x + N\, C_{conn}$$

Where $c_{LV}x$ , it is the product between unitary cost of low-voltage distribution network and the length of distribution lines needed to transmit electricity to the village. $N\, C_{conn}$ , it is the connection cost for each energy user multiplied by the number of users. The numeric value considered are taken from a tool developed by REA with the aim of calculate microgrid tariff according to a MYTO methodology [233]. $c_{LV}$ is assumed equal to 5300$/km, $x$ has been roughly estimated equal to 4 km thanks to *Google Maps*. $N$ is equal to 200 in the first scenario, while 208 in the second scenario (Adding productive load) and $C_{conn}$ is assumed equal to 137 $/connection. Hence, it results in an additional investment of 48865$ in the first scenario, and 49961$ in the second one. In the initial investment has also to be considered project design and administrative cost, accounting for almost 4000 $. Finally, must be added installation cost, accounting for almost 6000 $ [233].

## 7.2 Optimal results and cost analysis

HOMER software finds the optimal size of technologies to meet the load considering imposed condition (cost of technology, constraints, operating cost). As said in the methodology part, are evaluated three possible configurations: Solar microgrid (PV plus storage systems), diesel microgrid (all the load is satisfied through fossil fuel production), Hybrid microgrid (PV plus storage and diesel generator). For these three configurations are analysed variation of economic performance in function of the load and regulatory framework variation.

### 7.2.1 Solar microgrid

**Results**

According to HOMER simulation, the component of the solar microgrid are sized in order to meet the load considering constraint. The optimal mix that minimize LCOE and NPC for the two scenario is:

| **Scenario** | **PV plant** | **L.A. Batteries** | **Converter** |
|---|---|---|---|
| 1 | 286 kW | 746 kWh | 67.6 kW |
| 2 | 373 kW | 848 kWh | 47.2 kW |

*Figure 52, Optimal system architecture in the two scenarios for solar microgrid.*

In the first case, system architecture, together with operating, maintenance and replacement costs goes to determine an LCOE equal to 0.87 $/kWh and a total NPC of 1852360 $. Considering the impact of capital subsides on the initial investment LCOE is reduced up to 0.84 $/kWh and NPC to 1792360 $. As a matter of fact, capital subsides implies a reduction in CAPEX of 60000 $ (calculated on the base of tier 3 as explained in the assumptions). On the other hand, in the secondo scenario, the optimal architecture leads to a LCOE which is lower respect to the previous case, equal to 0.7 $/kWh, while NPC increase to 2047890 $, due to the enlargement of the system size. LCOE after subtracting 125400 $ (Tier 5 subsides per connection) of REF subsides is equal to 0.656 $/kWh and NPC decrease to 1922490 $.

### Costs analysis

The breakdown of Net Present Cost in function of technology component can help to underline which component has a larger impact on total cost. As can be seen from the figure, the life-cycle cost of Lead-Acid batteries has the highest contribution on total NPC, due to the high frequency of replacement respect to PV plant, which instead has a useful life of 25 years. Below there is the graph only for the second scenario, the first scenario graph is quite similar and so it has not been reported.

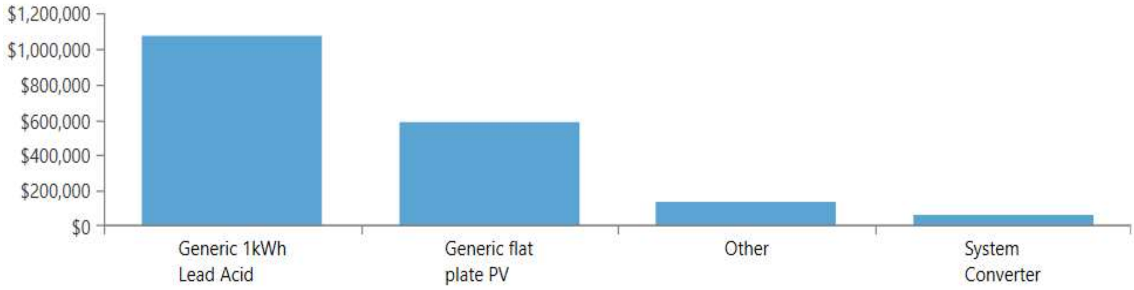



*Figure 53, Breakdown of NPC for solar microgrid in function of the main system component.*

Net present cost can be also subdivided in function of the different cost categories that compose total expenses. Initial capital investment is predominant in solar microgrid. Initial CAPEX is dominated by the PV plant capital cost which accounts, respectively, for the 55% and 59% in the two scenarios. Operating cost has a low contribution on total cost while since PV plant require low O&M expenses. Fuel cost is absent, being microgrid entirely based on solar energy. Replacement cost are relevant and are, almost for the totality, due to batteries substitution after the end of useful life for cycling. Terminal value of the asset (in the graph reported as "salvage value") is determined by batteries and converter which have not ended their useful life after 25 years.

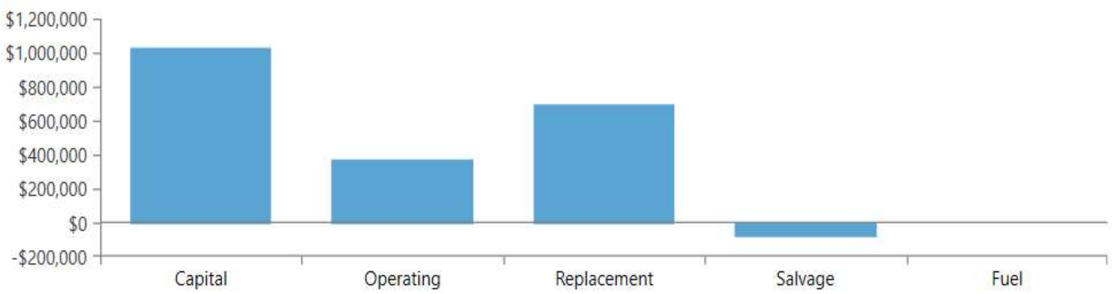



*Figure 54,Breakdown of NPC for solar microgrid in function of typology of cost.*

Cash outflow for a solar microgrid is not regular along the years, it is instead concentrated in the year zero, where initial investment take place, and in the years when replacement of the batteries occurs. In the other years, management cost and operating cost of technologies imply minimum yearly expenses. Cash flow per year for the different cost categories are reported in the graph below.

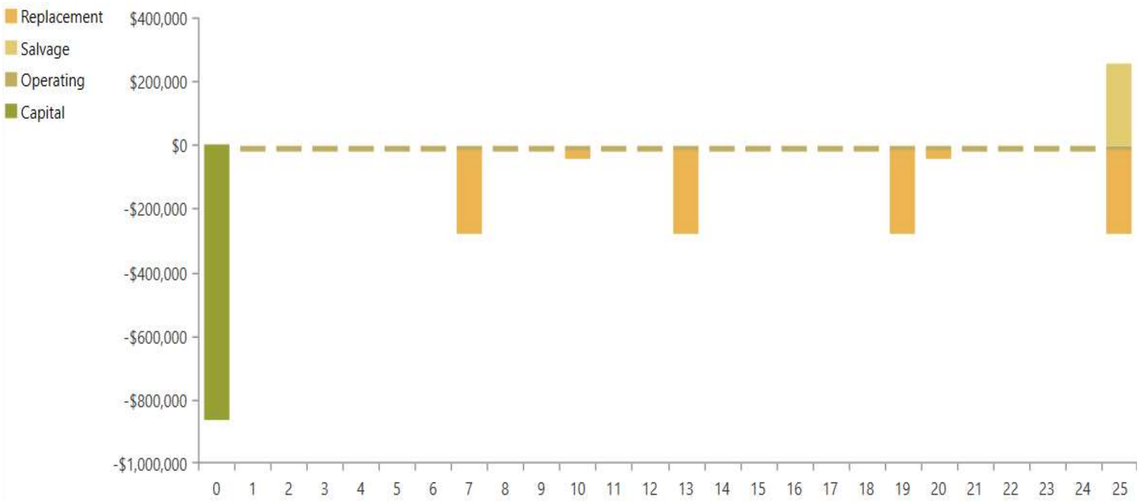



*Figure 55, Cash outflow along the years for solar microgrid.*

**Other considerations**

As far as concern batteries utilization can be done some observations. The load of first scenario imply a higher utilization of the energy storage system. As a matter of fact, the electricity consumption is mainly concentrated in the night hours (after 18 h), being absent productive load, which consume energy during business hours (9-17 h). Conversely, PV electricity generation happens during daylight hours (from 6 to 18 h). Considering annual throughput, the amount of energy that cycles through the storage bank in one year, it is equal to 96682 kWh/year in the first case. Since storage system is composed by 746 strings, the throughput for single battery is 129.7 kWh/year. In the second scenario, instead, total throughput in battery bank is 96830 kWh/year in 848 strings, 114 kWh/year per single battery. Thus, it occurs a lower throughput per year for single battery in the second scenario. Considering the ratio between annual battery throughput and total energy produced it is equal to 22% in the first scenario and 17% in the second scenario. Hence, showing that, in the first scenario, a higher share of total energy produced by the PV plant is stored in batteries for be later used. These characteristics has direct impact on economic performance. A battery cycling more energy per year face a faster degradation rate. Indeed, average battery life in the first scenario is equal to 6.17 years, one year lower than in the useful life in second scenario: 7.1 year. A shorter lifecycle brings to a more frequent battery replacement. Hence, battery replacement cost is higher in the first case than in the second case even if battery size is lower. Replacement cost, in the first scenario, has a higher impact on total life cycle cost of battery (777152 $ the 72% on total cost, respect to 679432 $ the 61% on total cost). The effect of a less efficient usage of the batteries, in the first case respect to the second one, can be also observed looking at the percentage of battery cost on total NPC. This share of battery cost accounts for the 54% on total NPC in the second scenario, while for the 58% in the first scenario considered.

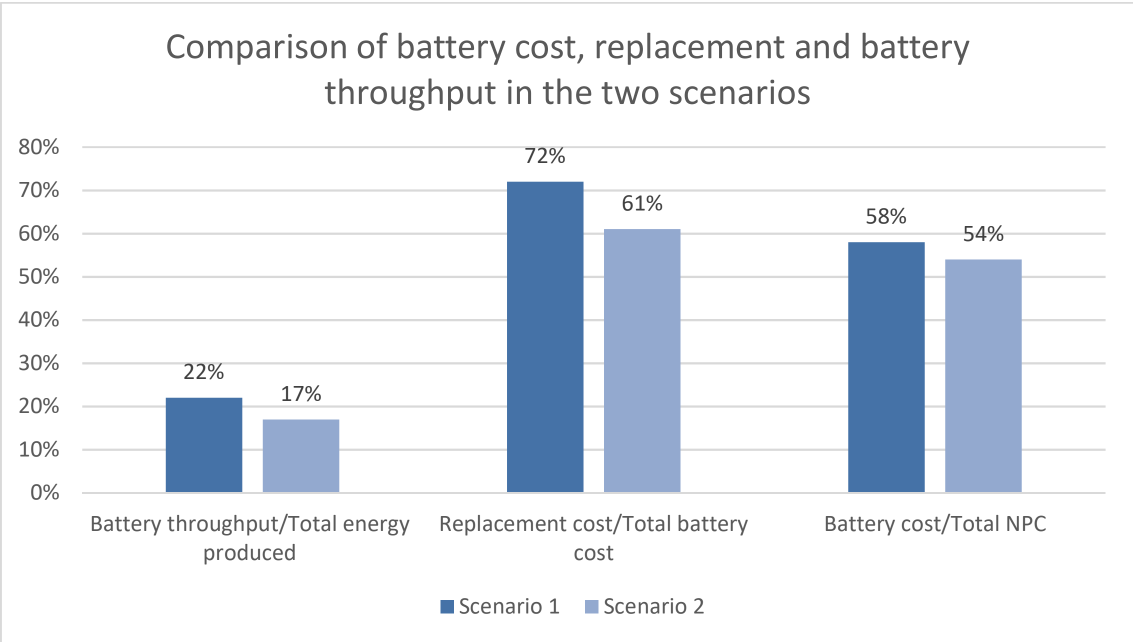



*Figure 56, Comparison of battery cost, replacement and battery throughput in the two scenarios.*

### 7.2.2 Diesel microgrid

**Results**

In the first scenario the optimal size of diesel generator, according to HOMER software simulation, is 47 kW. With considered fuel price, it determines an LCOE equal to 0.873 $/kWh in the first scenario. Total NPC is equal to 1860065 $. In the second scenario optimal size of diesel generator is also equal to 47 kW, being equal the peak load in the two cases. LCOE is significantly reduced in the second scenario considered, since the enhanced demand lead to a more efficient electricity production. LCOE accounts to 0.672 $/kWh, while NPC is equal to 1967808 $.

**Costs analysis**

Breakdown of NPC by cost component is not relevant due to the presence of the diesel gensets alone and the distribution system. Subdivision of cost by cost type, instead, shows that the life-cycle cost stream that is more relevant on total cost is fuel cost. Fuel cost account on the total actualized costs for the 69% in the first scenario and for the 68% in the second one. Conversely, initial CAPEX and replacement cost represents a minimum share of total costs being absent PV modules and batteries which are the most expensive items in the other configurations. Initial investment impact only for the 4% on total net present cost in both the scenarios. Replacement cost of generator impact for the 10% on total NPC.

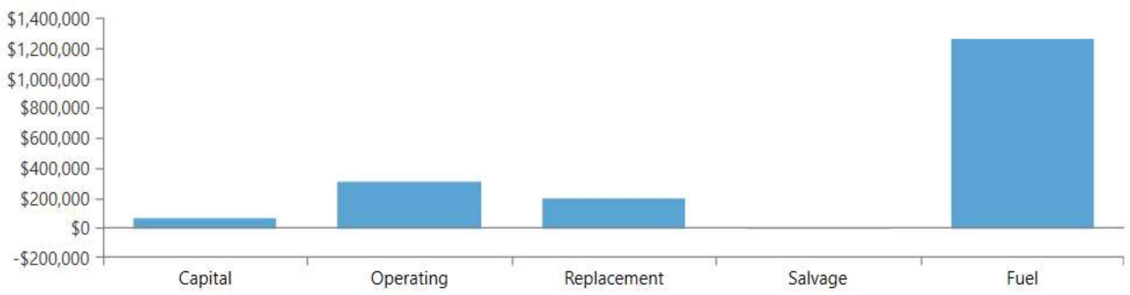



*Figure 57, Breakdown of diesel generator NPC according to cost type.*

As can be seen in the figure below, a system based only on diesel generator, implies a totally different cash outflow for investors respect to an only solar-based microgrid. In this case, cash outflows are quite constant over the length of the project and dominated by fuel cost. Moreover, since diesel generator is used almost continuously, it is frequent replacement of the generators which has a useful life of 15000 operating hours, almost 2 years. There is minimum contribution of salvage value since generator has a limited value, while storage systems and PV modules are absent.

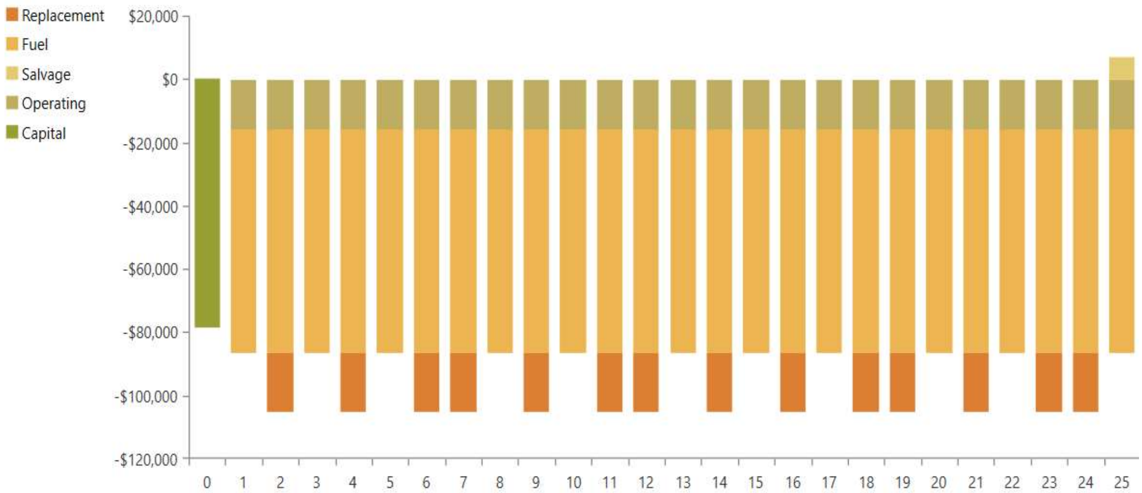



*Figure 58, Cash outflow by cost type for diesel generator.*

**Other considerations**

In the second scenario, despite of an increase in fuel cost and operating cost, LCOE decrease of the 23% respect to the first scenario. This decline is due to the increment in average load of village. As a matter of fact, in diesel generator, efficiency is function of the operating load of the systems. When the load on the system decrease, efficiency decline as well. Thus, operating the system with higher average load, means that the output (the energy produced) increase more than the energy input (the fuel itself). Calculation demonstrate this theoretic concept. In the second scenario, average electrical efficiency, calculated as the ratio between annual electricity output and yearly diesel energy input, is equal to 27.5 %, while in the first one is equal to 26.2 %. The same trend can be observed looking at specific fuel consumption, which is higher in the first scenario (0.387 l/kWh) than in the second one (0.368 l/kWh). Moreover, in order to avoid working at too low level of load (and thus efficiency), diesel generators are usually not operated below a certain value of output power, defined as minimum load ratio. Minimum load ratio is defined as a percentage of total rated capacity and, in this case, is equal to 25% of 47 kW (11.75 kW, the sky-blue area in the graph). Hence, there is a certain share of electricity that is produced just to operate at a load at least equal to minimum load ratio. Without batteries, as in this case, this energy is wasted. More energy wasted means a higher LCOE. Indeed, at the denominator of unitary cost formula, it is present the electricity served to final consumers. In the first scenario, being average load low, energy wasted is equal to 42915 kWh/year, the 28% of the total production. In the second case, average load is higher, and energy wasted declines to 23111 kWh/year, accounting for the 13.4% on the total electricity production of the system.

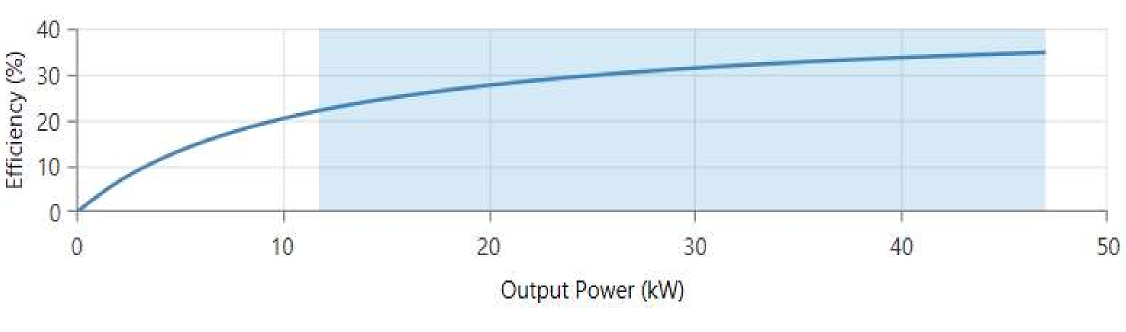



*Figure 59, Variation of efficiency in function of output power.*

In the case of diesel microgrid there is not the possibility to benefits of support mechanism like in the case of solar and hybrid microgrid since renewable penetration is equal to 0%. Hence, the LCOE above defined coincide with the real cost sustained by investors. Obviously, this is the worst scenario considering environmental impact, with $CO_2$ emission equal to, respectively, 154137 kg/year and 167128 kg/year in the two scenarios of load considered.

### 7.2.3 Hybrid microgrid

**Results**

The third configuration considered imply the complementary presence of diesel PV plant, with diesel generator, and storage systems. In the table below can be seen for the two scenarios of load the optimal sizing of the system according to HOMER software simulations. Introducing diesel generator, it is possible to reduce life cycle cost for PV plant and Lead-Acid batteries, achieving a reduction of NPC and LCOE respect to a system based only on solar energy.

| Scenario | PV plant | Generator | L.A. Batteries | Converter |
|---|---|---|---|---|
| 1 | 43.5 kW | 47 kW | 138 kWh | 16.2 kW |
| 2 | 83.6 kW | 47 kW | 147 kWh | 28.6 kW |

*Figure 60, Optimal sizing of the Hybrid microgrid system.*

In the first scenario electricity is generated at a unitary cost equal to 0.497 $/kWh with NPC equal to 1060151 $. As in the solar microgrid configuration, can be subtracted capital aid from REA to initial CAPEX. As a matter of fact, even if the system relies also on a diesel generator, it is present a penetration of renewable energy higher than the 30%, which is the minimum requirement to be judged as eligible for the incentive. Thus, real LCOE is equal to 0.469 $/kWh (lowered of the 6%) and NPC decreases to 1000151 $. In the second scenario LCOE before considering grants and after are, respectively, 0.404 $/kWh and 0.361 $/kWh (reduced of the 11%), while real NPC is 1057886 $. The impact of subsides in the second scenario is stronger, since is considered a higher unitary subsides due to the presence of productive load into the system. Optimal renewable energy fraction is different in the two scenarios: in the first case is 35.4%, while in the second case PV penetration is 51.5%. The reason for this difference is that, in the second scenario, additional loads occur during daylight. Thus, can be easily served with PV electricity.

**Cost analysis**

In both the cases, breakdown of net present cost in function of the system component is dominated by costs related to diesel generator. As a matter of fact, the size of non-renewable energy delivered to users is relevant in both scenarios. For shortness, below is reported only the subdivision for the second scenario, since the breakdown for first scenario is similar, with the exception of PV modules costs that are lower.

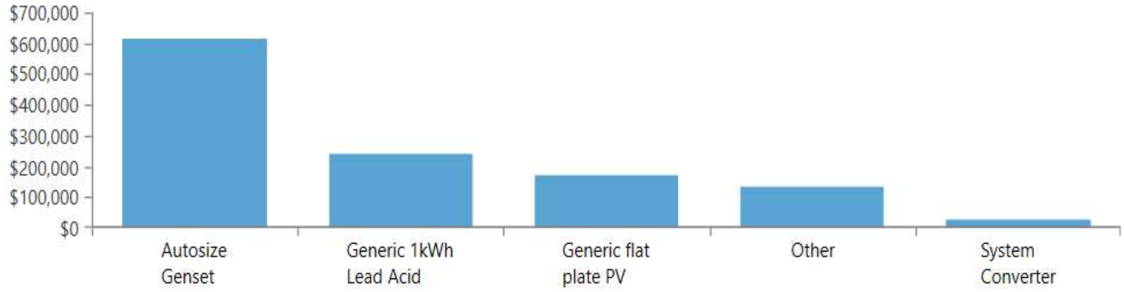



*Figure 61, Breakdown of NPC by component for Hybrid microgrid.*

Looking at breakdown of NPC by cost type, fuel cost is predominant. However, fuel cost, is significantly lower than in the configuration based on only diesel microgrid. In Hybrid configuration, the share of NPC allocated to fuel cost is around the 40% of the total, respect to the 68-69% of the only diesel system. In absolute terms, the hybrid system reduces total fuel cost of one third respect to only diesel case. Capital cost is characterized by the investment in PV plant, which account for the 33% of total initial investment in the first scenario and for the 47% in the second one, due to the additional daylight load which is met through PV electricity. Replacement costs are higher in the smaller system (first scenario), than in the larger one (second scenario), due to taller battery replacement cost. Indeed, battery replacement cost account for 182506 $ during project length, the 77% of total replacement cost. In the second scenario, instead total battery replacement costs are 159612 $, the 72% of the total. This fact is not surprising, since it is valid the reasoning made in the case of solar microgrid: load profile of first scenario lead to a more frequent cycling of the batteries that boost degradation mechanisms. Lifecycle of the battery is shorter in the first case, 4.8 years, against 5.4 years in the second case, and thus replacement is more frequent, enhancing costs.

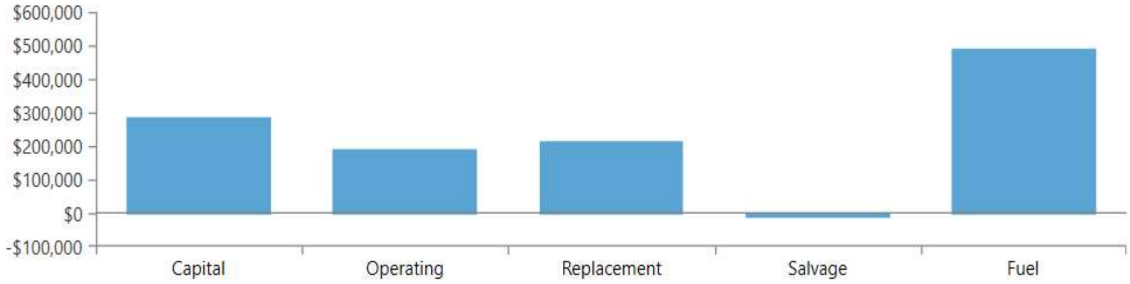



*Figure 62, Breakdown of NPC in function of cost type for Hybrid microgrid.*

Looking at the distribution of cash outflow during the years, hybrid configuration generates expenses which are a mix of the previous two cases. As a matter of fact, the presence of PV plant and batteries implies high investment cost as in the case of solar microgrid. Replacement cost are frequent and moderated as well and are mainly due to battery replacement cost. Moreover, the presence of diesel generator produces constant cash outflow for operating and fuel expenses as in the case of microgrid based entirely on diesel production.

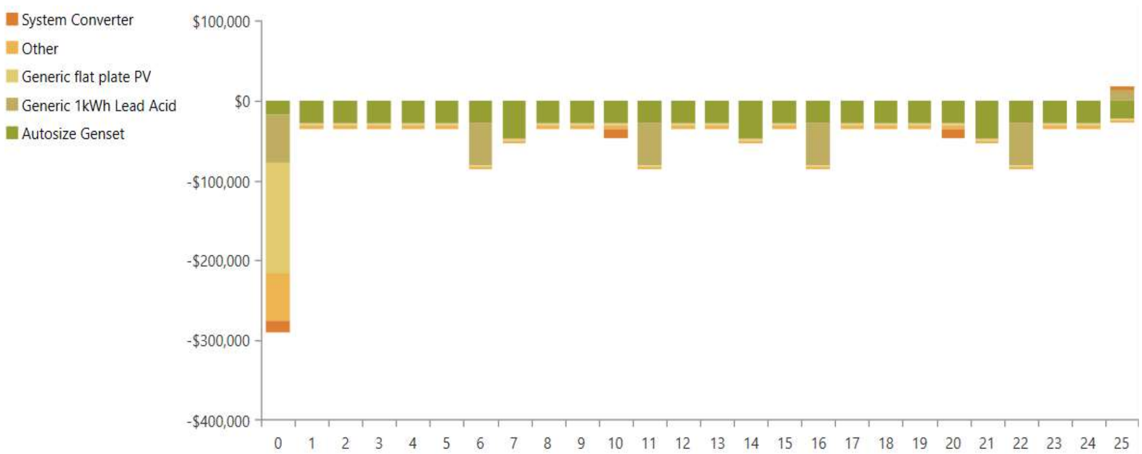



*Figure 63,Cash outflow per cost type in case of Hybrid microgrid.*

**Other considerations and comparisons with previous configurations**

One of the main barriers for private investors is the initial capital expenditures. Thus, it is interesting to analyse the impact of hybridization on the initial investment. Hybrid systems allow to reduce initial CAPEX respect to solar microgrid since the introduction of diesel generator imply a reduction in the size of PV plant and batteries. This reduction is evident both in absolute terms and relative terms respect to total NPC. In the first scenario initial capital cost in Hybrid system is 212764 $, the 20% of total NPC. While, in solar microgrid, capital investment is equal to 862767 $, the 47% of total NPC. In the second scenario initial investment in hybrid system is 289731$, the 25% of NPC, while, in the solar microgrid, initial capital expense account to 1.03 million $, the 51% of total NPC. The share of initial CAPEX on NPC can be seen in the figure below. Thus, hybrid systems costs, are more distributed along project duration and not highly concentrated in the initial investment as in solar microgrid. This characteristic may be a driver for investors for whom gather initial capital it is a hard and challenging task.

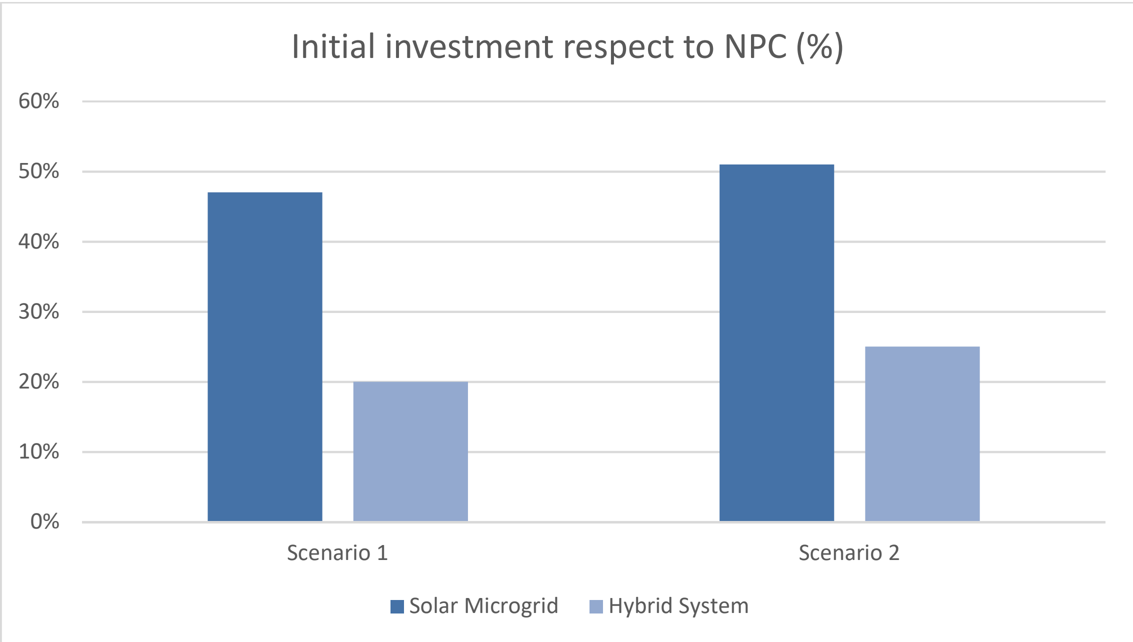
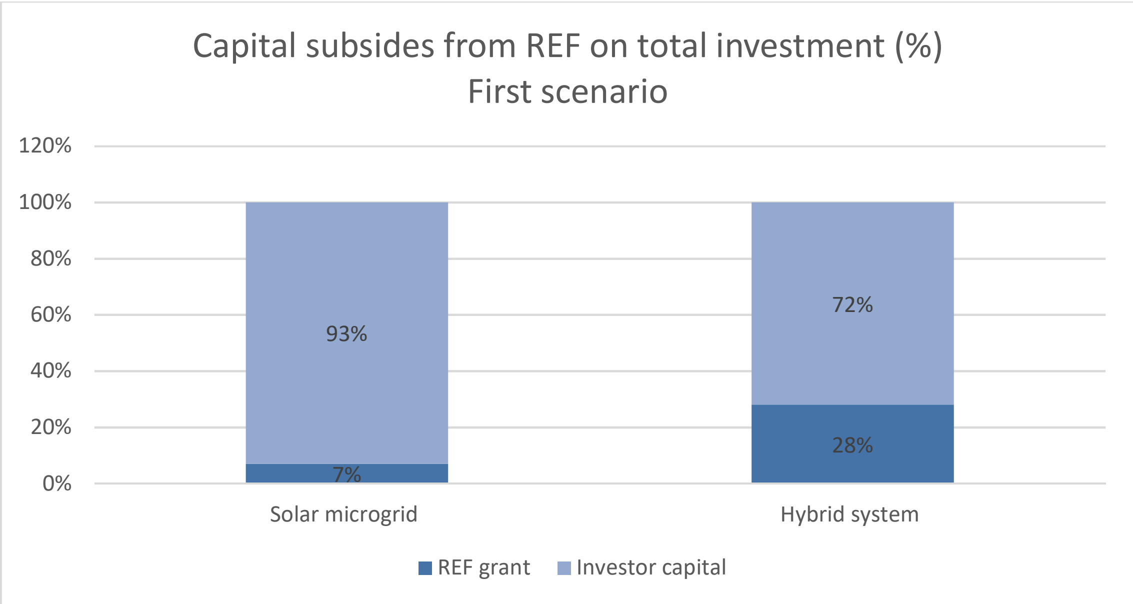



*Figure 64, Share of initial investment on total NPC for hybrid system respect to solar microgrid.*

The current structure of regulatory framework does not contribute the reduce the initial investment barrier in case of solar microgrid. As a matter of fact, the amount of capital subsides, provided by REF to private investors, does not depends on the size of the initial investment. It is instead calculated in function of the number of expected connections to the microgrid, which influence into a low extent the initial investment. The consequence is that REF contribution on initial investment in case of solar microgrid is minimum respect to total cost. In solar microgrid, capital subsides impact for the 7% on total initial capital investment in the first scenario, and for the 12% in the second scenario (recalling that in the second case it is considered a higher grant per connection due to the presence of productive load). On the other hand, in case of hybrid systems, subsides from REF has a higher impact on initial CAPEX. Indeed, capital subsides, represent a share of the 28% on total investment cost in the first scenario and of the 44% in the second scenario. Hence, provide a sharper contribution in relative terms to private investors. The situation is represented in the two graphs below, related to the two scenarios.



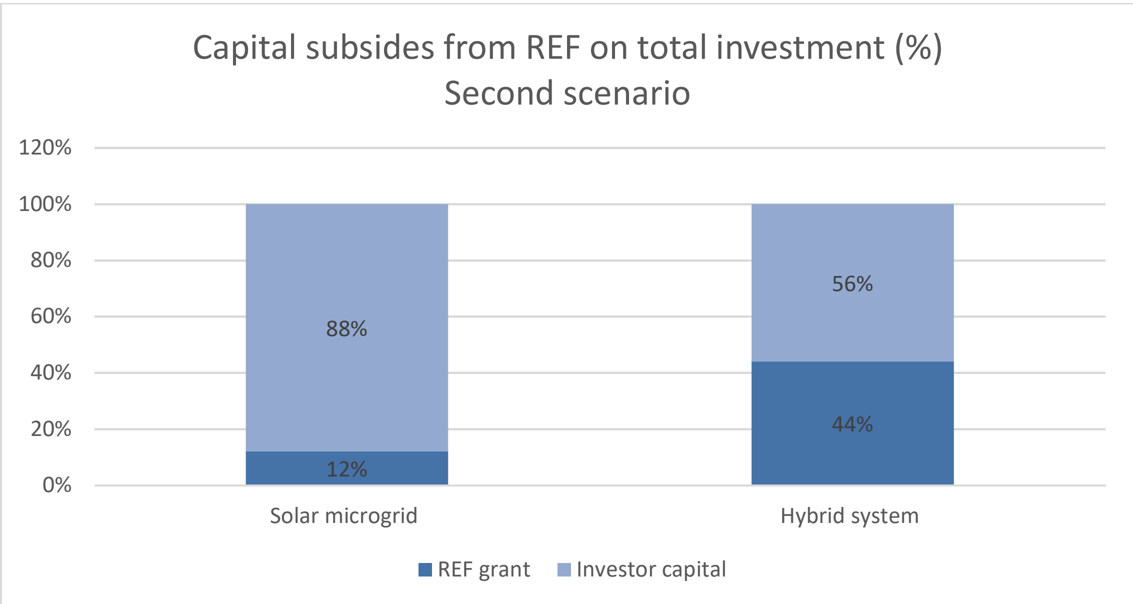




*Figure 65, Share of Capital subsides on total initial investment for solar microgrid and Hybrid system*

As far as concern emission, hybrid system represents a good trade-off between zero emission, as in the case of solar microgrid, and the elevated emission level caused by diesel generator alone. Indeed, diesel generator presents in the hybrid systems, produces in the first scenario 57512 kg/year of $CO_2$, achieving a reduction of the 62% respect to the case in which the diesel gensets alone is employed to meet the load. In the second scenario the reduction is even steeper since load profile permit a higher PV penetration. Are emitted 60038 kg/year of $CO_2$, the 64% lower than in the diesel alone system. Thus, this hybrid microgrid, even if rely on significant share of electricity from diesel generator to face demand in the less expensive way (the 64.6 % in the first scenario and the 48.5 % in the second scenario), is able to reduce emission in a relevant way respect to fossil fuel-based system.

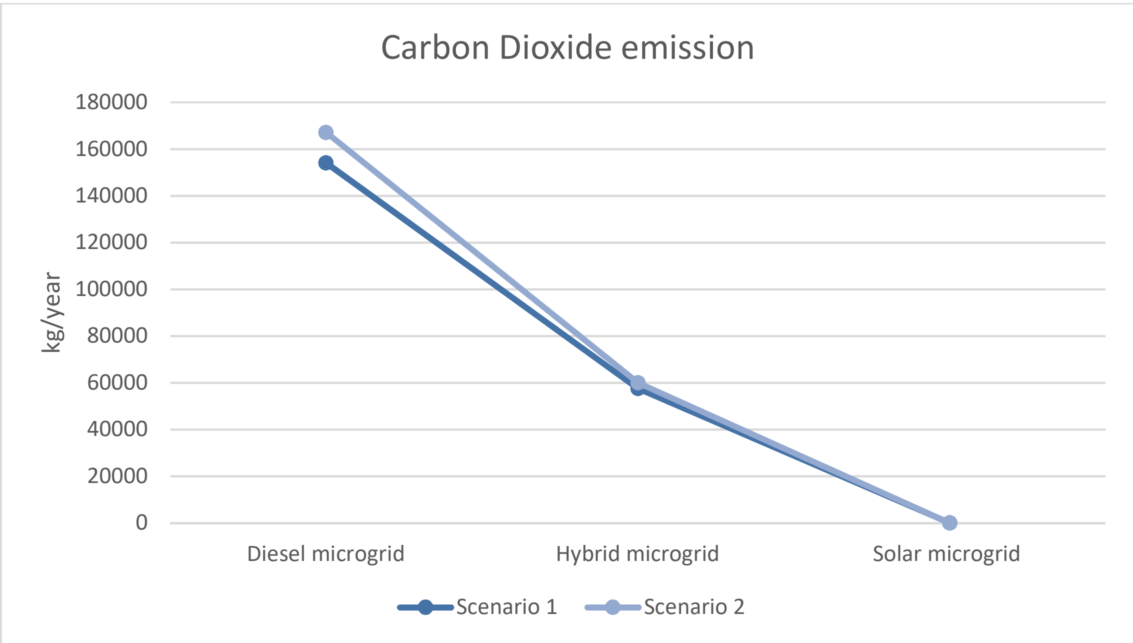



*Figure 66, Carbon dioxide emission per year in the three configurations.*

## 7.3 Comparison among results

The table below summarize levelized cost of electricity (after subtraction of subsides when are present) for the 3 configurations considered and the two scenario of load profile.

| Cost summary | Scenario Load factor | Solar microgrid | Diesel microgrid | Hybrid microgrid |
|---|---|---|---|---|
| **LCOE** | 0.29 | 0.840 $/kWh | 0.873 $/kWh | 0.470 $/kWh |
| | 0.40 | 0.656 $/kWh | 0.672 $/kWh | 0.361 $/kWh |

*Figure 67, LCOE summary for the 3 configuration and the 2 scenarios of load.*

### 7.3.1 Analysis on configurations

From the analysis of the results related to the three configuration it emerges that, with this load profile and with these assumption for technology costs, hybrid configuration is able to guarantee the most cost-effective performance. HOMER optimal hybrid configurations deliver electricity to user at a cost which is almost 0.30 $/kWh than the second-best option which is solar microgrid. Initial results for solar microgrid and diesel based microgrid are quite similar. However, after subtracting capital grant, not assigned to diesel microgrid, solar microgrid LCOE gains about 0.03 $/kWh cost advantage respect to diesel-based systems. The cost advantage that hybrid systems has over solar microgrid can be explained considering that, the introduction of diesel generator in the system, permit to reduce lifecycle cost linked to PV plant and Lead-Acid batteries which imply high investment and replacement cost in solar microgrid case. It is interesting to stress that cost difference between solar microgrid and hybrid system is significative. For example, considering solar microgrid in the second scenario and supposing a hypothetic simultaneous reduction of PV module price and batteries price of the 50% respect to the as-is input data. This reduction of costs may be determined, for instance, by an aggressive government support on the investment cost in cleaner technologies. However, even supposing this relevant cost reduction, LCOE of solar microgrid will be equal to 0.44 $/kWh, which is still higher than the LCOE of Hybrid systems with current input data (0.40 $/kWh without grant). Or else, the cost differences between Solar microgrid and Hybrid microgrid, can be noticed considering fixed LCOE of solar microgrid and letting variate diesel price to evaluate change in LCOE of hybrid system. As can be seen from the graph below, would be needed a fuel price of nearly 2.8 $/l to allow Hybrid systems

LCOE to equalize LCOE of solar microgrid which, obviously, is not linked to fuel price. This price for diesel is quite unrealistic in light of current average values, suggesting that there is relevant cost advantage for hybrid system respect to solar microgrid.

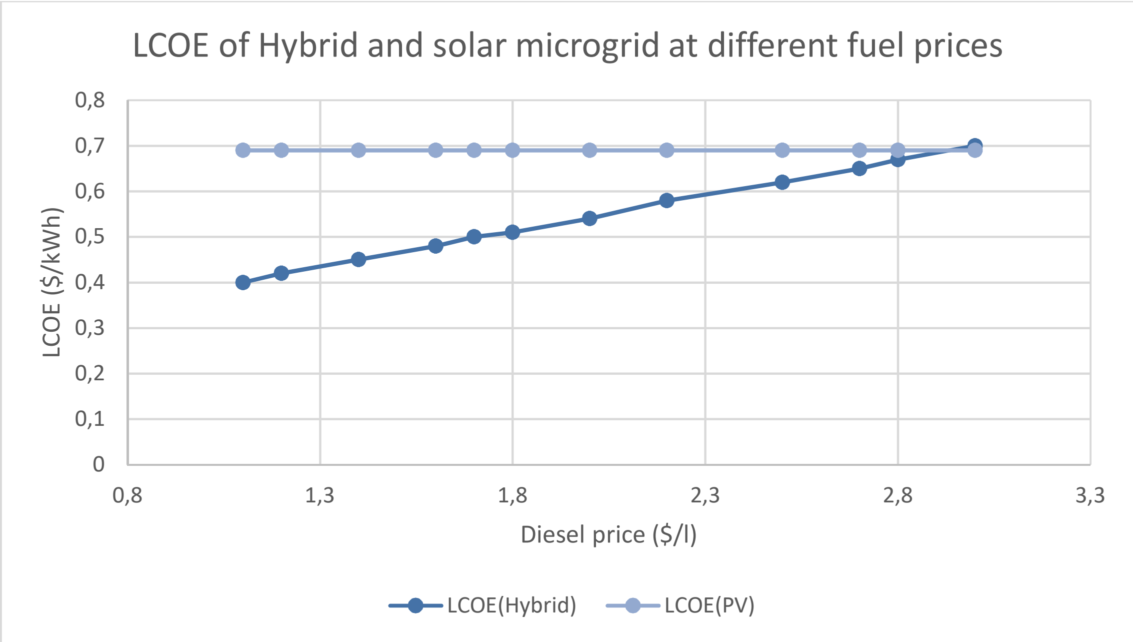



*Figure 68, Variation of LCOE of hybrid system for different level of fuel price respect to LCOE of solar microgrid.*

### 7.3.2 Analysis on Loads

Summary of results allows also to understand the economic differences determined by the two scenarios of load considered. The second load scenario, which has a higher Load Factor (0.40), imply a lower LCOE in all the configurations. In particular, the average decrement on LCOE, generated by LF enhancement, is equal to the 23% in all the configurations. Recalling what said before, this cost reduction is achieved since, enhancing load factor, it occurs: in the case of solar microgrid, lower battery cycling and, thus, lower relative cost of batteries; in diesel based microgrid, a more efficient usage of diesel genset during daylight hours and fewer energy is wasted just to operate at the minimum load ratio; combination of the previous effects in the hybrid microgrid system. It is important to remark that the reduction in LCOE, shifting from 1$^{st}$ to 2$^{nd}$ scenario, is due to the enhancement of load factor and not to a higher load imposed in scenario 2. As a matter of fact, solely a larger load would mean higher costs to investors. Hence, it raises also numerator of LCOE indicator. The importance of LF enhancement has been proved by simulating the following hypothetic case through HOMER software:

| **Configuration** | **LF** | **Community Load** | **$LCOE_{opt.}$** |
|---|---|---|---|
| Solar Microgrid | 0.29 | 410.8 kWh/day | 0.88 $/kWh |

*Figure 69, Data of a Hypothetic scenario to show importance of LF in reducing LCOE.*

It has been entered as input of a solar microgrid a LF of 0.29 (as in the 1st scenario), and daily demand of 410.8 kWh/day (as in the 2nd scenario), leaving unchanged all the other assumptions concerning technology costs and performance. These data generate an optimal LCOE of 0.88 $/kWh, which is higher than the LCOE achieved in the 1st and 2nd scenario. This simple calculation shows that, in order to reduce LCOE, it is not enough just to increase demand. What count, instead, is how demand is distributed over day hours (the average load), that goes to determine Load factor. Thus, it is important for private investors which are evaluating investment in a rural microgrid to look for the presence of productive load to reduce unitary cost of electricity. Moreover, the presence of income-generating activity may induce mechanism like tariff subsidization since WTP is theoretically higher for small firms and shops respect to low-income householders that usually populate rural areas.

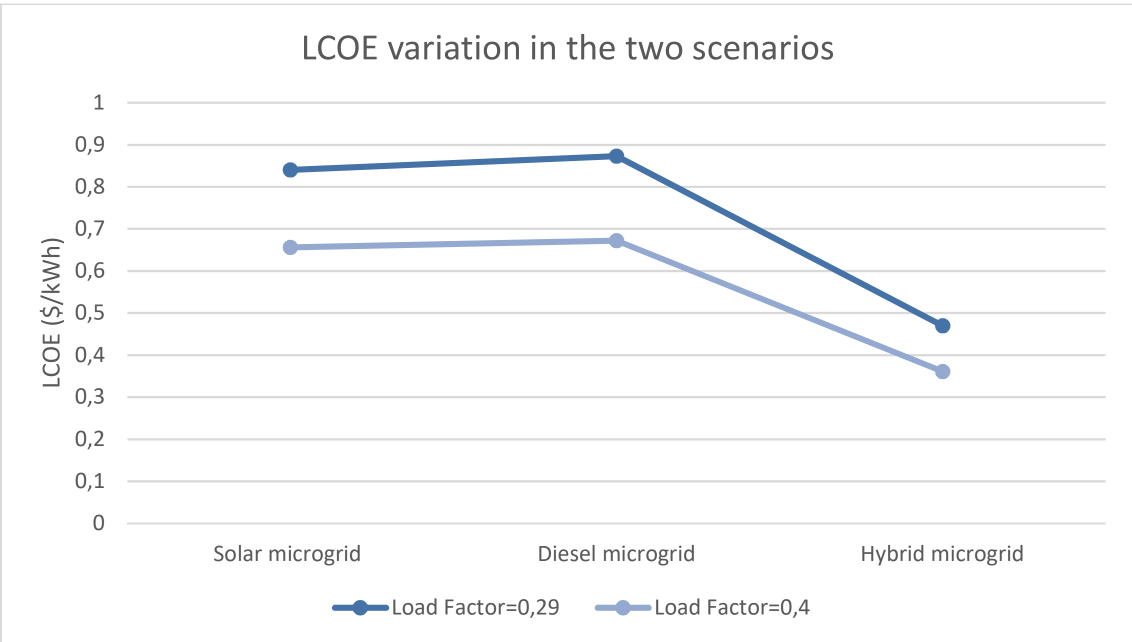



*Figure 70, LCOE variation in function of load factor.*

### 7.3.3 Analysis on Break-even distance

HOMER software calculates Break-even distances (or EDL) for isolated microgrid. The graph below summarizes EDL for each scenario and for each configuration.

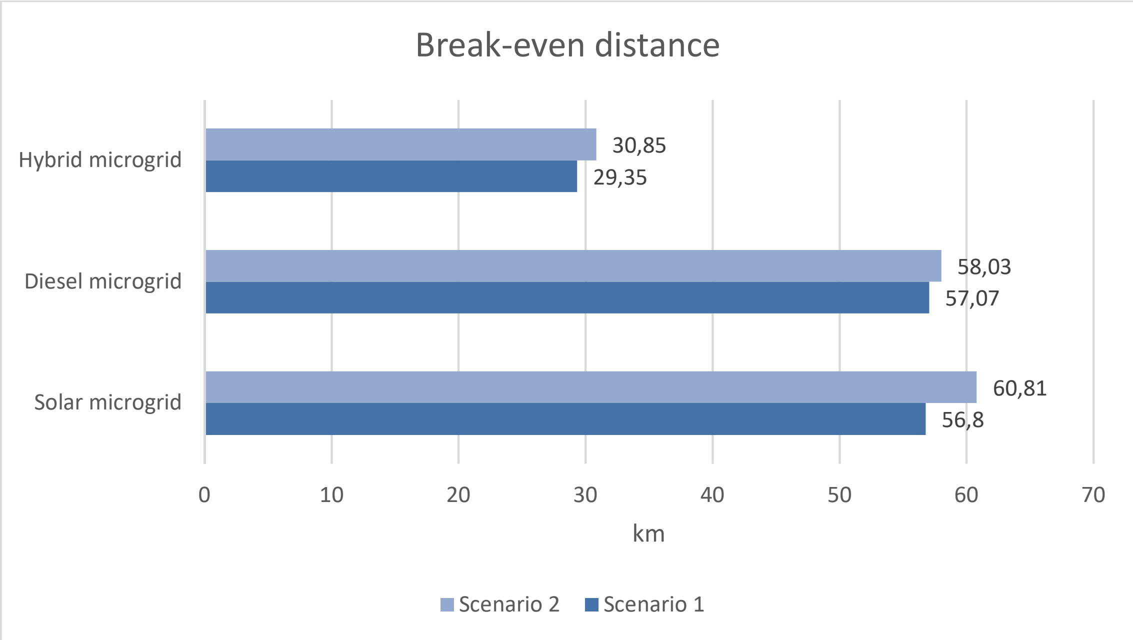



*Figure 71, Break-even distance for all the configuration considered.*

In the cases considered it is always the best option to implement a microgrid rather than extend centralized grid. As a matter of fact, distance from the centralized grid has been estimated to be equal to 95 km. This distance is higher than EDL in all the cases. At distances higher than break-even one, the net present cost of an isolated microgrid is lower than the cost for grid extension. As theory suggest, Hybrid microgrid present the lowest value of EDL since, this configuration, implies an NPC lower than other two configurations. The same is valid within the same configuration for different scenario. EDL of 2$^{nd}$ scenario is higher in any configurations than the one of 1$^{st}$ scenario since, the additional load of the second scenario, enhance NPC respect to the first one and, thus, break-even distance grows. Below can be seen a graph related to EDL individuation in case of hybrid configuration, second scenario. Other representation, being similar, are not reported. For distances from centralized grid lower than 31 km, the NPC of grid extension is lower than NPC of hybrid microgrid. For distances from electricity network superior to 31 km, the straight-line representing NPC of grid extension fall below NPC of isolated microgrid.

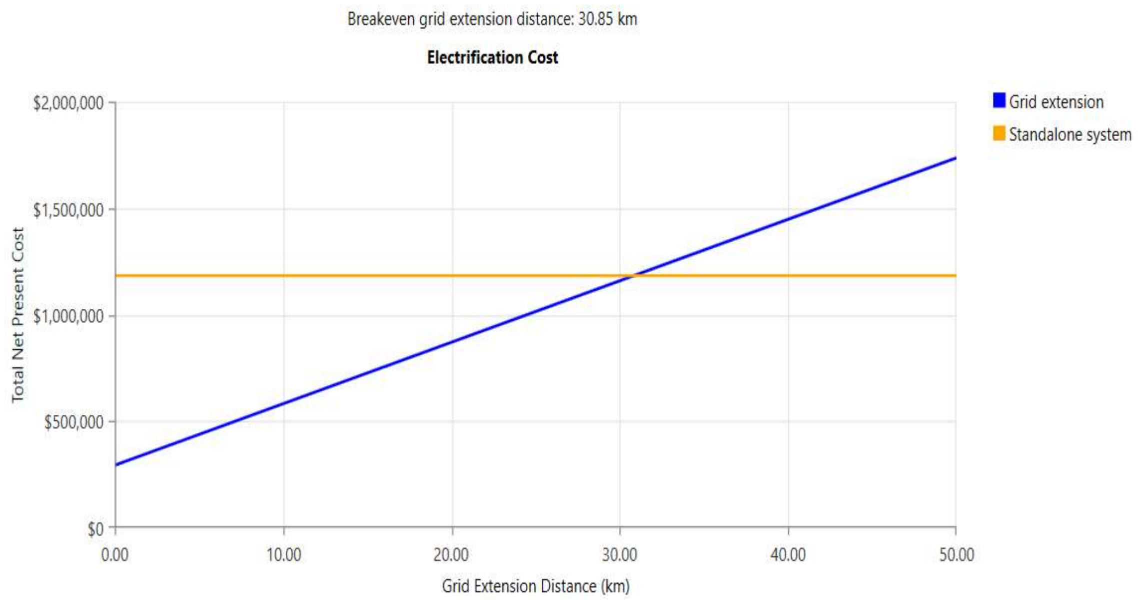



*Figure 72, Example of calculation of break-even distance.*

## 7.4 Economic results estimation and sensitivity analysis

Henceforward will be fixed just one configuration and one scenario of load. Will be studied the Hybrid configurations coupled with the "high consumption scenario" (LF=0.4). As a matter of fact, these cases in the previous paragraph shows the most interesting results from cost perspective. The aim now is to set the tariff and to calculate economic results that a private investor would realize with developing a business model.

### 7.4.1 Tariff setting

After having already dealt with cost structure of microgrid, now the focus shift on cash inflows estimations. In order to estimate revenues, it is necessary to fix a tariff to be charged to microgrid users. According to Nigerian regulatory framework, since the size of the microgrid is higher than 100 kW, investors must set the tariff according to MYTO methodology in order to get tariff validated from authorities [12]. This method tailor the tariff in function of long run marginal cost of generating electricity, adding a certain mark-up to guarantee remuneration to investors. Marginal cost of electricity can be estimated with LCOE generated by HOMER simulations. According to previous calculation the LCOE of this configuration is equal to 0.40 $/kWh, which is reduced up to 0.36 $/kWh thanks to REA support on initial investment. Thus, a cost-reflective tariff would be equal to 0.36 $/kWh. To set the tariff it is useful to reasons from user perspective, investors perspective and regulator perspective. Considering householders point of view, they would be willing to purchase electricity if their Willingness-to-pay (WTP) is higher than electricity tariff. It is important to recall that, usually, in unelectrified areas, householders pay relatively high amount of money to get a low service level from using portable batteries, candles, kerosene and energy kiosks for phone charging. Average monthly expenditures in unelectrified African village range from 4 $/month to 18 $/month, according to a survey from Van Acker et al [234]. Thus, it is reasonable to assume that householders would be willing to pay monthly amount equal or higher than these values, to get a higher service level through microgrid. WTP for energy unit of Nigerian householders has been estimated by World Bank for a document related to NEP project. According to this report, householders with average daily consumption of 1.4 kWh, are willing to pay for electricity maximum 0.53 $/kWh, and maximum 26.09 $/month [206]. As far as concern productive load, they would be willing to purchase electricity from microgrid if it is applied a unitary tariff equal or lower than the prices that they would paid in case of autonomous power production through fossil fuel generator. This price is on average 0.7 $/kWh [205]. Since there are these differences in WTP between householders and productive load, a possible strategy can be to charge two different tariffs to the two different segments. From investors point of view, it is important that unitary tariff of electricity ensure a fair remuneration to the investment made. Considering IRR indicator, investors will look for obtain an IRR higher than cost of capital (WACC=13.5%). Hence, a tariff that allow to get a 15%<IRR<20% can be considered as target. An IRR around the 15%-20% is also indicated by microgrid reports on Nigeria as a good return on similar projects [205], [204]. Shifting to consider authorities perspective, they will try to balance interest of community and profit of private investors. They will ensure that tariff is not too much elevated respect to long-run marginal cost of generation. It is reasonable to assume that regulatory commission will try to minimize tariff respect to user WTP, so as to maximize consumer surplus and guarantee electricity access to lower-income householders. It is also realistic to imagine that authorities will compare proposed tariff with the tariffs applied in other projects, already in operation. Average tariff of existing microgrid project in Nigeria is 0.578 $/kWh [205].

### 7.4.2 Expected economic results

An electricity tariff fixed equal to 0.46 $/kWh for all electricity users, would permit investors to reach the target IRR (15%). Charging this tariff, both householders and productive loads WTP are lower than the tariff. With this tariff householders pays on average 20.6 $/month for electricity provision. Moreover, the authorities are likely to accept this tariff since it is in line with the average tariff charged in other operating microgrid (10 cents per kWh lower than the average value). Thus, supposing this tariff, private investors expected economic results are:

| | |
|---|---|
| **NPV** | 291700 $ |
| **IRR** | 15% |
| **PBT** | 8 years |

Alternatively, can be decided to charge different prices to householders and productive load, considering the higher WTP of the latter. Authorities may favour this strategy since it is a way to privilege householders, increasing their consumer surplus. In the calculation, thus, it has been supposed to fix a tariff number one to householders and a tariff number two, higher than the first one, to productive load (rural firm, shops, health centre and school). Fixing tariff number one equal to 0.42 $/kWh (lower than before), and tariff number two equal to 0.58 $/kWh (higher than before), it would be produced as outcome similar results to the uniform tariff calculations

| | |
|---|---|
| **NPV** | 302184 $ |
| **IRR** | 15% |
| **PBT** | 8 years |

In this hypothesis, householders pay a monthly bill lower than the previous case, equal to around 18 $/month.

### 7.4.3 Sensitivity analysis of economic results

Tariff is fixed in function of the expected cost. However, real cost incurred over the project duration may turn higher or lower than forecast made in year 0. The uncertainties regard unknown future cost of technologies and the evolution of fuel prices. For example, battery replacement cost in future may turn to be different than expected due to enhancement in technological maturity. Future escalation of diesel prices is uncertain as well. Thus, it is interesting to calculate how these variable impact on NPV and IRR. These variations can be studied through sensitivity analysis (SA). This analysis permit to evaluate the magnitude of variation in an outcome when changing some input parameter. In this case are studied both positive and negative variation of the input parameters. Moreover, also converter replacement cost and generator replacement cost may variate in future respect to nowadays estimations. However, these items, has a lower impact on total cost of the microgrid, thus, has not been performed a sensitivity analysis for them.

#### SA Battery replacement cost

The first cost item analysed is battery replacement cost. The future expenditures for purchase new Lead-Acid batteries strongly impact on total project cost. As said before, Battery replacement cost account for the 13% on total Net Present Cost and for the 66% on total life-cycle cost of the battery. Thus, changing in this parameter are likely to strongly impact on economic indicator like NPV and IRR. In the calculation it has been supposed to let variate battery replacement cost multiplying current assumptions, 350 $/kWh, with a multiplier factor. The multiplier factor applied to capital cost is in the range between 0.6 and 1.1. The graph below shows variation in NPV and IRR. As expected, variations are relevant. For example, with a future cost equal to 210 $/kWh, NPV would growth up to 365000 $ (20 % higher than baseline case) and IRR would grow of the 13% respect to the current value. The trend for NPV and IRR varying replacement cost can be seen in the figures below.

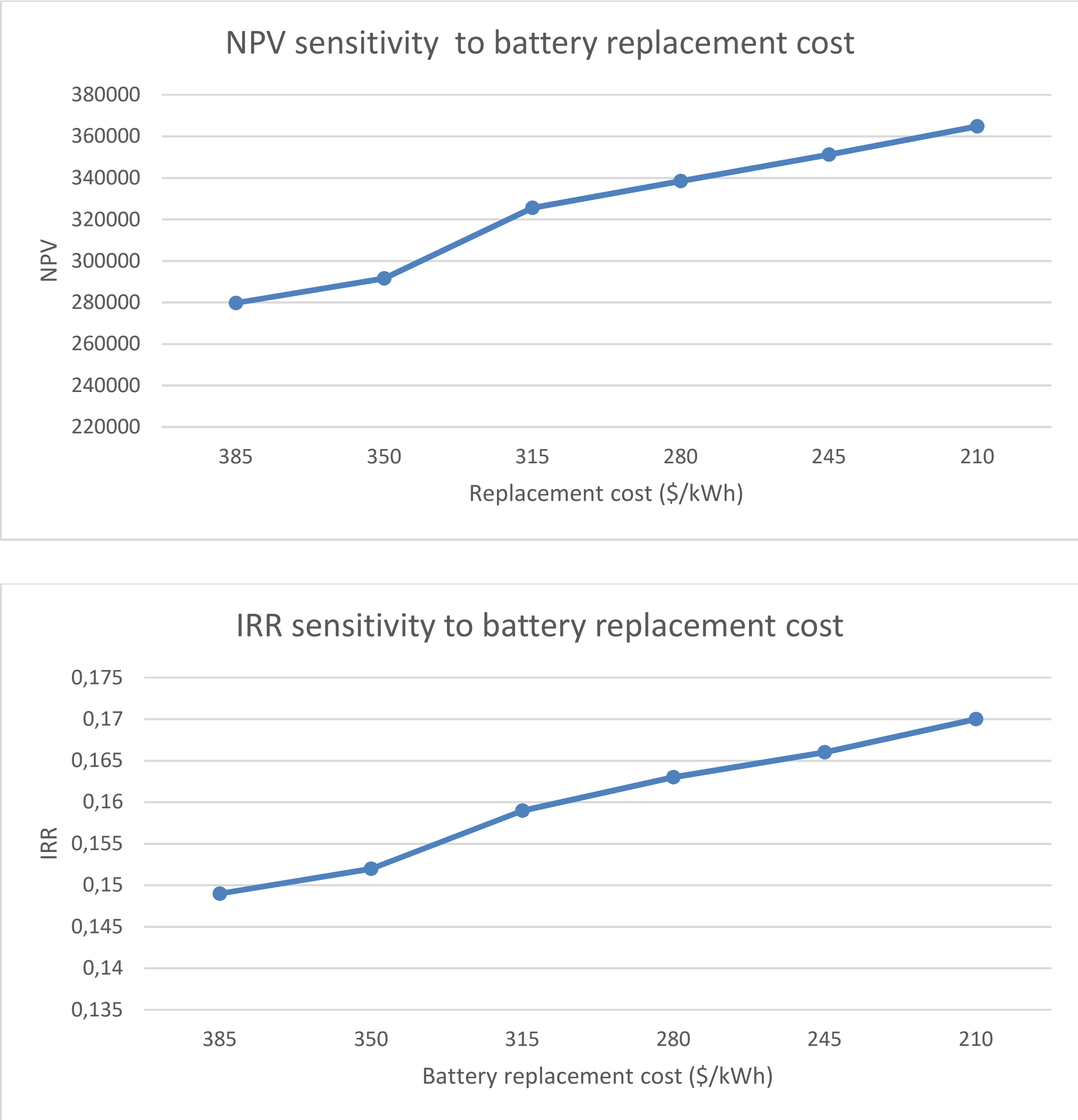
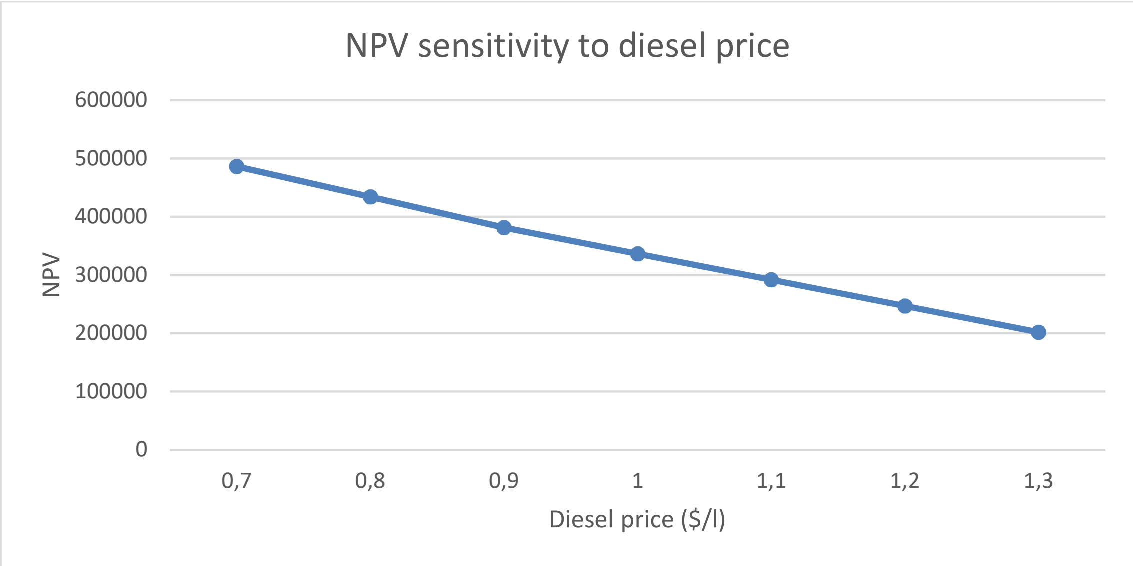



*Figure 73, Sensitivity of NPV and IRR to variation of battery replacement cost.*

**SA Diesel price**

Regardless of the accuracy in projection, fuel price remains still uncertain and linked to variation in world demand and supply. Diesel price strongly impact on economic results since represent almost the totality of life-cycle cost linked to diesel generator (80%), and the 40% of total NPC of the hybrid microgrid. It has been considered value of diesel prices ranging from 0.7 $/l to 1.3 $/l. It is important to recall that wholesale fuel prices it has been increased of a certain percentage in order to take into account transportation towards rural area. Thus, a decrease in diesel prices can be caused also by development in infrastructure for transportation that reduce unitary cost of fuel.  The importance of fuel cost is evident with sensitivity calculation. For example, increasing current price of 0.2 $/l (an increment of the 18%), imply a reduction of NPV of the 31% and a reduction of IRR of 27%. Conversely, a reduction of the diesel prices up to 0.7 $/l (a decrement of the 36% respect to assumed price), generate a growth of NPV of the 66% and an increment of the 47% in IRR. The trend for NPV and IRR varying unitary diesel cost can be seen in the figures below.



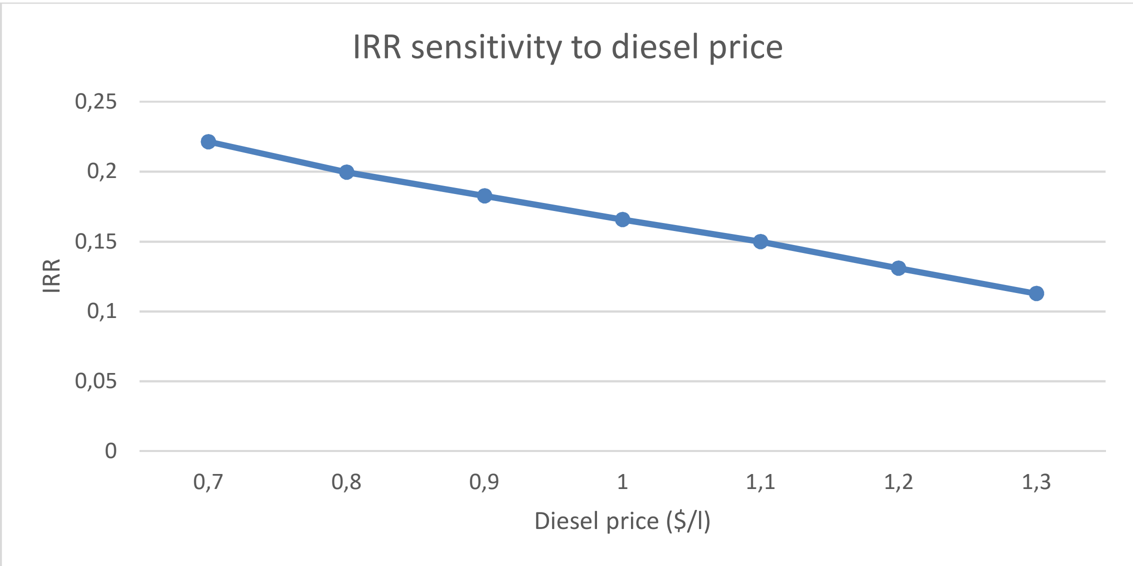




*Figure 74, Sensitivity of NPV and IRR to variation in diesel price.*

# Conclusions

According to economic results of the analysis conducted, hybrid microgrid shows lowest value of LCOE and NPC respect to the other two configurations studied (solar microgrid, diesel microgrid). LCOE of hybrid systems is about 0.30 \$/kWh lower than the LCOE linked to solar microgrid and diesel microgrid. As a matter of fact, in respect to solar microgrid, the hybridization allows to reduce the size of PV plant and the total capacity of Lead-Acid batteries. These two items contribute, in solar microgrid, to strongly enhance initial investment cost and technology replacement cost. Moreover, hybrid configuration, allows to avoid an excessive reliance from diesel fuel respect to a fossil fuel-based microgrid. Indeed, in diesel-based system, fuel consumption, has the most relevant impact on total NPC. Furthermore, hybrid systems, provide also a significant reduction of emissions in respect to the diesel-based case. The amount of $CO_2$, discharged into the environment each year by the hybrid systems, is lowered of the 65% (in the second load scenario) and of the 49% (in the first scenario of load), respect to a fossil fuel microgrid facing the same electric demand. Obviously, the solar microgrid, implies the elimination of any emission but also means higher initial costs for the investors. Thus, hybrid systems, with these assumptions, may represents a good trade-off looking either to financial or environmental dimension. An important aspect is that, the choice of an entrepreneur to opt for a hybrid system, rather than a solar microgrid, might be also driven by the current state of Nigerian regulatory framework. Indeed, also hybrid microgrid are eligible to receive capital subsides from REF when are grounded on a renewable penetration share higher than the 30%. Moreover, capital subsides for the initial investment, are not calculated in function of the size of the initial CAPEX. Conversely, subsides are defined according to the expected number of connections to the microgrid. This parameter, for limited variations in the future number of users, does not influence the initial investment into a relevant extent. Thus, it is difficult to gather a large capital aid with 200-300 connections per village (these numbers can be considered as a good proxy of average values in Nigerian villages according to REA's database). The consequence is that, the impact of capital subsidies in the case of hybrid systems, is steeper than in the case of solar microgrid, being the initial investment in the instance of solar microgrid significantly superior than the one in hybrid microgrid. The calculation exhibit that capital grant accounts for the 44% in case on an investment in hybrid microgrid, while, cover only the 12% of the initial investment in case of solar microgrid. The other comparative analysis performed, is based on the economic differences stemming from two possible load profiles for the village. The results show off that the second load scenario guarantee lower LCOE, in any configurations, than the first one. This cost advantage is due to the additional presence of productive loads to the consumption side of the microgrid system. These power utilization units generate an enhancement of the load factor of the microgrid, going to raise average load by withdrawing electricity during day light hours (from 9 to 17 h). The decrement of unitary costs of electricity linked to load factor growth is of the 23%, considering an average among different cases studied. This reduction of unitary costs, in the second scenario respect to the first one, is dictated by different factors. In case of solar microgrid, there is a lower amount of energy throughput in storage systems. As a matter of fact, the single battery string, in the first scenario, is cycled by 129.7 kWh/year. In the second scenario, this quantity is reduced of the 12%, up to 114 kWh/year for single battery string. This decrement lead to a reduction of batteries replacement cost and, hence, batteries life cycle cost. In case of diesel microgrid, in the second scenario, there is a more efficient usage of generator by operating it at higher values of load and. Moreover, less electricity is wasted since generated just to operate at the minimum load ratio. Finally, in case of hybrid microgrid, there is a joint contribution of the two previous reasoning. These results show the importance, for private investors in microgrid serving rural areas, to look for the presence of productive load interconnected to the systems. The considerations relative to break-even distance demonstrate that the village is located at a distance from the transmission network larger than EDL. Thus, the NPC of isolated systems is lower than the one of grid extension. It demonstrates that, with current assumptions for transmission network costs, the implementation, of any microgrid configurations, it is worth respect to an extension of the centralized grid. As far as concern the estimation of potential revenues that microgrid could realize, the analysis it is restricted to the hybrid configurations in the second load scenario. Indeed, this case, allows to achieve the most interesting results analysing costs. It is supposed to set a tariff equal to 0.46 $/kWh to all the energy users. The tariff is fixed in order to satisfy three constraints: tariff must be compatible with consumers WTP for electricity; tariff must permit a fair remuneration to investors (it is imposed a tariff that realize an IRR higher than cost of capital); finally, tariff must be in line with the tariff applied in other microgrids, currently operating in Nigeria, so that it increases the probability that authorities will validate the tariff by investors. With this tariff expected NPV is equal to 29200 $; IRR is equal to the 15%, which is indicated as in line with positive economic return in similar project by recent reports; PBT is equal to 8 years. Since future cost are uncertain, it is performed a sensitivity analysis on results, in order to verify how they changed in function of variation of input parameters different from the expected ones. The items that has the potential to induce highest variation in economic results are, for hybrid microgrid systems, battery replacement cost and diesel fuel costs.

# Appendix

## A. HOMER software, main features

HOMER (Hybrid Optimization Model for Electric Renewable) is a simulation software that allows to perform techno-economic analysis of microgrid projects. The software it has been developed by NREL (U.S. National Renewable Energy Laboratory) in order to foster design of microgrid. HOMER It is largely recognized and widely used in literature [14], [15], [17], [16], [18], [19], [26], [20], [4], [5], [1], [21], [22], [9], [24].

In this work it is used HOMER Pro, version 3.12.3. The software requires different input to run its simulation. First of all, have to be specified a geographical location where it is intended to evaluate the microgrid system. To each location are downloaded by the software natural resources data, like solar irradiation and average wind speed. These data are taken from NASA observation along the last 25 years. Then, need to be decided which technological components want to be tested in the microgrid simulation. For example, may be employed in the system PV panels, wind turbine, energy storage system, diesel generator, hydropower plant and so forth. For rural microgrid can be needed also data concern centralized grid, so as to calculate which is the break-even distances for grid extension respect to isolated system. For each component can be entered data regarding costs and technical performance or can be used default data provided by the software. Moreover, must be added information about a load to be met with microgrid generation. The software generates some default load profile representing typical consumption pattern of predefined categories of users: residential, commercial, industrial and community. Otherwise load profile can be manually included into the simulation. Other inputs that can be added to the simulation regard context specific assumptions concerning economic dimension. Thus, can be imposed a certain discount rate to calculation, inflation rate of the country and fixed and variable cost of the system. Finally, may be entered other constraints. For example, if it is allowed that not all the demand is satisfied, which is the desired renewable penetration for the system and whether want to be accounted penalties on pollutant emission generated by fossil fuel electricity production. After having received all input data, HOMER software, runs many simulations so as to size the component in a way that allow to satisfy load at the minimum cost possible. The main economic parameter considered by the software to rank solutions are NPC and LCOE.

The output of the simulations will be the optimal sizing of the microgrid system. Results can be analyzed for each component, examining cash outflow for each technology. It is also possible to perform sensitivity analysis, so as to understand how optimal results change in function of variation in input data.

## B. Indicator used in analysis

### LCOE

LCOE, which stands for Levelized Cost of Electricity, is an indicator commonly used to evaluate economic dimension of energy project. LCOE is recognized as a useful indicator since take into account actualized life cycle cost related to an energy investment. Moreover, it permits to compare results of different projects, which may be based on different technologies, riskiness, cost of capital, size and lifecycle [235]. Being *i* discount rate, T project duration, LCOE formulation can be calculated through the following steps:

$$\sum_{t=0}^{T}\left(\frac{LCOE_t}{(1+i)^t}\times E_t\right)=\sum_{t=0}^{T}\frac{C_t}{(1+i)^t}$$

Thus, LCOE is the value that make equal present value of cost $C_t$ to the product between energy produced $E_t$ and LCOE itself. The equation above can be rearranged in the following way [187]:

$$LCOE=\frac{\sum_{t=0}^{T}\frac{C_t}{(1+i)^t}}{\sum_{t=0}^{T}\frac{E_t}{(1+i)^t}}$$

$C_t$ include initial investment cost, operation and maintenance cost, fuel costs in case of fossil fuel plant, taxation, and financing cost. To total costs can be subtracted incentives from government, when available for project developer. The denominator is instead calculated decreasing installed capacity $S_t$ for the value of losses $d$ due to plant degradation.

$$LCOE=\frac{\sum_{t=0}^{T}\frac{I_t+O_t+M_t+T_t}{(1+i)^t}}{\sum_{t=0}^{T}\frac{S_t\,(1-d)}{(1+i)^t}}$$

The denominator of LCOE can be defined as NPC (Net Present Cost): the sum of present value of all costs, considering both CAPEX and OPEX.

## NPV

NPV (Net Present Value) is an economic indicator that take into account present value of all cash outflow and cash inflow occurring during the duration of a project. It is used in cost-benefit assessment in order to define whether a project is worth or not to be implemented. Using the discount rate, it is possible to understand value of future cash outflow and inflow. As a matter of fact, the present value of a cash outflow that will be faced in future is lower than the value that the same cost would have if occur in the present. The same reasoning can be extended to cash inflow with an opposite logic. In few words, discount rate considers opportunity cost of capital. Discount rate is typically coincident with weighted average cost of capital (WACC). The formulation of NPV is:

$$NPV = \sum_{t=0}^{T} \frac{CF_t}{(1+i)^t} + \frac{TV}{(1+i)^T} - I_o$$

Where $CF_t$ can be calculated by subtracting to revenues in the year *t,* annual costs in the same year. Revenues of an energy plant are realized through selling electricity or thanks to incentives mechanisms. Costs instead are mainly management cost, operating cost and maintenance costs of the plant. $TV$ is the terminal value of the project assets, actualized with the project duration T. $I_o$ is the initial investment. A project is worth to be implemented if has a NPV>0.

## IRR

IRR (Internal Rate of Return) can be defined as the discount rate that make equal to zero the net present value of an investment. Hence, IRR is the discounting factor that allow to equalize the present value of future cash flow with the initial investment. Considering how it is defined, IRR, could be calculated from the formulation of NPV. However, for the nature of formulation. it is not possible to isolate discount facture. Thus, to calculate IRR are needed software calculation based on iterative process. IRR is frequently used in order to estimate profitability of an investment. Generally, project that are expected to generate an IRR higher than capital cost are worth to be implemented for a firm. Moreover, projects with higher IRR are chosen to be implemented on a priority base.

## PBT

PBT (Pay-Back Time) is the time period needed to recover the initial investment summing cash flow generated by the project. PBT can be measured as ratio between initial investment and cash inflow per year, in case cash flow are even. PBT it is usually measured in years.  It is largely used since it is relatively easy to be used and understood by the majority of project stakeholders. On the other hand, a possible limitation is that PBT does not consider time value of money. To overcome these drawbacks can be used a variation of PBT, discounted PBT. In this case is considered present value of cash inflows occurring during project duration. Discounted PBT is used in this work.

## C. Average Load Assessment for consumption units

Estimation of average consumption per day for householders and productive load in the Nigerian village. The estimation has been conducted starting from average value from literature or internet website. The literature has been selected in order to use data as more recent as possible and related to the context analysed [6], [14], [18], [217], [218], [94], [9], [219], [220], [221] [19], [23], [167]. For each appliance, has been considered average value from similar work, thus, through a process of secondary data gathering.

1. Lights (CFL)

| Sources | Number per HH | Power(W) | Hour/day |
|---|---|---|---|
| 1 | 5 | 13 | 5 |
| 2 | 3 | 10 | 6 |
| 3 | 3 | 18 | 7 |
| 4 | 4 | 18 | 6 |
| 5 | 4 | 20 | 9 |
| 6 | 2 | 20 | 6 |
| 7 | 2 | 20 | 8 |
| **Average** | 3,285714286 | 17 | 6,714285714 |
| **Rounded value** | 3 | 17 | 7 |

2. TV

| Sources | Number per HH | Power(W) | Hour/day |
|---|---|---|---|
| 1 | 1 | 147 | 1 |
| 2 | 1 | 80 | 3 |
| 3 | 1 | 50 | 12 |
| 4 | 0,5 | 68 | 4 |
| 5 | 1 | 80 | 4 |
| 6 | 1 | 40 | 5 |
| 7 | 0,5 | 100 | 5 |
| Average | 0,857142857 | 80,71429 | 4,857142857 |
| Rounded value | 1 | 80 | 5 |

3. Radio

| Sources | Number per HH | Power(W) | Hour/day |
|---|---|---|---|
| 1 | 1 | 30 | 3 |
| 2 | 1 | 6 | 2 |
| 3 | 1 | 35 | 2 |
| 4 | 1 | 10 | 6 |
| 5 | 1 | 15 | 2 |
| Average | 1 | 19,2 | 3 |
| Rounded value | 1 | 19 | 3 |

4. Fan

| Sources | Number per HH | Power(W) | Hour/day |
|---|---|---|---|
| 1 | 0,6 | 58 | 2,86 |
| 2 | 1 | 6 | 7 |
| 3 | 0,7 | 49 | 4 |
| 4 | 2 | 30 | 9 |
| 5 | 1 | 80 | 3 |
| 6 | 0,5 | 60 | 5 |
| Average | 0,966666667 | 47,16667 | 5,143333333 |
| Rounded value | 1 | 47 | 5 |

5. Mobile phone

| Sources | Number per HH | Power(W) | Hour/day |
|---|---|---|---|
| 1 | 2 | 10 | 2 |
| 2 | 1 | 5 | 2 |
| Average | 1,5 | 7,5 | 2 |
| Rounded value | 2 | 8 | 2 |

6. Small Refrigerator (householder case)

| Sources | Number per HH | Power (W) | Hour/day |
|---|---|---|---|
| 1 | 0,1 | 84 | 24 |
| 2 | 0,4 | 127 | 24 |
| 3 | 0,02 | - | - |
| 4 | 0,5 | 150 | 24 |
| 5 | 0,5 | 50 | 24 |
| 6 | 0,19 | 150 | 24 |
| Average | 0,285 | 112,2 | 24 |
| Rounded value | 0,25 | 110 | 24 |

7. Large Refrigerator (used in small school and health centre)

| Large refrigerator | Rated power (W) | Hours/day |
|---|---|---|
| 1 | 600 | 16 |
| 2 | 100 | 8 |
| Average | 350 | 12 |

8. Miscellaneous load

| Miscellaneous | Rated power (W) | Hours/day |
|---|---|---|
| 1 | 20 | 24 |
| 2 | 80 | 24 |
| Average | 100 | 24 |

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