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Ph.D. Dissertation

An integrated approach to decentralised renewable energy systems planning for developing countries

Faculty of Engineering

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Ph.D. in Energy and Environment

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Abstract

This thesis focuses on the problem of global access to energy for developing countries and provides a thorough analysis of renewable-based mini-grid systems as a solution.

In the first section an intensive literature review shows current energy trends and challenges, with a special outlook on Sub-Saharan Africa. The energy forecast situation is assessed by combining data about electric consumptions patterns with an analysis based on the energy indicators for sustainable development issued by International Agencies. A proven methodology for the energy need assessment of rural communities is presented, aiming at obtaining reliable input data for the mini-grid development. This helps in reducing both the financial challenges by mitigating the uncertainties in electricity demand and the technical challenges by contributing to adequately size off-grid power generation systems, with a view to boost toward a common overall objective of mini-grid's optimization methods and tools.

Based on methodology outputs an integrated approach for system design and planning is developed, taking into account techno-economic trade-off and system reliability and flexibility.

Design process optimization is carried out through simulation of different combination of generation (PV, Wind, Hydro, multi-source) and storage systems (lead-acid, lithium, vanadium flow, flywheel). Distribution grid constraints have been addressed as well, including last-mile connections and users' wiring, in order to have an holistic vision in the design phase. Such integrated approach requires to adopt appropriate operation strategies to face real time power quality (voltage and frequency) fluctuations along with an effective capability to meet off-takers demand. Dump loads, device controllers and management options are discussed for both supply-side and demand-side.

The thorough analysis looks at economic aspects, therefore different operating strategies are investigated, and business performance has been deeply analysed and discussed. On a view to a global evaluation impact assessment, last part of the thesis focuses on sustainability analysis: beyond economic impact, other direct/indirect effects of mini-grids on environment and target communities are outlined. The tool used for Monitoring and evaluation of mini-grid is the Social Return on Investment (SROI), by adding a wide set of key indicators to measure monetized effects on education, health, security, environment and economy.

The combination of all methodologies and strategies aims at improving the systems design and operation, helping reduce capital expenditures and operating costs, thus allowing for a lower Levelized Cost of Energy over project's entire lifecycle.

Contents

1. Research statement

More than 1 billion people in the world still do not have access to electricity. The corresponding gap in access to modern energy services affects the socio-economic development of energy-poor countries and acts as a brake to economic growth.

One of the objectives of sustainable development is to ensure access to economic, reliable, sustainable and modern energy for all. However, insufficient financial resources, lack of effectiveness, poor planning and fast population growth are just some of the many challenges to achieve this goal.

Local utilities and governments struggle to find solutions that can offer an acceptable level of energy access to most of their population within the limited budgets they have to work with. A combination of different energy solutions is needed to optimally fill the gap.

The aim of this research is to better understand the opportunity to improve energy service delivery in low electrified context. The specific goal is to develop and contribute to models for the optimization of design and operation of isolated energy systems for the electrification of developing countries.

The work has been constantly driven by the need of answering the following questions:

I. How can we predict energy demand fluctuations over time in off-grid context?
II. What value added does hybridization bring in terms of generation and distribution systems flexibility?
III. How can we effectively provide clean and reliable technologies to bridge the electrification gap?
IV. What are the key characteristics of an appropriate planning for global energy access?
V. How can different service delivery options impact on projects sustainability?

1.1. Applied methodology

To address the research questions, a review of the literature on rural electrification, energy access, decentralised systems in developing countries with a focus on load characterisation was made as a first step in recognition of the state-of-the-art of the subject.
Several case studies have been investigated with the purpose of collecting real data from the ground at different stages, allowing to setup a sound database for this work.

Data collected included end-use consumption patterns, energy resources availability, economic, environmental and social features. Data about consumption patterns and energy resources are typically considered in terms of time series data (i.e. daily load profiles and hourly solar radiation, wind speed, water flow, etc.) which are needed in the design process. Technical issues (e.g. troubleshooting log sheets, components data sheets), Economic data (e.g. component costs, people willingness and ability to pay), Environmental (e.g. pollution constraints, land use, people displacement and resettlement) and Social features (e.g. local technical skills, social license, and cultural habits) have been employed in the multi-criteria approach.
The survey data also quantifies how, according to socio-economic conditions and as energy users gain access to more power through their supply source, appliance ownership and usage may change. Unique data on reliability and user satisfaction with different supply options were also collected to elaborate the Energy Need Assessment tool , which aims at defining load scenarios that can be used as input to Homer Pro for more accurate sizing, while socio-economic outputs have been validated on field during case study mini-grids commercial operations, where tariff and expected revenues confirmed the analysis outcomes.

Modelling and simulations have then been performed with MatLab, Excel, SimuLink and specific softwares such as EnergyPlan, PVSyst, Homer Pro to develop a set of scenarios with different options for load profiles forecast, and creation of corresponding novel technology mix alternatives to improve techno-economic sustainability.

By comparing the results from the base and improved scenarios, the benefits of the proposed solutions have been assessed in terms of levelized cost of energy and system flexibility. Running a range of reliability scenarios, the cost-reliability trade-offs have also been better understood across the output range.

1.2. Novelty contribution

Many studies have focused on methods for optimisation of mini-grids design and operation. However, many of these studies look at the supply side of the system, including the selection and sizing of the generating technology, storage and the control system algorithm, while other scholars investigated energy demand and off-takers behaviour. This thesis focuses on the value of optimizing the load flows by managing supply-side and demand-side as a whole, thus considering mini-grids generation, storage, distribution and off-takers as an integrated interdependent system.

Load flow analysis needs to look at system technical flexibility without forgetting service level requirements according to rural end users' characterization.

Due to the relevant role of rural electrification towards the sustainable growth of developing countries, a new set of indicators has been outlined, allowing to create a sound toolkit for programs evaluation who considers financial performances along with social and other monetizable impacts.

The element of originality of this work relies in the wide analysis, synthesis and improvement of the scientific literature which led to define outline the main fundamentals of this field of research and to set a reference framework for scholars.

Therefore, each chapter is structured according to: problem statement and literature analysis, methodology, application/simulation, results discussion.

1.3. Reference scientific production

This thesis embraces the desk research and on-field surveys activities which acted as basis for scientific papers and other publications. The author's work sourced as well from involvement in several project activities related to mini-grids in developing countries, within the framework of "Field Studies 4 Micro-Grids Optimization" (FS4MGO), an academic research group born in 2018 between international universities with the purpose of enhancing the global access to energy, in line with the United Nations Sustainable Development Goals, and fostering a sustainable economic growth in developing countries through clean and productive energy. The research group investigates renewable energies systems in different aspects:

- Energy Need Assessment methodology
- Load forecasting models
- Environmental Impact and Community engagement and capacity building tools
- Optimized sizing for financial plan viability
- Socio-economic impact evaluation guidelines

Active members are: University of Rome "Sapienza" (IT), Pisa University (IT), Massachusettes Institute of Technology (USA), Columbia University of New York (USA), State University of New York (USA) University of Oxford (UK) with the support of Makerere University (Uganda), Strathmore University (Kenya), African Centre of Excellence for Sustainable Development (Rwanda), Universidad Autonoma de Honduras, Centro Universitario de Oriente San Carlos (Guatemala), Universidad de Costa Rica.

Here follows the list of author's scientific production and project collaborations:

Papers

- **PA-1:** *Methodology for the Energy Need Assessment to Effectively Design and Deploy Mini-Grids for Rural Electrification.* Gambino V., Del Citto R., Cherubini P., Tacconelli C., Micangeli A., Giglioli R. Energies 2019, 12(3), 574; doi.org/10.3390/en12030574

- **PA-2:** *How hybridization of energy storage technologies can provide additional flexibility and competitiveness to microgrids in the context of developing countries*. Barelli, L.; Bidini, G.; Cherubini, P.; Micangeli, A.; Pelosi, D.; Tacconelli, Carlo. Energies 12:16(2019), p. 3138. doi.org/10.3390/en12163138.

- **PA-3:** *Ramp rate abatement for wind power plants: A techno-economic analysis*. G.F. Frate, P. Cherubini, C. Tacconelli, A. Micangeli, L. Ferrari, U. Desideri. Applied Energy, Volume 254,2019,113600, doi.org/10.1016/j.apenergy.2019.113600.

- **PA-4:** *Ramp rate abatement for wind energy integration in microgrids.* Frate G.F., Cherubini P., Tacconelli C., Micangeli A., Ferrari L., Desideri U., Energy Procedia 159 (2019) 292-297; doi: 10.1016/j.egypro.2019.01.013

Other publications

- **PU-1:** *RE-thinking Access to Energy Business Models. Ways to Walk the Water-Energy-Food Nexus Talk in Sub-Saharan Africa.* Gambino V., Tacconelli C., Micangeli A., et al. RES4Africa Foundation, 2019. ISBN 978-88-492-3804-4.

Case study projects

- **PR-1:** *Feasibility of hydropower, solar mini-grid and national grid-extension in Nintulo, Zambezia (Mozambique, 2019)***.** 180kW hydroelectric power plant, solar mini-grid clusters and MV distribution line options. Partner: Enabel – Belgium Cooperation Agency.
  Activities: field data campaign and energy need assessment

- **PR-2:** *Solar hybrid mini grid in the village of Rutenderi (Rwanda, 2018-19)***.** 50 kWp hybrid solar PV for productive uses and LV distribution smart grid for 600 connections. Partner: Absolute Energy.
  Activities: field data campaign and energy need assessment

- **PR-3***: Ilumina Project: access to energy for local development and women empowerment (Mozambique, 2019-20)***.** 120 kWp solar PV with storage, diesel backup and low voltage distribution smart grid. Partner: AVSI Foundation and Technical Solidarity.
  Activities: load profiling, sizing model simulation

- **PR-4***: Sustainable energy Services for Idjwi island (Democratic Republic of Congo, 2019-20).* 150 kWp hydroelectric and PV solar multi-source mini-grid for 800 customers. Partner: AVSI Foundation and Ministry of Environment of the DRC.
  Activities: Energy need assessment, sizing model simulation

- **PR-5**: *Energy and training for a sustainable growth in Bukasa island (Uganda, 2017-19).* 100 kWp hybrid solar PV and LV distribution smart grid for 500 connections. Partner: Absolute Energy.
  <u>Activities: Monitoring and evaluation, data collection and analysis for SROI analysis</u>

- **PR-6**: *Sustainable energy services for Kitobo island (Uganda, 2017-19).* 228 kWp solar PV with vanadium redox flow battery storage, diesel backup and LV distribution smart grid. Partner: Absolute Energy.
  <u>Activities: Monitoring and evaluation, data collection and analysis for SROI analysis</u>

The goal of this integrated approach is **to bridge "traditional" academic research, devoted to the development of robust design criteria and optimization models, with evidence coming from the field.** These include both technical data – not limited to the electric parameters but always viewing **the community plus microgrid as an energy system** as a whole – and the communities needs and experiences, rigorously assessed with specialized methods.

1.4. Thesis overview

Chapter 2: Global Access to Energy

This chapter introduces the theme of energy access within a global perspective and in particular reference to developing countries (DCs).
This chapter depicts the current energy trends, needs and challenges, with a special outlook on Sub-Saharan Africa. The energy demand is assessed by combining data on consumptions patterns and electric sector with an analysis based on international agencies reference.
In particular, emphasis is given to the issue of rural electrification which is pivotal in promoting economic growth and it is the focus of the following chapters.

This chapter sources information from literature review, as listed in the Bibliography.

Chapter 3: Demand Analysis

This chapter describes the development, implementation and application of a new procedure to address end-uses load profile estimate in rural areas. The procedure allows having a tool which is a support to develop the proper input data required by the most advanced off-grid systems sizing methods and software tools.

Thus, the approach for applying a proven methodology for the energy need assessment of rural communities aims at obtaining reliable input data for the mini-grid development. This helps in reducing both the financial challenges by mitigating the uncertainties in electricity demand and the technical challenges by contributing to adequately size off-grid power generation systems, with a view to boost toward a common overall objective of mini-grid's optimization methods and tools.
Hence, taken in consideration that target communities differ in terms of needs and context conditions, this chapter describes an inclusive methodology that can be adapted case-by-case. It provides an effective applied solution the lack of proven guidelines from project developers or literature, giving priority to data collection methods able to achieve a large sample representative of the market, with high accuracy in estimating the energy consumptions from electricity substitutes.
The implementation of the procedure is also presented and finally, the procedure has been applied in forecasting the average load profile and sizing of 3 off-grid PV-battery-diesel systems in rural Rwanda.

This chapter is based on the paper **PA-1:** *Methodology for the Energy Need Assessment to Effectively Design and Deploy Mini-Grids for Rural Electrification.* Gambino V., Del Citto R., Cherubini P., Tacconelli C., Micangeli A., Giglioli R. Energies 2019, 12(3), 574; doi.org/10.3390/en12030574

Chapter 4: Technology integration

This chapter focuses on off-grid small-scale power systems which represent one of the most appropriate energy strategies to address rural electrification. Specifically, the chapter introduces the architecture of renewable energy-based mini-grids, describes the main features of generation and storage systems components and technical specification.

The main aim is to explore opportunities for different technologies combination, with benefits and drawbacks; on this purpose an analysis of potential hybridization of storage technologies is deeply investigated, by simulating an enhanced mechanical and electrochemical ESS within an operating advanced mini-grid. The case study is the Kitobo Island power plant in Uganda, equipped with vanadium flow battery systems, on which the author's field work mainly was focused along this research period.

Above mentioned analysis will be the basis, in the following chapters, for the development of methods and models which address more specifically the system design process.

This chapter is based on the paper **PA-2:** *How hybridization of energy storage technologies can provide additional flexibility and competitiveness to microgrids in the context of developing countries*. Barelli, L.; Bidini, G.; Cherubini, P.; Micangeli, A.; Pelosi, D.; Tacconelli, Carlo. Energies 12:16(2019), p. 3138. doi.org/10.3390/en12163138.

Chapter 5: System design

This chapter deals with a first step development, implementation and application of a new approach to perform a system capacity planning. Particular features of the procedure are the capability to combine more generation sources to be employed in the system planning.

An enhanced method which considers techno-economic trade-off with a strong need of ensuring system reliability and durability, according to the evolution of energy demand over time as forecast in Chapter 3.

Specifically, in the chapter it is highlighted that the need as input datum – in the traditional sizing techniques – of the Loss of Load parameter, may lead to un-appropriate sizing in rural areas. Therefore, an appropriate sizing methodology including definitions of the Value of Lost Load parameter and of the Levelized Cost of Energy is developed and described. Comparisons between the traditional methodologies and the new one are carried out in order to highlight the advantages of the proposed one. Moreover, the new methodology is applied to perform optimum sizing of a PV-Hydro-BESS mini-grid in DR Congo as reference case for energy balancing simulation.

This chapter is based on the results of the project **PR-4**: *Sustainable energy Services for Idjwi island (Democratic Republic of Congo, 2019-20).* 150 kWp hydroelectric and PV solar multi-source mini-grid for 800 customers. Partner: AVSI Foundation and Ministry of Environment of the DRC.

Chapter 6: Distribution

This chapter deals with different options for rural electrification distribution systems. Existing low-cost technologies are reported from literature review, with an eye to the appropriateness and adequacy of selected context.

Users' connection and metering options are presented in order to highlight the role of energy dispatch and off-takers.

Energy losses may be relevant in the distribution side due to voltage drop, materials inadequacy, incorrect planning, energy theft so an appropriate example of designing and basic engineering process is presented, based on the Idjwi mini-grid project.

This chapter is based on the results of the project **PR-4**: *Sustainable energy Services for Idjwi island (Democratic Republic of Congo, 2019-20).* 150 kWp hydroelectric and PV solar multi-source mini-grid with LV distribution network reaching up to 800 customers. Partner: AVSI Foundation and Ministry of Environment of the DRC.

Chapter 7: Operation

This chapter deals with a new approach to allow developing simplified integrated analyses of dispatch strategies and real time power control. In the previous Chapters the discussion over capacity planning and system sizing mainly looked at power and energy availability in the long term. Nevertheless, during operations there can be power quality issues in small time-steps, which need to be addressed. Voltage and frequency fluctuation are explained and supply technologies (dump loads, flywheel) and management options (demand-side actions, Internet of Things, smart metering) are proposed embracing simplified electrical models of system components in order to address optimal dispatch strategy.

In the reference study, an analysis of wind production data generated from one year of actual wind data is used to test the power smoothing performance of a range of battery systems with various storage and power ratings. Different ramp rates thresholds and the effect on battery durability where also assessed. Wind generation ramp rates end up causing voltage and frequency issues in grids or supply limitations in microgrids, which can effectively be limited using energy storage.

The chapter brings in the case study of the papers **PA-3:** *Ramp rate abatement for wind power plants: A techno-economic analysis*. G.F. Frate, P. Cherubini, C. Tacconelli, A. Micangeli, L. Ferrari, U. Desideri. Applied Energy, Volume 254, 2019, 113600, doi.org/10.1016/j.apenergy.2019.113600 and **PA-4:** *Ramp rate abatement for wind energy integration in microgrids.* Frate G.F., Cherubini P., Tacconelli C., Micangeli A., Ferrari L., Desideri U., Energy Procedia 159 (2019) 292-297; doi: 10.1016/j.egypro.2019.01.013

Chapter 8: Economic

In this Chapter the study classifies and analyses business models of 21 mini-grid projects in Sub-Saharan Africa, identified among 32 pre-selected cases on the basis of selection criteria which took into consideration: i) geographic coverage; ii) location; iii) technological solution; iv) services provided; v) system size; vi) source of power; vii) project status.
Process for identification of the most promising business models has gone through the analysis of project techno-economic, social and operational parameters. Four main business models are highlighted as a way to suggest possible integrated approaches, exploring private-led, public-private, private-community as well as private-private models. Each model presents a different integration of productive uses of energy and energy-related services: provision of electrical appliances, agro-business activities, water and irrigation supply, cooling services, storage solutions and complementary activities such as micro-credit and technical assistance.

The chapter is based on the publication **PU-1:** *RE-thinking Access to Energy Business Models. Ways to Walk the Water-Energy-Food Nexus Talk in Sub-Saharan Africa.* Gambino V., Tacconelli C., Micangeli A., et al. RES4Africa Foundation, 2019. ISBN 978-88-492-3804-4.

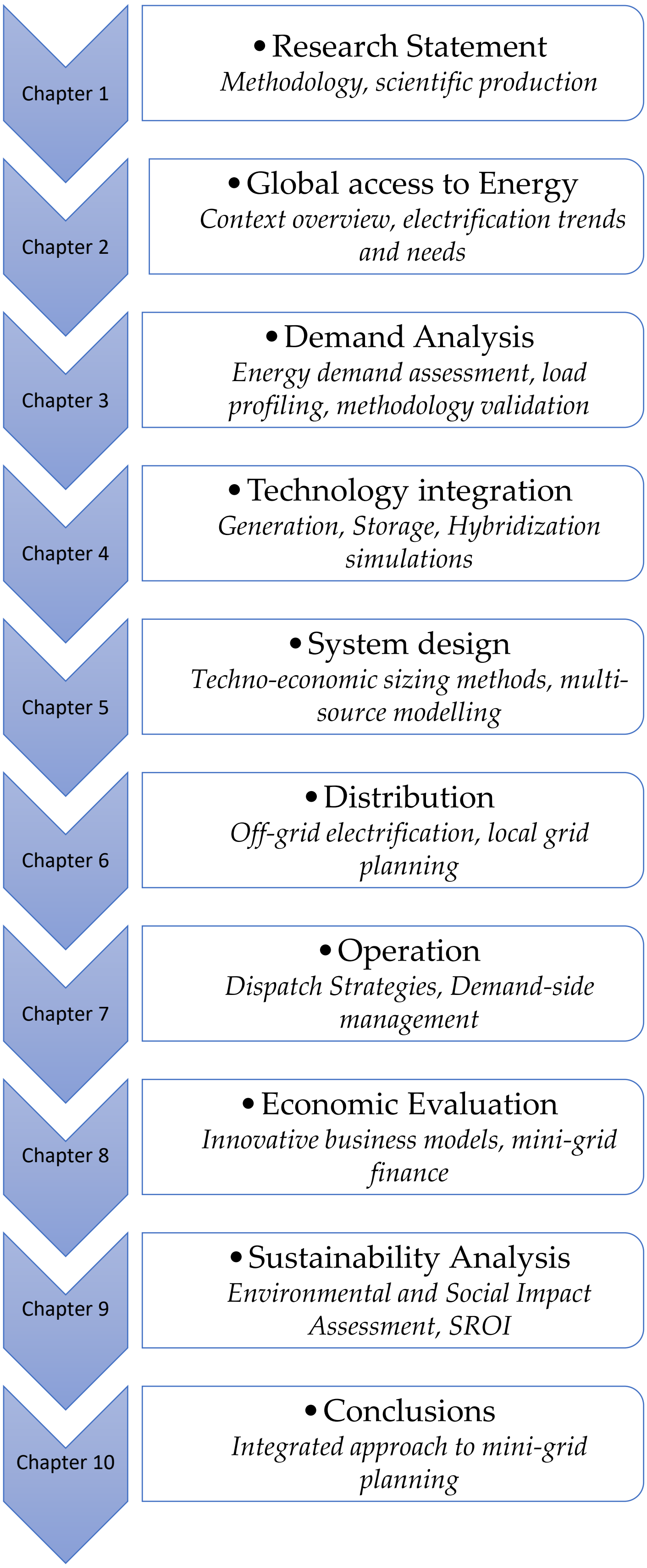
Chapter 9: Sustainability analysis

It this Chapter a thorough impact assessment has been revealed. Beyond economic impact, other direct/indirect effects of mini-grids on environment and target communities are outlined. A possible tool is presented for mini-grids monitoring and evaluation, called Social Return on Investment (SROI), using a wide set of key indicators to measure monetized effects on education, health, security, environment and economy. The research study on SROI regards 2 mini-grid projects in Uganda: Kitobo and Bukasa Islands, where interviews and field surveyed helped to provided substantial data for a first preliminary analysis.

The chapter is based on the ongoing projects **PR-5***: Energy and training for a sustainable growth in Bukasa island (Uganda, 2017-19).* 100 kWp hybrid solar PV and LV distribution smart grid for 500 connections. Partner: Absolute Energy. And **PR-6***: Sustainable energy services for Kitobo island (Uganda, 2017-19).* 228 kWp solar PV with vanadium redox flow battery storage, diesel backup and LV distribution smart grid. Partner: Absolute Energy.

Chapter 10: Conclusions

A summary of thesis contributions is given, and future research directions are discussed. Recommendations are outlined for projects developers and operators, along with strength and weaknesses of the study outcomes, paving the way for future models' improvement.



The above chart shows the Thesis’ concept workflow.

2. Global Access to Energy

Developing countries are affected by the lowest per capita values of total primary energy supply as well as electricity consumption. They mostly rely on traditional biomass as primary source of energy and they have weak power infrastructures. These conditions are even worse in rural areas where thousands of scattered villages are isolated and characterized by no access to any kind of service.

Tackling the problem of access to energy in DCs basically means to address (a) the problem of access to electricity and (b) the problem of access to modern fuels and efficient use of traditional biomass.

Considering the concept of profitability as well means to recognize the link between energy and economic development and hence that the approaches in exploiting the energy resources contribute in determining the growth of any electrified context. In this frame, specific energy strategies can be undertaken, and appropriate energy technologies can be implemented in order to promote sustainable development. This aspect is even more important in DCs where the impact on local development due to enhancing access to energy is more tangible.

Within this frame, this thesis deals with rural areas and with the problem of access to electricity. Specifically, it focuses on an integrated approach for decentralised renewable energy systems planning and implementations. Two main observations can be recognized as general motivations of this research theme, as previously outlined by Mandelli, S.[1]:

- electricity supply is essential to promote development in rural areas, nevertheless the features of these areas bring about economic and technical constraints to the implementation of traditional technologies based on the centralized electrification approach. Therefore, rural electrification via off-grid solutions based on renewable energy sources (RESs) can be the most viable option
- the design process of these systems is extremely inaccurate and there are several challenges to overcome. Therefore, specific approaches and methodologies are required to tackle these issues. Moreover, achievements in off-grid rural electrification design can have favourable reflection on applications in industrialized countries where there is nowadays a growing integration between grid-connected small-scale power systems (i.e. Distributed Energy Cooperatives, Energy Communities) and the centralized grid.

Moreover, it is worthwhile to mention that the research field of renewable-based mini-grids is receiving a growing interest since the beginning of the past decade. Furthermore, it involves a number of engineering disciplines, but also other subjects (e.g. social, environmental and economic sciences), leading to the development of several research areas. Within this context, the thesis contributes in the progress of the research field by revising the literature in order to identify the main research themes and hence to provide scholars with a reference framework.

2.1. Electrification rates

Energy poverty is defined as lack, scarcity, or difficulty in accessing modern energy services by households. The International Energy Agency defines a household as having energy access when it has reliable and affordable access to both clean cooking facilities and electricity, which is enough to supply a basic bundle of energy services initially, and with the level of service capable of growing over time [2].

The geographical distribution of such phenomena is uneven across the world. People without electricity are mostly in Africa (53%) and developing Asia (43%) involving a fifth of the world's population.

Lack of access to modern energy services is concentrated in rural areas in which 80% of energy-poor people live. The sub-Saharan Africa remains the region with the lowest energy consumptions per capita and with the largest concentration of energy poverty, despite the considerable amount of potential available resources .

Africa accounts for only 6% of global energy demand and a little more than 3% of electricity demand. The average energy consumption per capita in most African countries is well below the world average.

To underline the uneven distribution of this phenomena just consider that more than two-thirds of people without access to electricity in the world today live in sub-Saharan Africa whereas North Africa reached almost universal access to electricity by 2018, in the same period the electrification rate in sub-Saharan Africa was limited to 45%, a very low value compared with other parts of the world [3].

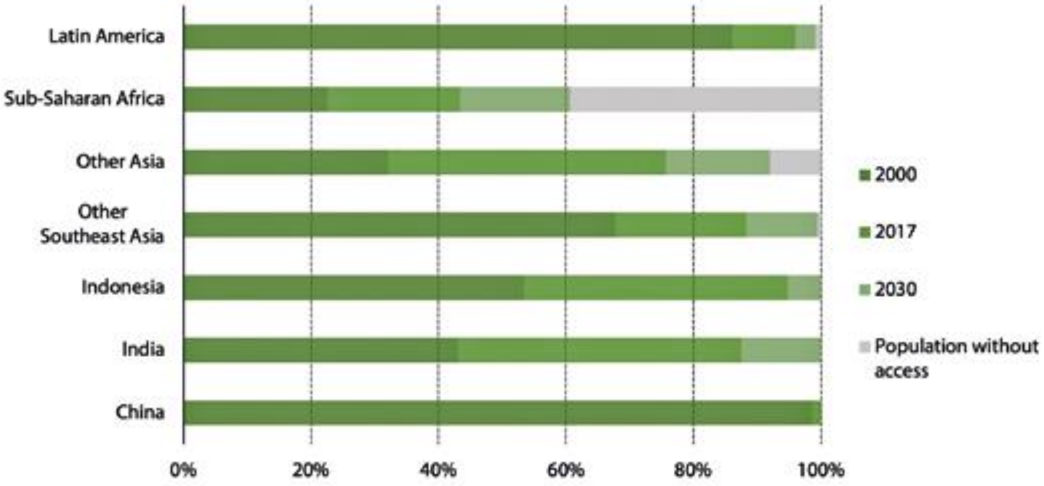


Figure 2-1: Progress since 2000 and outlook to 2030 for electricity access. Source: IEA

According to the IEA, the energy poverty scenarios all over the World are expected to evolve significantly by 2040, and most countries are expected to reach the target of universal access to energy. That is not going to happen in the Sub-Saharan Region, in which more than 90% of people without access to energy will be located.

Additionally, most of the progress on access to energy in the sub-Saharan region will involve urban areas through the extension of the national electricity grids, the 95% of the population without electricity will be therefore concentrated in rural areas in which small businesses and communities that can afford it will use inefficient, polluting, and expensive alternative solutions for essential services.

The lack of access to modern energy is therefore linked to low-income levels and blocks rural populations in a condition of economic and social deprivation.

All aspects of the community's economic development are affected directly by the lack of energy, i.e. time availability, agricultural and economic productivity, and other opportunities for income generation, making poverty eradication almost an impossible challenge.

Providing clean and modern energy to rural area reduces the time currently spent, especially by women and children, in gathering traditional fuels used for cooking and make it available to income-earning activities or education.

Moreover, energy is crucial to increase technology and mechanical power in the production process and agricultural practices, currently dominated by human or animal energy, thus contributing to economic development and food security.

The region now faces a dual challenge: how to provide access to the 600 million currently deprived while at the same time reaching the millions born every year in areas without access to electricity.

Breaking this cycle will allow the African continent to unlock access to improved economic opportunities, improved healthcare, universal education, and, consequently, longer and better life for its population[4].

Despite all these encouraging achievements, the world is still off-track to comply with the targets of Sustainable Development Goal 7- ensure access to affordable, reliable, sustainable and modern energy for all by 2030.

In fact, most of recent progress in electricity access has been made in developing Asia, with China reaching universal energy access in 2015 and India announcing the complete electrification of the country through the *Saubhagya* scheme[1]. Sub-Saharan Africa is still lagging behind, with more than 600 million people still lacking access to electricity. Even though over 200 million people have gained access since 2000, this increase was lower than the overall population growth [5].

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[1] SAUBHAGYA. Available online: https://saubhagya.gov.in (accessed on 1 May 2020).

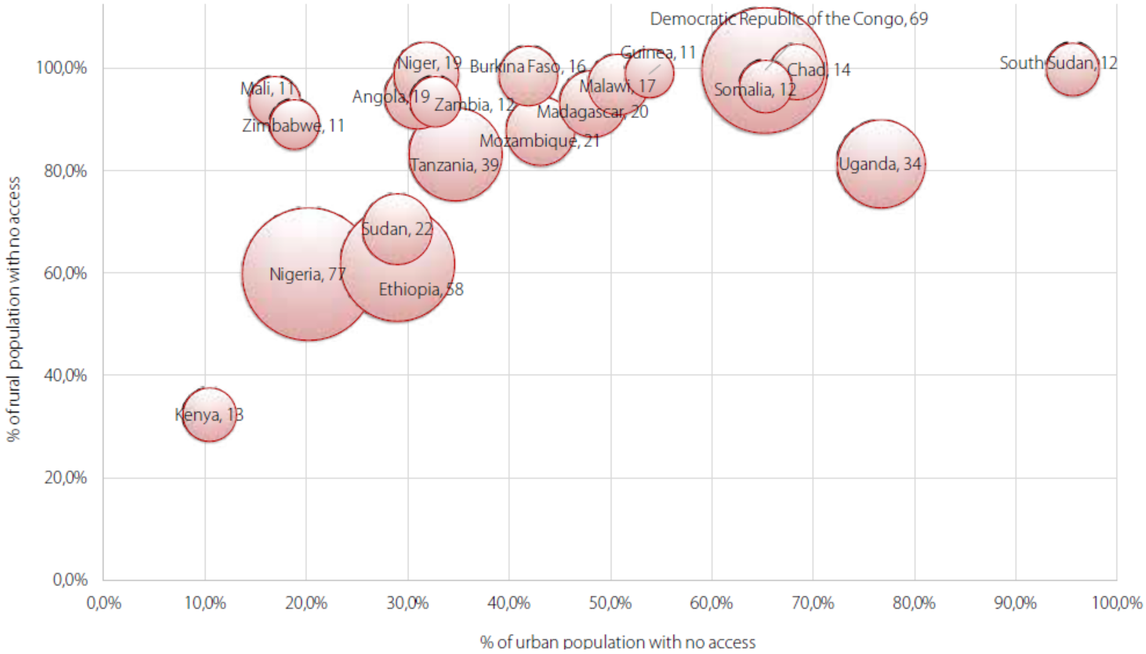
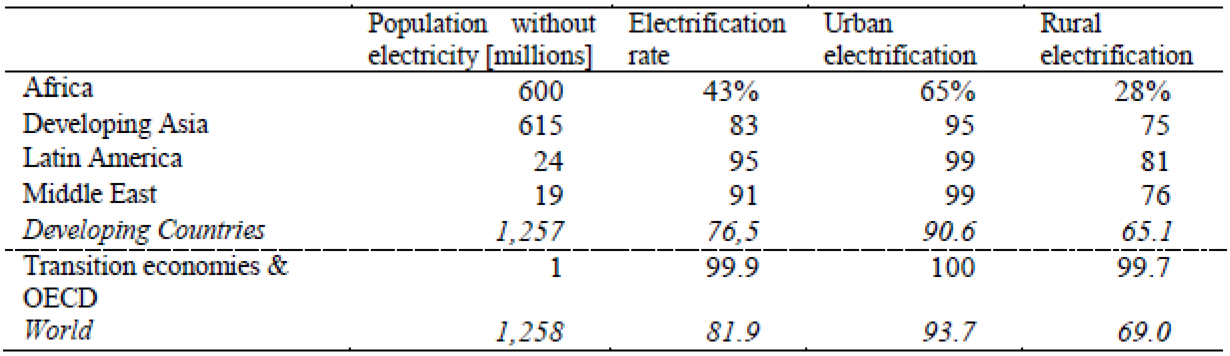


Figure 2-2: Millions of people without access to electricity, with respect to urban and rural population lack of access. Bubbles represent the twenty countries with the highest amount of population without access. Source: IEA

As a result, Sub-Saharan Africa's share in the global access deficit has more than doubled between 1990 and 2016 [6] . Following United Nations' projections, Africa's population in 2050 will be more than double than today, reaching 2.5 billion people starting from today's 1.2 billion [7].
To assess future needs, this figure should be evaluated considering two phenomena: (i) the urbanization rate, that is expected to rise from 40% in 2015 to 56% by 2050, (ii) future migration trends and their drivers, such as conflicts, political instability, environmental factors, employment opportunities and more.

International migration is a growing phenomenon, but it is mostly an intra-African rather than extra-continental one: in 2017, around 19.4 million people resettled by moving within African states [8]. There is also an ongoing trend of rural to urban migration within single countries, which is another challenge to face in order to guarantee access to energy for all. In the next decades, Africa will experience a very fast urbanization, and it is estimated that in 2030 there will be 17 cities with more than 5 million people and 5 cities with more than 10 million people, whereas in 2015 there were 6 and 3 respectively. However, the need for electrification remains mostly a rural issue.

Despite the fact that rural electrification is rising more rapidly than urban electrification due to lower population growth, in Sub-Saharan Africa over 80% of the people without electricity live in rural areas with an electrification rate for urban households estimated at 71%. This number is way ahead of the 25% rate reported for rural ones [9]



	Population without electricity [millions]	Electrification rate	Urban electrification	Rural electrification
Africa	600	43%	65%	28%
Developing Asia	615	83	95	75
Latin America	24	95	99	81
Middle East	19	91	99	76
Developing Countries	*1,257*	*76,5*	*90.6*	*65.1*
Transition economies & OECD	1	99.9	100	99.7
World	*1,258*	*81.9*	*93.7*	*69.0*

Figure 2-3: Regional aggregates for electricity access. Source: IEA

2.2. Energy within Sustainable Development Goals

Access to modern energy is today considered essential to encourage development and to fight poverty [10]. Sustainable energy, being a basic condition to enable access to services, resources and public goods, therefore constitutes an essential prerequisite for human and social progress, along with environment conservation. Access to energy is essential for clean water supply and sanitation, for the development of agriculture (irrigation, mechanization, food processing and transportation), for the support of ICTs and for enabling access to healthcare, education and other basic social needs.

The Sustainable Development Goals (SDGs)[2], also known as the Global Goals, were adopted by all United Nations Member States in 2015 as a universal call to action to end poverty, protect the planet and ensure that all people enjoy peace and prosperity by 2030 in the context of the Agenda 2030. The SDGs and the correlated 169 targets demonstrate the scale and ambition of this new universal agenda which is based on the Millennium Development Goals and aim to complete what they are not managed to accomplish. They aim to fully realize the human rights of all and to achieve gender equality and the emancipation of all women and girls. They are interlinked and indivisible and balance the three dimensions of sustainable development economic, social and environmental dimensions.

Figure 2-4: Sustainable Development Goals. Source: United Nations

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[2] https://www.undp.org/content/undp/en/home/2030-agenda-for-sustainable-development.html

“Goal 7: Ensure access to affordable, reliable, sustainable and modern energy for all[3].

The global targets of SDG 7 of UN are:

- By 2030, ensure universal access to affordable, reliable and modern energy services;
- By 2030, increase substantially the share of renewable energy in the global energy mix;
- By 2030, double the global rate of improvement in energy efficiency;
- By 2030, enhance international cooperation to facilitate access to clean energy research and technology, including renewable energy, energy efficiency and advanced and cleaner fossil-fuel technology, and promote investment in energy infrastructure and clean energy technology;
- By 2030, expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, in particular least developed countries, small island developing States, and land-locked developing countries, in accordance with their respective programmes of support.”

Access to affordable, reliable and sustainable energy is crucial to achieving many of the Sustainable Development Goals, from poverty eradication via advancements in health, education, water supply and industrialization to mitigating climate change.
Africa is among the regions most exposed to the effects of climate change. Its ecosystems already suffer disproportionately from global climate change and future impacts are expected to be substantial. This will have implications for food security, migration and development. All African countries signed the Paris Agreement, and through their Nationally Determined Contributions (NDCs), they committed to contribute to the global effort to mitigate GHG emissions (IPCC, 2019). Africa accounts for a relatively small, but nonetheless growing share of the world’s carbon dioxide (CO_2) emissions.

Besides the 2030 Agenda, African countries have committed to implement the African Union Agenda 2063, which is both a vision and a plan to build a more prosperous Africa in 50 years.

More in general, DCs are characterized by low-income economies, with low energy consumption per capita. Access to electricity and use of modern energy service are not available for the majority of the population, especially in rural areas. Although these countries are often rich in primary resources, these are rarely used at local level. Current energy systems are still weak and characterized by low reliability. These countries are identified by a general low electrification rate and by a high percentage of population still relying on traditional biomass for their energy needs.

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[3] https://www.undp.org/content/undp/en/home/sustainable-development-goals/goal-7-affordable-and-clean-energy/targets.html

2.3. Electricity access tiers

Until recent years, energy policies reflected the paradigm of the expansion of centralised-grid systems to foster access to electricity, which tended to promote an "all or nothing" attitude which excluded the people too distant from the existing grid from the possibility of achieving access [11].

For this reason, the lack of a supportive and comprehensive policy and regulatory framework to enable investments in decentralised RE solutions is often cited as one of the main gaps to be filled in order to ensure the necessary involvement of private sector investments, along with the lack of off-grid market information, data and transparency, of debt finance, of capacity among market players and of interaction between them inside and outside of local markets[12].

To assess the quality of the policy and regulatory environment, in 2016 the World Bank developed the Regulatory Indicators for Sustainable Energy (RISE) [13], a global policy scorecard grading 111 countries in the three dimensions of energy sustainability: energy access, energy efficiency and renewable energy. In particular, to support and monitor electricity access, 8 indicators were developed with a score 0-100 based on the ratings of various sub-indicators:

(1) existence and monitoring of officially approved electrification plan,

(2) scope of officially approved electrification plan,

(3) framework for grid electrification,

(4) framework for mini-grids,

(5) framework for standalone systems,

(6) consumer affordability of electricity,

(7) utility transparency and monitoring and

(8) utility creditworthiness.

The resulting average of all 8 indicators leads to the overall score for electricity access, which is detailed and ranked for Sub-Sahara African countries in Figure 2-5

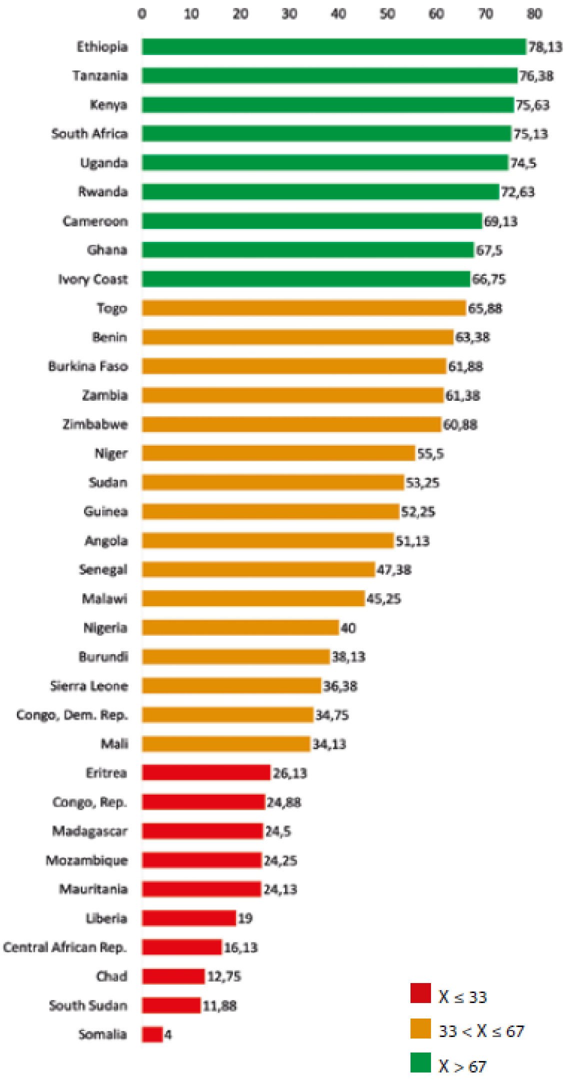
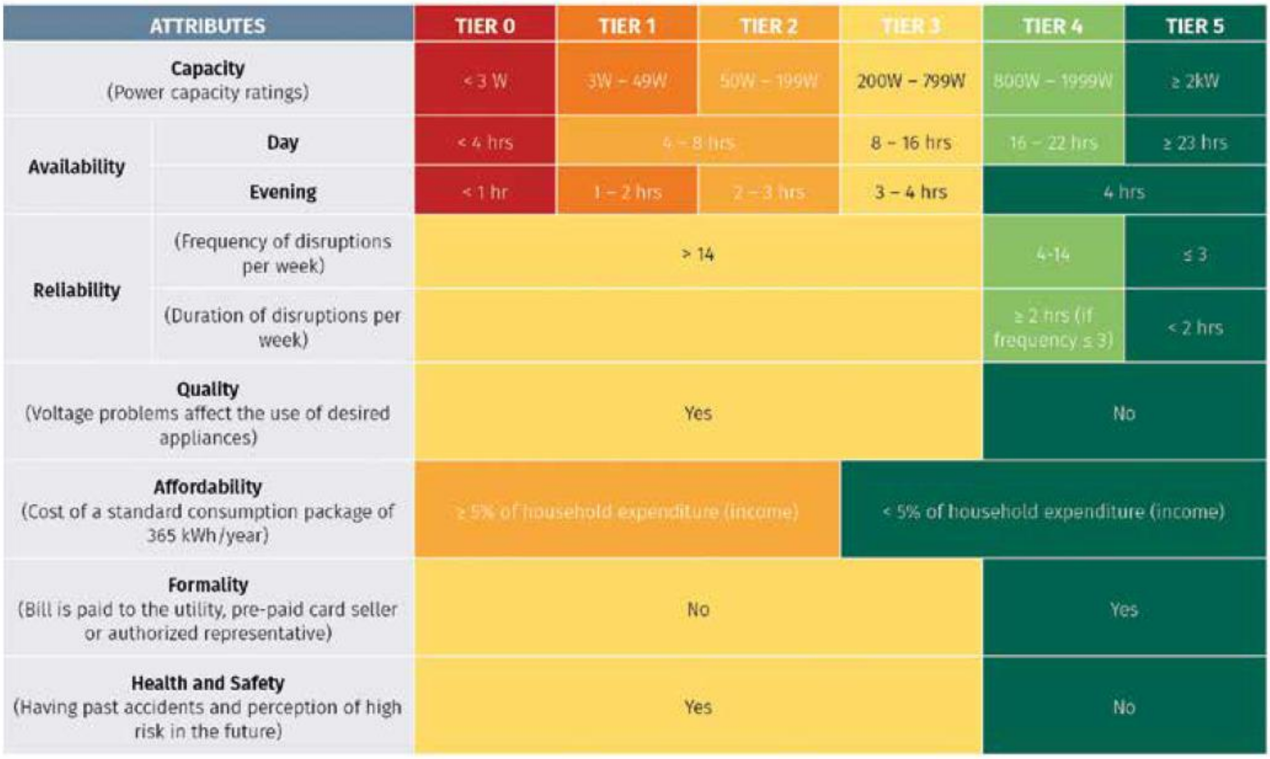


Figure 2-5 Overall RISE 2017 score for electricity access for Sub-Saharan Africa countries. Source: RISE

The difficulty of measuring access to energy and refer to a universal reference classification lies within the multi-dimensional nature of access to energy. Access to electricity has typically been measured as having a household electrical connection, while access to modern cooking solutions has been measured as cooking with clean nonsolid fuels [14].
However, in the last years, the idea of energy access as such binary parameter has been overtaken to find a more comprehensive metric that uses a technology-neutral multi-tier framework[15] and has been supported by reference definitions on access to energy published by SDGs, IEA and World Bark among others.

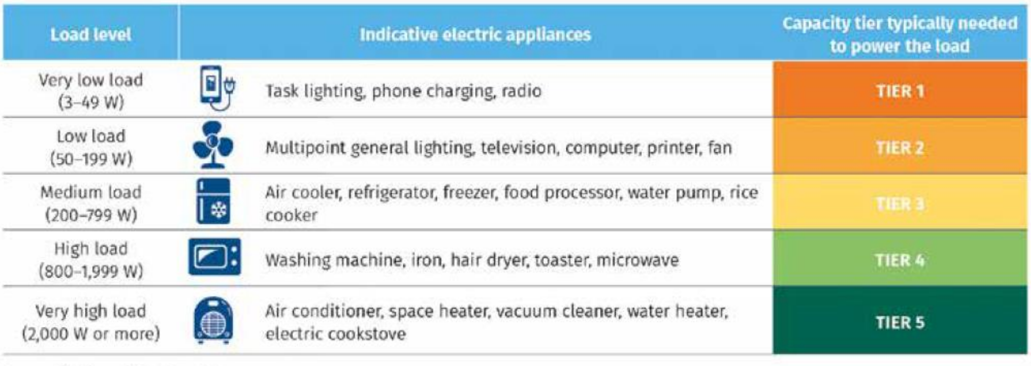
A methodology of Multi-Tier Framework (MTF) was proposed by SE4ALL in 2013 [16] in order to reflect the multi-dimensional nature of access to energy and quantitatively describe the level of electricity supply by assigning a score (tier) to a set of attributes that qualify the level of access provided (capacity, availability, reliability, quality, affordability, legality, health and safety).
Figure 2-**Errore. L'origine riferimento non è stata trovata.**6 shows the matrix used to assign to household an overall tier of access by using the lowest score in any of the attributes, whereas Figure 2-7 shows the indicative electrical appliances, the related load level and the associated capacity tiers.



ATTRIBUTES		TIER 0	TIER 1	TIER 2	TIER 3	TIER 4	TIER 5
Capacity (Power capacity ratings)		< 3 W	3W – 49W	50W – 199W	200W – 799W	800W – 1999W	≥ 2kW
Availability	**Day**	< 4 hrs	4 – 8 hrs		8 – 16 hrs	16 – 22 hrs	≥ 23 hrs
	Evening	< 1 hr	1 – 2 hrs	2 – 3 hrs	3 – 4 hrs	4 hrs	
Reliability	(Frequency of disruptions per week)	> 14				4-14	≤ 3
	(Duration of disruptions per week)					≥ 2 hrs (if frequency ≤ 3)	< 2 hrs
Quality (Voltage problems affect the use of desired appliances)		Yes				No	
Affordability (Cost of a standard consumption package of 365 kWh/year)		≥ 5% of household expenditure (income)			< 5% of household expenditure (income)		
Formality (Bill is paid to the utility, pre-paid card seller or authorized representative)		No				Yes	
Health and Safety (Having past accidents and perception of high risk in the future)		Yes				No	

Figure 2-6 Multi-tier Matrix for Measuring Access to Household Electricity. Source: World Bank

In other words, in the multi-tier approach to measuring access to energy, the combination of attributes reflects the performance of the energy supply and thus, the tier assigned or achieved directly reflects the project’s impact on target population development, including socio-economic and environmental dimensions. The relevance of the matter beyond the technical discussion can be effectively given by reporting an interesting case study which attests the impact of the MTF applied to a survey implemented in Ethiopia by the World Bank in the first months of 2017. World Bank indicator reports a 45% level of access for Ethiopia in 2018[4].



Load level	Indicative electric appliances	Capacity tier typically needed to power the load
Very low load (3–49 W)	Task lighting, phone charging, radio	TIER 1
Low load (50–199 W)	Multipoint general lighting, television, computer, printer, fan	TIER 2
Medium load (200–799 W)	Air cooler, refrigerator, freezer, food processor, water pump, rice cooker	TIER 3
High load (800–1,999 W)	Washing machine, iron, hair dryer, toaster, microwave	TIER 4
Very high load (2,000 W or more)	Air conditioner, space heater, vacuum cleaner, water heater, electric cookstove	TIER 5

Figure 2-7 Load levels, indicative electric appliances, and associated Capacity tiers. Source: World Bank

The MTF survey [17] provides a similar figure for the level of access, but gives a lot of extra information on the actual level of access reached, as showcased in Figure 2-8 : only 43% of people that fall in Tier 0 have no electricity access at all, but the rest of them have access to inadequate off-grid solution or even to a particularly unreliable grid.

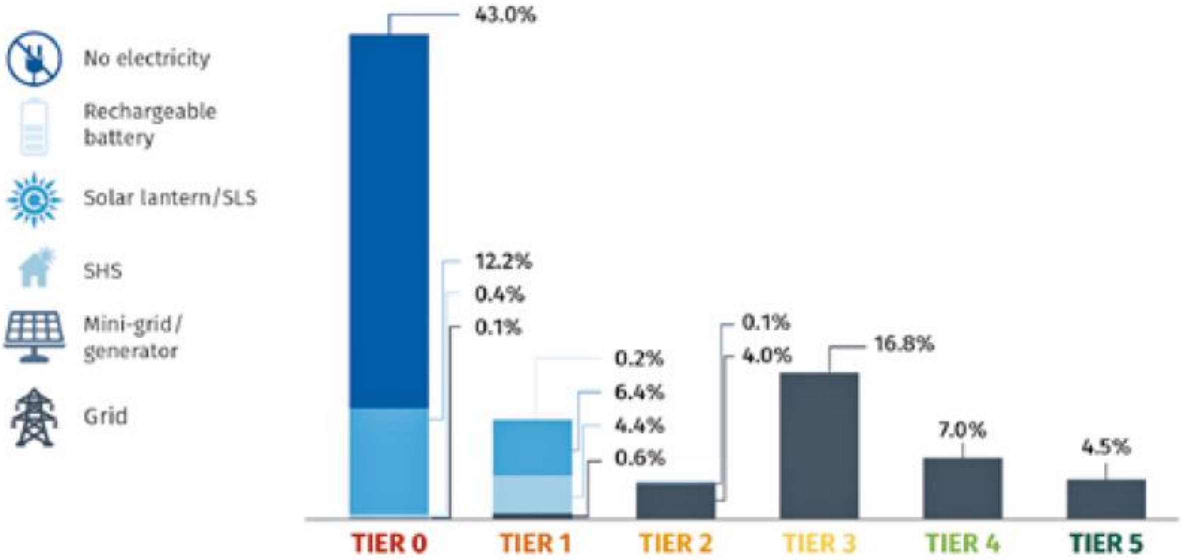


Figure 2-8 Disaggregate data divided per energy source. Source: World Bank

MTF surveys provide data also on energy spending and use, willingness to pay for off and on-grid solutions, user preferences and satisfaction with current access status. It's clear how this information is useful to assess the need of people with access to move to higher tiers and which are the adequate

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[4] https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS

tiers of supply for new users. The output of the MTF implementation in Ethiopia suggests, for example, that 96% of unconnected households have the willingness to pay for a grid connection, and that the main impediments towards this goal are the distance from the grid and the complicated administrative procedures to get a connection. The evidence indicates also a high willingness to pay for Tier 1 and Tier 2 systems, which off-grid solar solutions are the most suitable for, and thus they should be prioritized to achieve a large access to electricity.

Such results reveal how MTF surveys can effectively be used by Sub-Saharan African governments to better define energy access targets, to update their policies accordingly, and to better quantify their investment needs.

A recent review of the academic literature has found that a majority of researchers observe positive economic impacts of electrification in developing countries [18]. These observed impacts have included increases of household income, significant household cost savings from reduced fossil fuel and battery expenditure, increases of female employment rates, a higher uptake of trainings and education aimed at increased productivity, higher overall consumption levels, and local migration from non-electrified to electrified villages.

Increases in income through electrification occur when new appliances are run and boost economic activities. This is commonly referred to a productive use of electricity. Electric appliances for productive use can be grouped into requiring either light, medium or heavy amounts of electricity. The potential for adding value tends to increase with the electricity demand of the machines, implying that finance and/or savings can translate into more income generation potential. For instance, a 1 kW solar hammer mill which is able to treat roughly 40 kg of produce per hour costs around USD 4,000. Another example is the case of cassava and maize milling in Uganda, where it can more than triple the crops' value by weight. Considering that in Uganda maize in grain form sells at around 0.25 USD/kg (prices vary a lot depending on the season), while milled grain sells for roughly 0.75 USD/kg, the machine would be required to run with a 20% capacity factor during a two-month maize harvest period for the investment to be recovered.

2.4. Rural context

In DCs, rural areas are generally scattered populated, geographically isolated and difficult to access. The main sources of income for rural households are pastoralism, cattle raising, agriculture, fishing, tourism or forestry [19] . The road conditions exacerbate the limited accessibility, and hence service suppliers cannot guarantee regular visits, thus preventing local populations from participating in national or regional markets. Moreover, high educated people (i.e. teachers, doctors, technicians, etc.) are despondent to dwell in such areas [20]. Rural areas are also affected by high illiteracy rate, gender inequality, lack of access to health care, infrastructure and clean water supply. When it is available, often only the high-income households, few enterprises and community bodies can afford connections since electricity may cost as much as 10 times more than in urban areas [21]. When there is no centralized grid connection, electrification occurs in those areas reached by local fuel supplies, and it is based on off-grid small-scale power generation systems; historically diesel generators and recently renewable-based systems usually aid-financed[22] [23] .

Different categories have been employed in the literature to subdivide rural energy uses, mainly:

(i) energy for *household basic needs,*
(ii) energy for *community services* and
(iii) energy for *productive uses*.

2.4.1. Energy for household basic needs

Households account for the majority of energy consumed in rural areas. They require energy mainly for cooking and lighting. Up to 80% of energy consumption is devoted for cooking that indirectly can supply also space heating [24]. These needs are mainly covered by non-commercial or traditional biomass (i.e. firewood, charcoal, crop residues, dung, etc.). The rest of the energy is consumed for lighting, while further appliances (fans, radios, TVs, etc.) are employed only when modern energies (electricity, gas or LPG) are available and households can afford them.

2.4.2. Energy for community services

Electricity plays a crucial role for improving access to public services, education and health being the most important. In education electricity is needed to improve schools' facilities (lights, ITC, etc.) and to attract teachers to rural areas. Health clinics and hospitals require electricity to deliver adequate treatment and care. Moreover, electricity contributes in improving access to clean water and for telecommunication systems[1].

2.4.3. Energy for productive uses

Productive uses of energy refer to commercial and industrial activities and specifically include the needs coming from agriculture and rural processing units. In most DCs, food security and income generation highly depend on agricultural production [25], consequently an increased use of modern energy services can strongly contribute to improve rural areas welfare. Energy uses for agriculture cover irrigation and post-harvest processing. Moreover, small farmers may set up Micro and Small Enterprises (MSE), often household-based and managed by women. Their activities include milling, fruit and vegetable processing, fish and vegetable storage and packaging, pottery making and other processes.

Also, the development of rural industries is a key component of rural welfare improvement. They include a range of small and micro businesses and industries such as small shops, kiosks, barbers, community radios, charcoal and brick manufacturing, potteries, bakeries, welding, mechanics etc. .

A reasonable range for electric supply considers power rate in a range from a few to hundreds of kW.

2.5. Water-energy-food Nexus (WEF approach)

In addition to the energy challenges, access to clean water is a significant problem in many areas of rural Sub-Saharan Africa. The majority of the rural population has either no access to a clean water source at all or drinking water must be fetched from a long distance which causes a major burden for local households [26]. About 60% of the population in rural Sub-Saharan Africa areas rely on rainfed, small-scale farming activities as the primary income source [27]. Due to the dependency on periodic rainfalls, these forms of agriculture are often seasonal which limits the households' ability to generate a stable income over the year. This in turn makes it more difficult for developers to achieve financial sustainability of their off-grid energy systems in rural areas. In addition to this, rainfed farming practices are particularly vulnerable to the effects of climate change.

The three dimensions "water", "energy" and "food" are deeply interdependent, requiring integrated approaches on a policy and a project development level to achieve the SDGs [28]. Yet policy-making and planning approaches are often sector-driven [29] which can result in conflicting, counterproductive strategies [30]. By contrast, an integrated approach goes beyond the sole provision of household electricity and incorporates clean water supply, irrigation, and agriculture and fish-processing activities, enabling to capture different types of value: needs-based irrigation increases food producers' resilience against droughts and breaks the cycle of seasonal income as well as ice production allows for a more efficient value chains of fish products.

Such processing services can lead to a more stable income generation and diversification of economic activity. The availability of clean water improves the quality of life and health conditions in a community. Finally, these water and food related energy demands help to drive economic sustainability of off-grid projects by increasing their utilization.

This approach is yet to be tested at scale as most off-grid systems not yet provide integrated services but are usually focused on either agro and fish processing, irrigation, clean water supply or the domestic provision of electricity. It needs to be tailored to the demands of communities, require multi-criteria planning with multi-stakeholder engagement [31] featuring joint efforts from developers, communities, financiers, and researchers as well as policy-makers to set the formal framework for frictionless project implementation.

2.6. Rural Electrification strategies

This section deals with mini-grids power systems which represent one of the most appropriate energy strategies to address rural electrification both as a first step in the electrification process or as a building-block for future grid development. Specifically, the main options for rural electrification are: main grid extension, mini-grids, individual systems.

2.6.1. Grid extension

Extending the national grid is the often the most obvious and desirable solution to increase access. According to BloomberNEF[5], connecting new customers via grid extension costs between USD 266 and 2,100 per household; however, the cost increases as distance from the existing infrastructure grows and as density of demand decreases. Potential customers in remote areas generally have a low-income status, a scarce ability to pay and a low annual energy consumption that seldom justify such costly extensions. Furthermore, the mere presence of the grid does not directly translate into energy access, as low take-up rates have been reported by the World Bank in various Sub-Saharan African states [32] . Lastly, actual grid off-takers are often served by an unreliable service: a survey conducted by Afrobarometer across 36 countries found that only 4 out of 10 Africans enjoyed a reliable electricity supply from the grid [33].

2.6.2. Mini-grids

Mini-grids represent the optimal alternative to grid extension for rural communities that have an adequate size, are densely populated and have enough economic strength to justify such investment [34]. Historically, rural mini-grids were powered by diesel generators and relied entirely on fossil fuels.

Small-scale power systems are gaining more and more consideration in electric utility planning of both developed and DCs and overall, IRENA estimates that between 50 and 250 GW of off-grid diesel capacity worldwide could be hybridized with renewables [35]. Nevertheless, this is not a new approach. In fact, at the sunrise of the electrical era, systems were quite decentralized, and small generation plants, together with batteries, supplied electricity via *dc* grids only to nearby limited areas of dense load.

The first era of small-scale power was ended by the emergence of *ac* grids which drove to the construction of huge transmission grids and large generation plants [36]. The resulting structure of the electrical industry was the state-owned vertical integrated regulated monopoly which can be considered as the classical paradigm of centralized electrical system [37]. This approach has been followed both in developed and DCs, but while developed countries were able to extend the coverage area of the electric grid also to rural areas, DCs are still facing considerable difficulties in increasing power production and electrification rates.

Rural areas are the most afflicted by this situation since governments paid more attention to urban areas where economic activities are relevant. Moreover, rural electricity supply generally results to be expensive within the centralized approach, and hence the utilities have always been reluctant to extend the service to rural areas. Typical actions taken up by DCs governments to address this issue, were the establishment of separate organizations – the *Rural Electrification Agencies* – that were made responsible for rural electrification programs [38].

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[5] https://medium.com/climatescope/3q-2018-off-grid-and-mini-grid-market-outlook-70ed47656c31

The primacy of the centralized approach gradually decreased in developed countries during the '80s, due to the introduction of competition into the electric industry [39]. Also, DCs pursued reforms trying to attract foreign private capitals in order to increase the efficiency in the electrification process. It is in the new post-reform frame that a second era of small-scale power systems seems to arise [40].

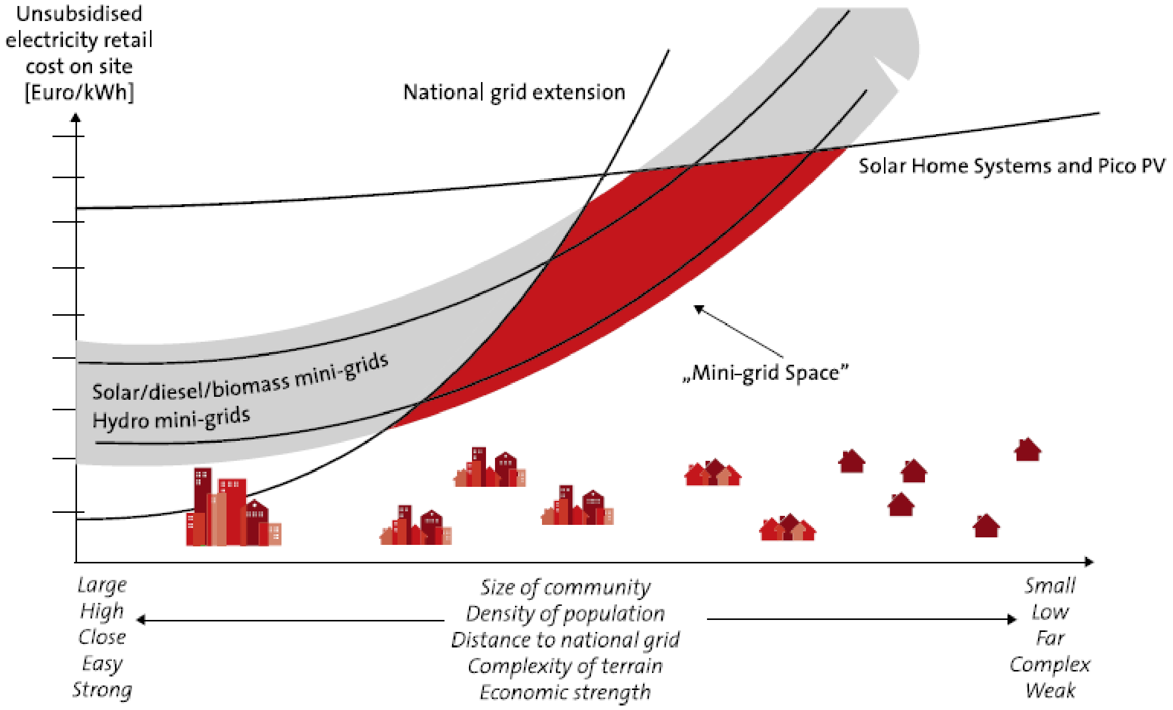

Figure 2-9: Mini-grid "space". Source: Mini-grid policy toolkit, Inensus 2015

Besides the introduction of competition, other factors contributed to renew the interest towards a strategy based on small-scale power systems. Most of the listed factors are driving forces in developed countries as well as in DCs. Nevertheless, further reasons can be associated specifically to DCs and rural areas:

- accessibility: small-scale systems are preferred for the remotest locations where costs make unfeasible the extension of the main grid;
- load demand: rural areas have very low demand and low load factors, thus fitting with small-scale generation systems [41] ;
- poverty fight: the growing attention on the links between modern energy and poverty has led to consider electricity as a main component within rural development programmes and small-scale systems as the preferable option [42] ;

In developed countries we are nowadays experiencing a growing integration between grid-connected small-scale power generation systems (i.e. Distributed Energy Cooperatives) and the main centralized grid [43], while in DCs off-grid small-scale power systems can today play a pivotal role in rural electrification

2.6.3. Individual Systems

Regardless of the source, any system that produces electricity that is not connected to a grid and typically gives power to a single person or household [9], falls under the category of "individual system". However, this term generally refers to photovoltaic devices with a variety of power ratings, which start from Pico Solar systems (below 11 Wp) [44], comprising single light systems such as solar lanterns that provide a level of supply below Tier 1, and simple multiple-light systems, providing also mobile charging.

Plug-and-play solar home systems (PnP SHS) are packaged kits with photovoltaic panels for 11 Wp or more, which are equipped with 3-4 lights and other basic appliances, such as a fans, radios, TVs, and so on [45]. SHS can reach up to 100 Wp of photovoltaic panels and even more, making them capable of operating direct current (DC) appliances for productive use, such as refrigerators, solar water pumps or other processing tools in agriculture or other crafts [46].

In addition to devices and kits marketed by companies as plug-and-play solutions, there is a parallel segment of "component- based systems", which are assembled by the users acquiring the various elements (photovoltaics panels, batteries, inverters, etc.) separately on the market.

Individual systems such as Pico Solar, PnP SHS and component-based systems, have been estimated to have reached over 360 million people globally in 2017, but there is still a big potential market estimated in 434 million households [44].

Sub-Saharan Africa in particular, given the population growth in off-grid areas with disperse demand, is a big market for these devices, and has already several active players especially in the countries with a strong mobile money ecosystem due to the ever so common adoption of a pay-as-you-go (PAYG) business model. In addition, potential customers also include the segments of population served by an unreliable grid, as well as existing customers in need for components replacement and service upgrade.

Environmental	◎ growing concern as for the GHG emissions ◎ public awareness as regards the impacts of the electric industry ◎ opposition to construct new transmission lines
Economic	◎ to avoid Transmission & Distribution related costs ◎ to tackle the current risky nature of large scale plant investments ◎ to reduce power plants costs with CHP generation ◎ to better exploit profit margins within the competitive market
Technical	◎ increased performance of the small power technologies ◎ development of electronic metering and control equipment ◎ increased consumer demands for highly reliable power supply
Political	◎ to decrease dependence from fossil fuels ◎ to increase primary source diversification ◎ to reduce vulnerability of the supply chain in centralized systems
Social	◎ increasing public desire to promote "green technologies" ◎ growing interest towards energy autonomy and sustainability

Table 2-1: Major factors that contributed in a renewed interest for small-scale power system

2.6.4. Combined delivery models

Looking at an individual community without access to energy, decision makers should analyse various factors when planning to deliver electricity with grid extension, mini-grid or individual systems. The population’s energy needs should be carefully investigated: assessing needs for domestic users, existing or potential business and anchor loads, as well as identifying tier of supply and size required, is essential to forecast the total magnitude of the demand to be served. Furthermore, distance from the existing grid is one of the main factors influencing the feasibility of grid extension, along with the density of the settlement. In fact, mini-grids are ideal for communities distant from the grid if households are clustered enough to limit the investment in the local distribution network, and individual systems are best suited to provide access to dispersed loads.

Specialized software can support decision makers in developing a systematic plan that harmonizes the three delivery modes in the optimal way.

The Open Source Spatial Electrification Toolkit (OnSSET)[6] model has been elaborated by KTH Royal Institute of Technology (KTH) and other important partners. It estimates, analyses and visualizes the most cost-effective electrification option (grid, mini-grid and individual systems) for the achievement of electricity access goals, taking into account data as population density, proximity to transmission, night-time lights, RE potential and so on. A more in-depth analysis can be performed by using a desktop version of the tool using Python, which can provide higher level of input/output detail and customized electrification results.

With a similar purpose of geospatial electrification planning, the Universal Energy Access Lab, a project by Massachusetts Institute of Technology (MIT) and Instituto de Investigacion Tecnologica Comillas (IIT Comillas), developed the Reference Electrification Model (REM), a software capable of performing an automated cost-optimal electrification design for a given region combining the three delivery modes, and has been used to develop Rwanda’s national electricity master plan [47].

Its uniqueness lies in the capability of considering individual consumers, as each customer is automatically localized through satellite imagery and has a load profile assigned, as well as in grouping them into optimal electrification clusters so that total system costs are minimized. Then, optimization techniques output the optimal generation mix and network layout for each mini-grid and grid extension, along with the clusters or single-users to be supplied with individual systems.

To get a sense of the impact of demand levels in determining the outcome of optimal cost allocation of electricity delivery modes, an appropriate reference is the Electrification Pathways, another model developed by the World Bank, the Energy Sector Management Assistance Program (ESMAP) and KTH Division of Energy Systems Analysis, available as a web-based open source application for developing universal access scenarios in Zambia, Nigeria and Tanzania[7].

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[6] http://www.onsset.org/

[7] http://electrification.energydata.info/presentation/

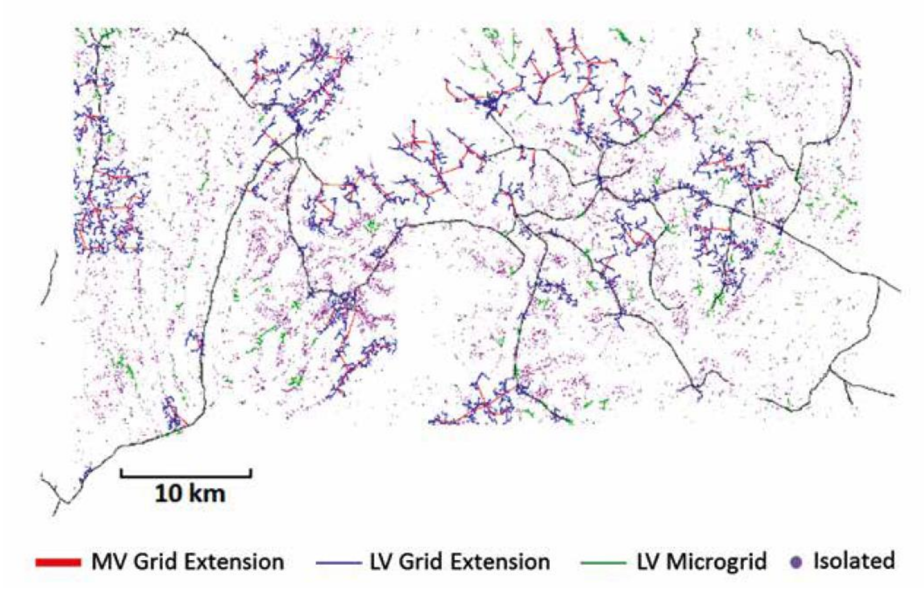

Figure 2-10: Example of REM outputs for a reference case study electrification solution. Source: Amatya, R et al. (2018)

The model provides a more simplistic output, giving at a 1 by 1 km resolution the least-cost option among the three delivery models. The model uses as inputs geographic information systems (GIS) data of population density, distance from existing and planned transmission infrastructure, proximity to road network, night-time light, as well as energy resource availability. Taking as a reference the Dodoma region in Tanzania, Figure 2-11 shows how increasing the target level of access drastically changes the feasibility of grid extension and mini-grids in comparison with individual systems.

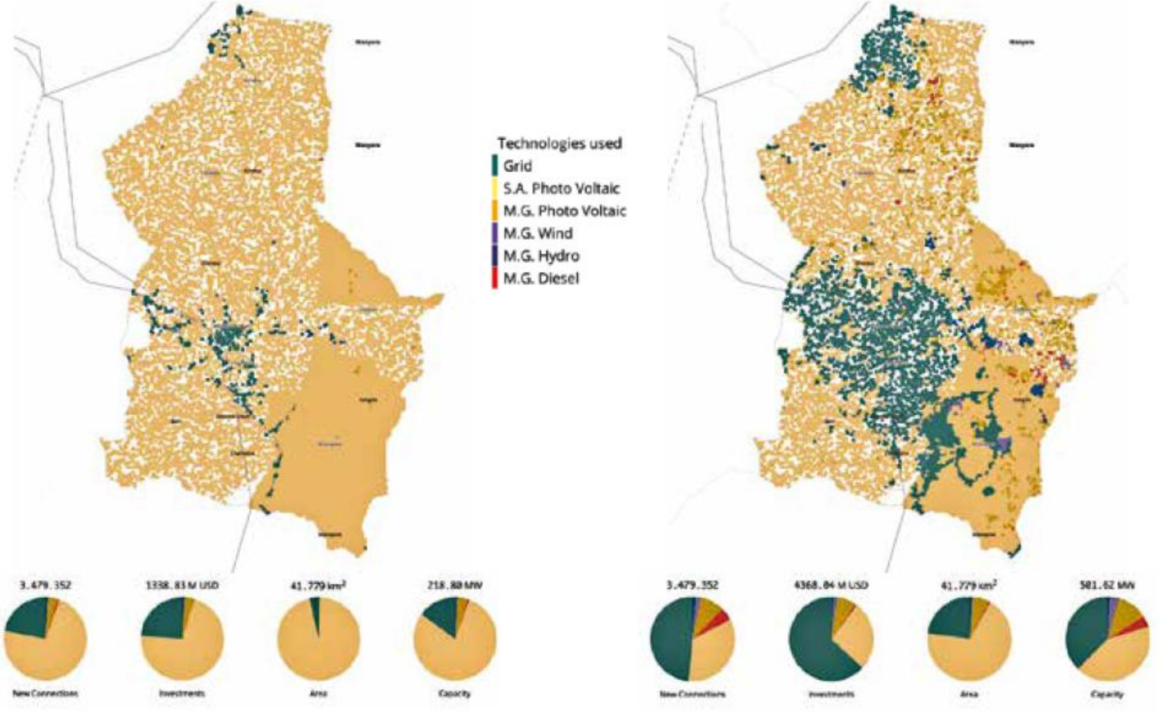

Figure 2-11: Comparative results of universal access pathways with Tier 3 and Tier 4 service for the Dodoma Region of Tanzania, with a diesel price of 0.82 USD/l. Source: World Bank, KTH

The usage of such tools can greatly help in the definition of national electrification plans as well as support developers in scoping market opportunities. However, the fact that the quality of the outputs is highly dependent on the accuracy of input data must be stressed. For instance, in the assessment of the current electrification network, their usage might be hindered by the fact that distribution companies in Sub-Saharan Africa hardly have structured and digitized information on their low-voltage distribution lines [48].

2.7. Literature review

The main objective of this section is to introduce an analytical overview of the main research themes, and relating scientific literature, on the issue of off-grid systems for rural electrification in DCs. This has been accomplished by carrying out a comprehensive literature review of the main international journals addressing this topic.

(i) Technology: layout and components:
Analysis and descriptions of systems' layout and components; development of new technologies and/or components; advancements in technologies and/or components

(ii) Models and methods for simulation and sizing:
Proposals and improvement of models and methods for systems simulation and sizing. The models and methods can imply the use of both commercial and non-commercial software tools

(iii) Techno-economic feasibility analyses:
Techno-economic feasibility analyses of systems and components; methods and studies about required data for this kind of feasibility studies (e.g. energy sources and energy demand assessments, costs assessments)

(iv) Case study analyses:
Analyses of the performance of existing plants (reliability, efficiency, lifetime, technical or management problems, etc.); non-technical case studies, such as studies about business models, financial performances, social impacts of the considered systems

(vi) Impact assessment tools
Screening of current impact evaluation methodologies and tools for project performance assessment and monitoring.

3. Demand Analysis

In order to successfully deploy decentralized energy systems in developing countries, it is necessary to standardize effective methodologies and procedures to develop off-grid/mini-grid systems. Considering that the energy need assessment provides inputs and assumptions used in business modelling and mini-grid design, the accuracy of its results directly affects the technical and financial feasibility studies.

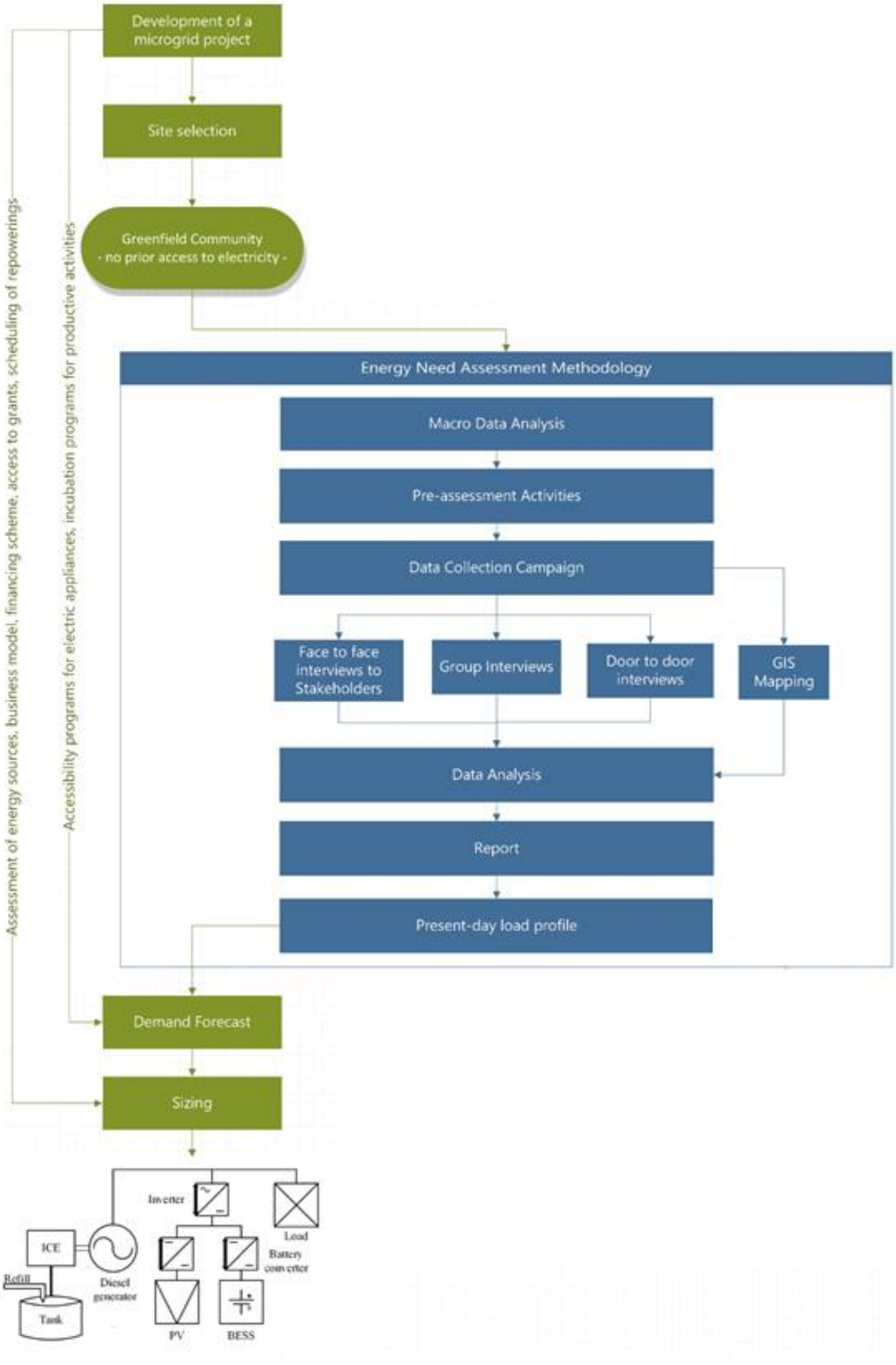

Figure 3-1: Development process flowchart for greenfield mini-grid projects. Own elaboration

Thus, the approach for applying a proven methodology for the energy need assessment of rural communities aims at obtaining reliable input data for the mini-grid development. This helps in reducing both the financial challenges by mitigating the uncertainties in electricity demand and the technical challenges by contributing to adequately size off-grid power generation systems, with a view to boost toward a common overall objective of mini-grid's optimization methods and tools.

Hence, taken in consideration that target communities differ in terms of needs and context conditions, this chapter describes an inclusive methodology that can be adapted case-by-case. It provides an effective applied solution the lack of proven guidelines from project developers or literature, giving priority to data collection methods able to achieve a large sample representative of the market, with high accuracy in estimating the energy consumptions from electricity substitutes.

3.1. Energy needs assessment – *Ref. Paper PA-1*

Accurately estimating incipient electrical load of rural consumers is fraught with challenges. Load estimation error is propagated through the design phase, potentially resulting in a system that is unduly expensive or fails to meet reliability targets [49]. Thus, the proposed methodology aims at increasing the accuracy by focusing on methods for data collection and data analysis, which are not stand-alone activities, but they should be applied as part of the assessment process.

The relevance of the accuracy of surveyed data is widely recognized in literature. In [50] the authors compared load profiles and performance metrics based on interviews and on measurements relating to a rural mini-grid in Tanzania, finding distinct differences between estimations and measured data. The largest difference was in the calculated energy, which is also reflected in the load factor and capacity factor, which are underestimated by 34–117% using the interview-based method, whereas the estimate of the peak load shows a much smaller error (11%). The large overall differences in the performance metrics could have major implications for the dimensioning and operation of mini-grids. Lastly, it must be reported that the authors claim that the performance metrics calculated from the interviews are similar to those reported by other scholars.

In [51], instead, it can be found a discussion on the techno-economic consequences of estimation errors on energy consumptions of seven small-scale off-grid PV systems in Malawi. The results show that PV array and battery sizing scale proportionately with load estimation error and that the cost of load over-estimation is approximately US$1.92 to US$6.02 per watthour, whereas under-estimation can precipitously degrade reliability. Thus, the economic gain of more accurate average daily load estimates has been shown, but a methodology for improving the estimates is lacking and greater discussion among the research and practitioner community regarding target reliability standards for off-grid systems is needed.

In [52] the problem of the inaccuracies of the primary input data for energy estimation is also addressed by comparing pre-installation predictions and actual measured consumptions for eight solar powered micro-grids in Kenya. The analysis shows that the ability to accurately estimate past consumption based on survey or audit data, even in a relatively short time-horizon is prone to appreciable error: the predicted total is more than four times the actual (426 Wh/day per customer vs 113 Wh/day). Thus, the study reveals that predictions were poor, with error arguably most influenced by duration of use estimations and the general survey approach; furthermore, the authors state that the general reliability and accuracy of surveys methods applied has not been demonstrated. It should be reported that the one applied differs from that described in the proposed methodology on a crucial aspect: the energy-use surveys were conducted by entrusting potential customers with prediction on typical duration of daily use of each appliance whereas the proposed method is based on current use of appliances and electricity substitutes estimated through an advanced data analysis and such results determinate both current and forecast load profiles by applying correction factors to willingness to acquire new appliances once they had electricity access.

The aforementioned studies focus on errors in load estimate as result of low accuracy in the calculation of average consumptions coming from surveys. They do so disregarding a number of factors that play an important role in the energy need assessment and, in addition to those mentioned before, it should be also take into consideration accounting for the probability of connection of new customers and demand growth of the old ones, considering if there are any programs to facilitate the purchase of appliances and the stimulation of productive activities [53]. This study aims just to highlight that there are many factors coming into play to explain the discrepancy between the estimated energy needs and actual consumptions as measured during the operational phase of the project and that, in any case, such discrepancy is relevant enough to justify the real need for implementing more effective assessment methodologies.

3.2. State of art

There are several references concerning how load curves are developed in greenfield projects to design mini-grids. Here follow a couple of valuable examples with a view to mention the process of load profiling applied by using survey to assess the energy needs as starting point.

Camblong et al. [54] have reported in 2009 the use of surveys to assess the energy needs of villages in three regions of Senegal to install micro-grids. The data collection campaign was conducted by three teams composed of a supervisor, two interviewers and a data collector. Their action comprised “village surveys”, made with people chosen by the head of village, “household surveys” and “technical surveys”. The team compared the results in terms of Willingness to Pay and Electricity Substitute Expenses and hypothesized different service levels for the households as well as consumption for public services such as lightning or water pumping. The resulting load profile for a sample village is reported in [55], along with a design proposal.

More recently, Sandwell et al. [56] published in 2016 a survey of energy demand and usage patterns in households in several unelectrified villages in Uttar Pradesh, India. By acquiring demographic data and daily activities patterns of the respondents they obtained firstly the current hourly demand profile of basic electricity demand (named "basic" demand) and secondly a forecast demand profile (named "aspirational" demand), by combining the basic loads with aspirational loads, formed of desirable devices, assuming their usage in line with census statistics and literature. Lastly, they used a Monte Carlo simulation to highlight the daily and seasonal variation and design a solar PV-genset (powered by diesel or biomass) hybrid system with battery storage to effectively satisfy the energy demand.

Another relevant matter in deriving the load profiles is the energy equivalence given by the different sources that are going to be substituted by the electricity supply. Such calculation is often disregarded or approximate whereas it is considered as crucial in the proposed methodologies and the data collection is structured to provide all the necessary data.

Even if non-electric lightning sources offer generally poor lighting levels, with low conversion efficiency with respect to the fuel used [57] they represent the main sources of energy in unelectrified communities and complementary sources in those electrified. In literature, there are studies that adopt this approach, such as a comparative analysis of the technology, economics and CO2 emissions between kerosene-based lamps and modern bio-energy systems and solar photovoltaics, which considered fuel consumption, power rating, luminous flux, efficacy and useful life of devices [58].

Another example is given by a paper on the energy profile of a South-African off-grid village where the sources of lighting were candles and paraffin lamps [59]. Overall energy consumption, expressed in megajoule, were obtained by differentiating the energy sources, but without considering explicitly which source could be substituted by electricity, so without estimating a possible electric energy load profile.

In the recent years, the Massachusetts Institute of Technology (MIT) launched an initiative, the D-Lab, devoted to develop and advance collaborative approaches and practical solutions to global poverty challenges [60]. In particular, D-Labs' Off-Grid Energy Group focuses on providing information and resources to design and implement programs that increase energy access for organizations based in off-grid regions [61], following a bottom-up approach, where local organizations active in a certain area or community drive the needs assessment, solution identification and project implementation [62]. Among its activities, D-Lab developed an Off-Grid Energy Roadmap, which first step consists in the assessment of energy needs and market opportunities [63]. At this scope a specialized set of tools was developed and published in 2017: the D-Lab Energy Assessment Toolkit (EAT) [64] This toolkit aims to gather and analyze data about current energy access and expenditures, aspirational energy needs, existing supply chain and community institutions and stakeholders (private sector, government, NGO) [62]. Thus, such documents were taken as reference since it deals with energy needs of off-grid regions in general (e.g. clean cookstoves) but it is not focused on mini-grids, representing the first difference with the proposed methodology. The second one stands in for whom it is intended: on one side EAT is designed for local organizations seeking to increase energy access in their own communities and to make informed decisions about how to meet the specific needs in their community through market based initiatives, on the other side the proposed methodology aims to address the requirements of the mini-grid developers and meet constraints of the business-oriented projects. In fact, D-Lab specifies that their community-based assessment approach is not intended to replace studies that track energy access on a national level, or to generate market intelligence reports for external organizations looking to expand their business or programs into new markets. However, there are several similitudes between the two methodologies that come into the light also thanks to the support document on user research framework [65]. Firstly, promoting an approach to illuminate needs of stakeholders as a pillar of the data collection activities. Secondly, the importance of triangulation given by the use of three data collection tools (even if the focus group is replaced by group-interview in the proposed methodology): combining several methods can result in convergence (which adds credibility to qualitative research and the results obtained) or divergence (which signals unrecognized or unarticulated needs). Lastly, the emphasis on flexibility of tools to best suit the specific scope of the assessment and the given context: even if both methodologies provide validated implementation tools, they are only intended to be a guide as it is assumed that the evaluation team is able to make decisions about the scale and scope of the assessment and modify the questions accordingly.

The bottom-up approach promoted by the proposed study, according to guidelines by MIT D-Lab, was already pursued by a research team that published the results of a detailed field study of rural energy consumption patterns dating back to 1976-1980, related to six villages in India having already access to electricity [66]. It contains several methodological indications arising from the experience of the researchers, such as the importance of (i) establishing a relationship with the villagers, (ii) carrying out preliminary field activities and tests before conducting the data collection campaign, (iii) cross-checking in-built consistency between data from different sources and (iv) training of field investigators as added value to improve the reliability of the data collection’s results.

The application of proxy techniques to obtain some crucial indicators of energy need assessment, as foreseen in the proposed methodology, is supported, among others, by a study on residential energy use and costs in 2013 in Kenya, with particular regard to the willingness to pay for a given service [67]. The survey did not in fact directly ask what the respondent would be willing to pay for recharge portable battery kits service, whose answers are considered as uniformed, unrealistic and inconsistent in areas without previous access to the proposed service, rather it was deduced from current expense levels and feedback from the focus groups. Furthermore, the study also highlights the use of surveys as tools to provide useful information for the sustainable design and operation of energy development project.

3.3. Proposed Methodology

In order to address the requirements of mini-grid developers, the proposed methodology is specifically focused on the energy need assessment for rural electrification projects. This specification is fundamental to point out how and why this methodology differs from others which deal with the energy needs in general. In fact, taking as reference the Energy Assessment Toolkit developed by MIT D-Lab[8], the main differences consist of the assessment's focus on mini-grid and in for whom it is intended. That means that the methodology gives priority to (i) data collection methods able to achieve a large sample representative of the market and (ii) high accuracy in estimating the energy consumptions from electricity substitutes, which are crucial to provide reliable data for load profiling.

The proposed energy need assessment uses different methods and tools in order to apply a data collection methodology based on multi-source strategy, including both qualitative and quantitative approach. Different tools are used for measuring the indicators identified whereas data coming from different sources are compared and processed by using a weighed analysis.

In order to summarize the main activities, the energy need assessment is composed of, the methodology can be divided into three macro-phases:

1. first phase: macro-data analysis and pre-assessment activities;
2. second phase: data collection campaign;
3. third phase: data analysis and reporting.

The first phase is focused on the review of conventional indicators and literature. The aim of this phase is to analyze and describe the context of intervention, utilizing and comparing data already collected by other related projects, relevant macro statistics and background data.

In the second phase, a field investigation is carried out in the villages of intervention and surrounding areas. The overall objective is to provide a description of the population living in the targeted villages with a view to assessing the electricity demand and the ability to pay of users (potential or existing) by customer groups. A set of additional information is gathered to best suit the specific objective of the assessment formulated on a case-by-case basis. The field investigation was conducted by applying a multi-source data collection strategy in order to provide highly reliable results. Furthermore, particular attention was paid to opinions and suggestions from population and local authorities in order to promote a bottom-up approach and lay the groundwork for a participatory project development.

In the third phase, data analysis of the inputs collected during the first and the second phase is conducted, and a detailed report is instructed to show an evaluation and validation of the results, including the main findings, the correlations among the main variables and recommendations for the program interventions.

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[8] https://d-lab.mit.edu/research/energy/energy-needs-assessment-toolkit

3.4. Data collection campaign

The objective of this second phase of the assessment is to properly collect data from direct sources in order to provide a description of the population living in the targeted villages with a view to assess the electricity demand and the ability to pay by customer groups in terms of existing and potential demand.

Thus, the energy consumption modelling coming from the proposed assessment methodology is based on a bottom-up approach, which is used to model consumptions of each end-use and hence to identify areas for efficiency improvements at user level and is based on statistical or engineering models [68]. Current and forecast data are fundamental for the mini-grid development, as highlighted in literature, since power system engineering refers to load forecasting as the domain of models able to provide data for setting the best planning and operating of grids [69].

Furthermore, the methodology emphasizes the importance to carry out the data collection activity with a focus on not only statistical results but also gathering opinions and suggestions from population, local authorities and stakeholders in order to promote a bottom-up approach and lay the groundwork for a participatory project development.

In fact, community engagement strategies can draw together various elements that can maximize sustainability and transformative potential of mini grids, even if it requires time and budget allocated, that have been to date underrepresented in the literature on mini grid deployment models [70]. Much of the literature focuses on a top-down approach rather than bottom-up approach and practitioners should consider a shift in rhetoric and conceptual approach to community engagement by recognizing its added value for the project impact [70].

Thus, pursuing the assessment of the entire community, particularly in terms of energy needs and potential increasing demand, the proposed data collection campaign is structured to provide disaggregated results on stakeholder consultation, household survey and business activities survey. For avoidance of doubt, please note that these survey types differ from the three data collection methods explained below.

In order to explain how this phase is developed, here follow key features of data collection methodology that required to be defined before proceeding: target areas of intervention: the ground is divided into sub-areas to apply the defined sampling strategy; cluster sampling: target market is classified into customer groups, such as households, small businesses and anchor loads (however, if any context's peculiarities, the classification may be revised, and questionnaires updated accordingly); data collection methods: multi-source data collection strategy represents an essential aspect of the proposed methodology; three methods should be applied in order to achieve high accuracy of results: (1) face-to-face interviews with stakeholders, (2) group interviews and (3) door-to-door interviews; each method is described in detail in the following paragraphs; GPS mapping: to mainly record main potential customers, village boundaries and distance from the national grid.

Depending on the data collection method, different sampling procedures should be applied.

3.4.1. Data collection method 1: face-to-face interviews with stakeholders

The first method to be applied is the face-to-face interview, which is a qualitative data collection method. It is applied at least to the following stakeholders: local authorities, technical officers at village and district level, representatives of local associations, representatives of financial institutions, owners or managers of the main business activities. Special focus is on anchor users and productive users of electricity.

Interviews with key stakeholders should be conducted in order to detect the general perspective of the market from their point of view, the community background, needs and potential constraints (e.g. access to credit constraints) as well as aggregate data on current energy sources used, relative expenditure and price of key products available in the local market (e.g. fuel). The interview also aims at identifying the main business activities, anchor loads, current or potential productive use of electricity as well as public institutions and existing infrastructures requiring reliable electricity supply.

A set of guiding questionnaire is prepared for interviews that should also take into consideration all inquiries based around the main questions, depending on the specific case study, as well as additional probing questions added as needed.

Sampling strategy: qualitative interviews should be conducted with at least one representative for political sector, local associations, whereas the target is to reach 100% of main business activities, productive users of electricity and financial institutions.

3.4.2. Data collection method 2: group interviews with population

The second method applied during the data collection campaign is the group interviews, which is a hybrid quantitative and qualitative data collection method. It is targeted at household's level to collect mainly quantitative data through a survey by using closed-ended questions but also qualitative data through a short discussion stimulated by open questions at the end of the session to let personal opinions and concerns come to light. The strength of this method is that it is efficient and time saving: it allows collection of a large sample of data at once, from up to 25 participants per group. It is also a good tool for the community engagement, even if it requires to be properly carried out by an expert evaluation team.

Sampling strategy: a random sampling procedure is used in each site of intervention with the support of the chairperson to collect the people. The only selection criteria is that under 18 are not admitted. Three group interviews per site should be conducted in order to reach the target number calculated by applying Equation 1 reported below.

3.4.3. Data collection method 3: door-to-door interviews with small business activities and households

The third method applied during the data collection campaign is the door-to-door interview, which is a quantitative data collection method. It is targeted at households and small business activities, recorded separately, through a short-structured survey questionnaire.

The strength of this method is to allow the evaluator to visit each building sampled, implying high reliability of the data source on energy issues and collection of GPS coordinates with a view to allow the project developer to lay the groundwork for a remote monitoring & evaluation framework over the project life.

Sampling strategy: the sampling procedure applied in each site of intervention consists of two stages: in the first one, a section of the target area depending on the sub-villages or the organization of the targeted village according to local authorities; in the second one, a simple random sampling from each section. It must be specified that households and small business activities are recorded separately. Sample households size for method 3 are based on Equation 1 - T. Yamane, Statistics: An Introductory Analysis, 3rd Editio. Harper and Row, New York, 1973Equation 1 [71]:

$$n = \frac{p(1-p)\times N}{p(1-p)+\left[\left(\frac{d}{z}\right)^2\left(N-1\right)\right]}$$

Equation 1 - T. Yamane, Statistics: An Introductory Analysis, 3rd Editio. Harper and Row, New York, 1973

Where p = 0.5 (for maximum variability in normally distributed attributes)
N = population (i.e., number of households in this case)
d = level of precision (10%)
Z = Z – value (1.96 for Confidence interval of 95%)

Considering that number of existing business activities is not usually available in advance, it should be estimated to plan the field mission on the basis of previous experience in the area or census statistics, if any, or alternatively literature reference. For instance, based on their extensive experience in rural areas of East Africa, a ratio between small business activities and total households of 6-8% has been considered. With the aim of visiting all of them, the evaluation team should target to reach at least 80% of the total estimated number.

3.4.4. GIS mapping

A GPS mapping of the main potential customers and village boundaries is carried out by using a GIS software, guaranteeing the quality of the geolocation with a high degree of confidence. Particular attention must be paid to the distance from the national grid and between villages. Among the geo-localized items, the following should be ensured within the area of intervention: infrastructures, social institutions, existent anchor loads and main business activities. Additionally, GPS coordinates of sample households and business activities as explained above in the door-to-door method should be collected.

3.5. Data analysis and outputs

The data analysis of the inputs collected during the second phase of the energy need assessment should be conducted in order to compare and process input data coming from different sources by using a weighed analysis. The analysis should consider appropriate sampling weights for the estimated parameters to reflect the probability of sampling households and businesses from different sources as well as adjustments for non-response. Cross-checking should be carried out in order to find out discordances between data.

The different data sources are at first managed separately to observe disaggregate data. At the same time, since the market is divided into customer groups during the data collection campaign, data analysis is carried out using different data categories.

The process mainly consists of five phases:

I. Data entry and processing: to get raw data organized into different data sources and different customer categories;
II. Analysis of raw data: raw data are studied question by question;
III. Cross-checking: results of disaggregated data analysis are compared;
IV. Aggregation: data from different sources, already processed in previous phase, are aggregated to obtain final results;
V. Modelling and algorithms: final results represent variables to calculate all the indicators reported in this assessment by applying algorithms.

The assessment provides the following overall outputs:

- GPS mapping of the target area, showing its borders, distances from the national grid, positions of the productive or commercial activities and sampled households: this output resumes key data for the distribution grid design and evaluation of the best cost-effective technical solution.
- Summary and preliminary assessment of the different institutions, organizations, business leaders, or leading members of the community who may help organize the finance, maintenance, and operation of the mini-grid: this output is relevant to design ancillary activities to support the socio-economic environment of a rural electrification project.
- Assessment of current and potential anchor loads: these customer group are crucial to ensure the project sustainability and their energy needs significantly affect the load profiling and, consequently, the mini-grid sizing.
- Average consumptions & expenditures for electricity substitutes per each customer group: it represents the key set of indicators to obtain a reliable load profiling.
- Willingness and ability to pay for electricity supply per each customer group: these indicators are particularly relevant to set electricity tariff plan.
- Load profiling of current and forecast electricity demand: this is considered one of the most important output of the energy need assessment and its reliability is based on accuracy of results given by data collection and data analysis, representing the core phases of the energy need assessment.
- Suggestions and recommendations for the project developers on (i) business model design, (ii) engineering design of energy management systems and (iii) formulation of supporting activities for socio-economic development.

3.6. Methodology validation: case study in Rwanda

The presented methodology for energy need assessment has been tested and improved time after time since 2012. So far, it has been applied in 13 data collection campaigns for a total of 57 villages assessed in Central America and East Africa. More than a mini-grid has been already realized based on its results. The presented case study, held in May and June 2018, was carried out with the purpose of validating the methodology. The evidence of its reliability is given by comparing a key output of the energy need assessment with the actual value adopted in the mini-grid implementation: the willing to pay of potential customers. It is a very sensitive and representative indicator since it directly affects the project sustainability and it comes from other outputs such as the average consumptions & expenditures and the assessment of current and potential anchor loads. With reference to the Village C (Table 3-3), the assessment returns a flat tariff of 2,940 RWF/month to reach the higher penetration rate of potential market. The actual flat tariff negotiated between the mini-grid developer, local communities and authorities was about the same: 3,000 RWF/month.

A comprehensive market assessment has been conducted in three villages in a rural area of the Eastern Province of Rwanda, where three mini-grids are planned to be developed. The specific purpose of the market study was to assess the electricity demand and the ability to pay by households, businesses, social institutions and anchor customers.

Potential customers living in the target areas were categorized into four customer groups and other minor sub-groups: households (domestic use of electricity), small business activities (commercial and artisan use of electricity with appliances requiring power up to 5 kW), public services (use of electricity for public benefit) and anchor loads (productive use of electricity or other businesses with appliances requiring power over 5 kW and at least a consumption of 2 kWh/day) considered as stakeholders in the Table 2Table

Demographic data			**Survey main figures**		
Eastern Province of Rwanda	Total Population	Total Households (HHs)	**Survey Method 1** Stakeholder consultation	**Survey Method 2** Group interviews	**Survey Method 3** Door-to-door interviews
Village A	3,850	950	12	101	101 HHs + 35 Small Bus
Village B	4,456	991	29	90	107 HHs + 46 Small Bus
Village C	3,804	877	19	104	97 HHs + 38 Small Bus
Total	**12,110**	**2,818**	**60**	**295**	**305 HHs + 119 Small Bus**

Table 3-1: Main survey figures of the data collection. Own elaboration

Errore. L'origine riferimento non è stata trovata.3-2 summarizes instead the main survey f igures considering gender balance and the sampling size.

Data Collection Campaign	**Total**	**Method 1**	**Method 2**	**Method 3**
Villages A-B-C	Sampled data*	Stakeholder consultation	Group interviews	Door-to-door interviews
Male	369	35	199	170
Female	77	10	96	135
Households surveyed	**600**	**45**	**295**	**305**
% of total HHs	21%	n.a.	10%	11%
Male	89	n.a.	n.a.	89
Female	30	n.a.	n.a.	30
Small businesses surveyed	**119**	n.a.	n.a.	**119**
% of total Small bus	69%	n.a.	n.a.	69%
Male	15	15	n.a.	n.a.
Female	0	0	n.a.	n.a.
Anchor businesses surveyed	**15**	**15**	n.a.	n.a.
% of total Anchor bus	100%	100%	n.a.	n.a.
*Stakeholders are not included in the sampling size calculation.				

Table 3-2: Main survey figures considering gender balance and the sampling size. Source: own elaboration

The assessment is described by using disaggregated results for every surveyed village in order to highlight differences among potential markets for each mini-grid. The study analyzed all the direct or indirect aspects related to the energy needs from greenfield projects up to operating mini-grids.

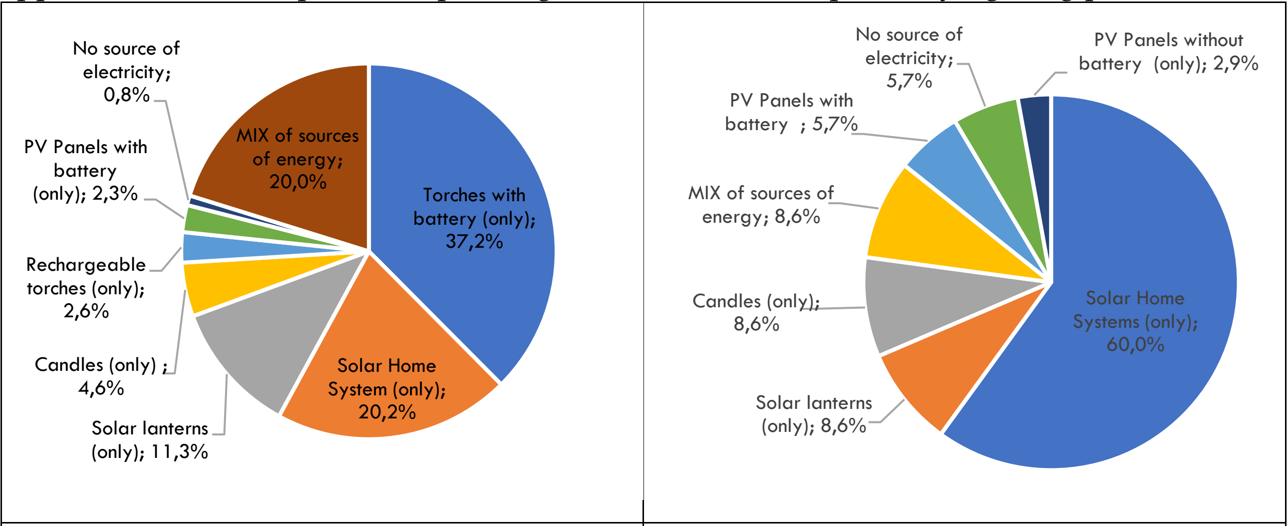
3.7. Results on energy concerns

In order to provide the detailed results given by the most important indicators about energy concerns, the following description and figures are only **related to the village A**, located in the Eastern Province of Rwanda.

First of all, considering that rural electrification projects might only address the needs for lighting and electrical devices, the energy consumptions for cooking are analyzed separately from other sources of energy mentioned below: Almost all the people living in the targeted villages use firewood corresponding to 9,102 Wh/day and related average monthly expenditure of 11,035 RWF per household.

The current sources of energy for lighting and appliances used in the community, including sources of electricity and electricity substitutes, are given in Figure 3-2. Data analysis results show the exclusive use of a source and the mixed use of different sources. That is important firstly for the estimation accuracy of the average consumptions and expenditures in energy per customer group and secondly to identify potential customers within a given customer group, which might be supported by specific project activities, especially among small businesses.

Electrical appliances usage and their dissemination in the communities represents an indicator for household wealth. Regarding the energy need assessment, analysis of current electrical devices is crucial to estimate the energy load profile of the community and to provide reliable input data for the mini-grid design, especially considering that the appliances absorbed power is quite higher than the one required by lighting products.



(a) **(b)**

Figure 3-2: Sources of energy current used per cluster of customers. (a) Sources of energy currently used by households, b) Sources of energy currently used by small businesses. Source: own elaboration

Current energy consumptions and expenditures for lighting and electrical devices per customer represent two crucial indicators of the energy need assessment, which are calculated separately per each customer group to favour undertaking of specific actions .

VILLAGE A			
Customer group	Average Daily Consumptions from electricity substitutes per customer (Wh)	Average Monthly Expenditures for electricity substitutes per customer (RWF)	Average cost of electricity unit (RWF/kWh)*
Households	156	3,856	824
Small Businesses			
Retail shop	550	5,988	436
Bar	1,111	8,869	319
Barber shop	2,799	13,601	194
Tailoring	0	0	0
Bicycle mechanic	350	4,908	561
Anchor loads			
Mills	7,245	78,800	435
*** Assuming 30 days per month for HHs and 25 days per month for businesses**			

Table 3-3 Average consumptions and expenditures for electricity substitutes per customer

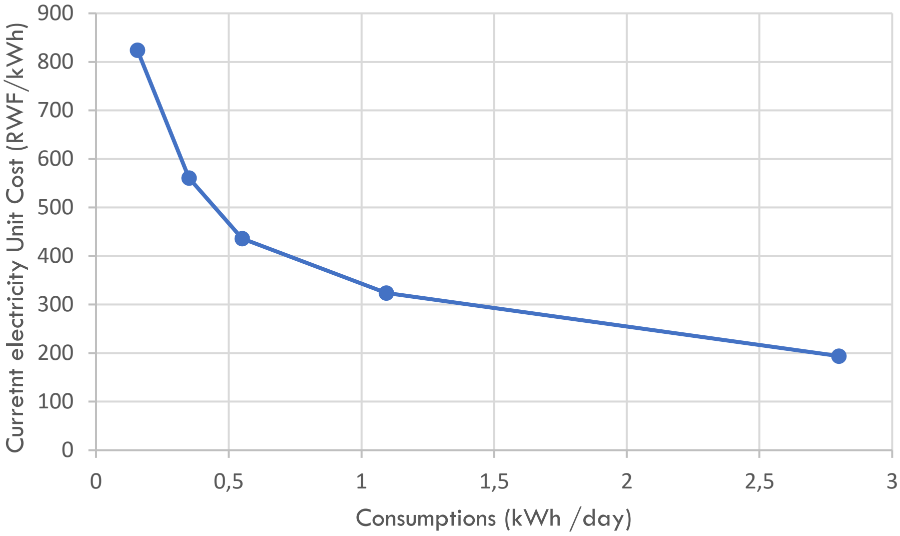


Figure 3-3: Correlation between Current Electricity Unit Cost and Consumptions

The first part of the energy need assessment focuses on the current demand for electricity so the substitution potential for the mini-grid, whereas another relevant part concerns the potential unexpressed demand for electricity that would arise in case a mini grid was available.

Demographic growth together with increase of business activities represent two indicators of the potential increase of energy demand. In fact, according to the Fourth Population and Housing Census of Rwanda, performed in 2012 (RPHC4) [72], projections of rural population claim an increase of the size of rural population by 23.2% to 35% between 2012 and 2032. On the other side, the survey results reveal that 54% of small business started up less than one year ago. Considering this general foreword, the **assessment of potential energy demand** is mainly based on (i) the willingness of acquiring electrical devices in the future, divided into customer groups, and (ii) potential business opportunities.

A preliminary identification of potential opportunities was conducted: the general perception is that there are no relevant opportunities for strong anchor loads, however, there is a clear business attitude and intention to start new small business activities.

Among potential business opportunities raised as result of direct questions to people interviewed, the most promising businesses result to be selling refrigerating products and bakery. Furthermore, even if 5 entrepreneurs are willing to activate new milling service, the milling market seems to be saturated with 6 mills already existing for 950 households. They currently operate for a couple of hours per day and it would be preferable to optimize such activities instead of opening new ones.

With reference to the forecast of how many new devices will be acquired for business purposes it must be specified that results only represent a preliminary estimation of the number and type of potential businesses, since an in-depth analysis, which includes real financial capability and business sustainability, should be conducted case-by-case to both optimize the plant sizing and eventually select business activities to be supported by the project. In other words, it is assumed that, in rural contexts, the more vibrant is the current economy the more extensive is the room for improvement in the upcoming future, whereas a lower economic development would require a stronger action on improvement of socio-economic environment, including capacity building and access to finance, among others.

Due to the lack in quantity and quality of measured data in greenfield projects , surveys are necessary to assess the **Willingness To Pay** (WTP), considering that previous studies have warned against the tendency of rural households to overstate their WTP, as mentioned in [73].

In order to clarify the meaning given in this research, WTP is the maximum price at or below which a consumer will definitely buy or consume one unit of a good or services [74], which is represented by the electricity tariff in this case. There are different methods to evaluate the WTP. Considering the most common ones, WTP can be obtained either by asking directly how much an individual is willing to pay for a service, resulting in an 'expressed' WTP, or by calculating the current energy expenditures, resulting in a 'revealed' WTP [75].

In rural context, as users move from basic lighting to paying for additional services, the slope of WTP reduces as income poverty appears to come into play. In fact, beyond the basic level of services, WTP become a factor of income elasticity meaning, in other words, affordability [76]. This specific aspect can be quantified by considering the Ability To Pay (ATP), which is a parameter only dependent on the income level of the interviewee, and it's directly related to the affordability of the tariff for the users [77]. WTP and ATP of rural household consumers are closely related since a higher (or lower) rate of willingness to pay is strongly affected by the share of disposable income assigned to electricity as a service in the overall household income [77]. That is why it should be taken into account what is the percentage of household budget devoted to energy consumption versus other development priorities, such as education or water.

As explained in the previous paragraphs, the potential marked was divided into three main customer groups in order to better analyze, among other, the revealed WTP of each group, which results to be fundamental to set the electricity tariff plan. Values in terms of RWF/kWh are reported in the Table3-3.

3.8. Load profiling

The energy load profiling considered the current energy demand and a detailed load profiling on possible sub-scenarios was carried out considering tentative electricity tariff plans.

To profile the load curves, a market penetration was assumed depending on the willingness to pay as well as to change from SHS or PV panels with battery to reliable 24/7 energy supply. However, it must be specified that the penetration rate should be adjusted taking into consideration financial variables in predicting economic activity of the mini-grid (e.g.

multi-phase construction, grid layout and related access to, taxes and inflation rate, etc.), which are typical of the business planning and not part of this study.

The energy demand was calculated by using the Equation 3-2 in which two correction factors have been considered: the SHS Correction Factor (C1) and the Commercial Demand Factor (C2), taking as a reference the guidelines issued by GIZ [78]:

$$Et = Eh \times C1h \times C2h + Eb \times C1b \times C2b + Ea \times C1a \times C2a$$

Equation 3-2 : Energy demand formula. Source: GIZ

Where:
Et = Total Daily Energy Consumptions for Electricity Substitutes at a given Flat Tariff Threshold
Eh, b, a = Total Daily Energy Consumptions for Electricity Substitutes of Households (h), Small Businesses (b) and Anchor Loads (a)
C1h, b, a = SHS Correction Factor for Households (h), Small Businesses (b) and Anchor Loads (a)
C2 h, b, a= Commercial Demand Factor for Households (h), Small Businesses (b) and Anchor Loads (a)

Firstly, it was taken into account the number of people using SHS that do not consider to improve their quality of life through a reliable electricity supply and their related current energy consumptions. Thus, the SHS Correction Factor (C1) in the Equation 3-2 reflects such component of SHS users and decreases the total estimated daily consumptions. In this case, C1 for households is 98.5%, C1 for small businesses is 98.0% and C1 for anchor loads is 100%.

Secondly, the commercial demand was worked out by classifying different consumer categories, as defined in the rest of the study: three thresholds were identified among the estimated monthly expenditures and how many users were able to pay at least such values, representing the percentage of potential market intending to apply for connection at a given electricity tariff. Thresholds are given in the table below in terms of monthly flat tariff, whereas percentages represent the Commercial Demand Factor (C2) in the Equation 3-2.

Market penetration considering the Willingness To Pay: Commercial Demand Factor (C2)

	Flat Tariff Thresholds (RWF/month)		
Customer groups	10,035	7,000	2,940
Households	24%	24%	38%
Small businesses	39%	66%	73%
Anchor loads	100%	100%	100%

Table 3-4: Market penetration considering the WTP

The table above shows that the poorest part of the population, given by the first quartile of data analysis on the average monthly income, have a low current energy consumption as well and therefore willingness to pay. In other words, it is unlikely that they will apply for electricity connection.

Lastly, the study also focused on getting to know what are the current electrical devices in use and for how long they are used, in order to model load evolution, based on possible additional devices that customers may plan or wish to have. Thus, the demand assessment focused on the time of use of electrical appliances, the distribution of the energy demand throughout the day, the peak power demand and the number of customers in each category.

The Table summarizes variations of energy consumptions depending on the flat tariff applied.

Village A	1-Flat tariff 2,940 RWF/month		2-Flat tariff 7,000 RWF/month		3-Flat tariff 10,035 RWF/month	
Type of customer	Consumptions [Wh/day]	Percentage of total energy [%]	Consumptions [Wh/day]	Percentage of total energy [%]	Consumptions [Wh/day]	Percentage of total energy [%]
Households	48405	34%	30403	26%	30403	30%
Small business	49783	35%	44862	38%	26510	26%
Anchor loads (mills)	43469	31%	43469	37%	43469	43%
Total	**141657**	**100%**	**118734**	**100%**	**100382**	**100%**

Table 3-5: Current energy demand by type of consumer. Source: own elaboration

In conclusion, taking into account the market penetration, the recommended flat tariff should be set below 2,940 RWF/month. The daily load profiles of the community with this flat tariff applied shows that domestic loads reach their peak during the evening, between 7 p.m. and 11 p.m., while business activities reach their peak between 5 p.m. and 6 p.m. that is when the mills operate. During the rest of the day business activities' total consumption is lower than households since the present businesses are mainly small commercial or artisan activities and do not represent a productive anchor load.

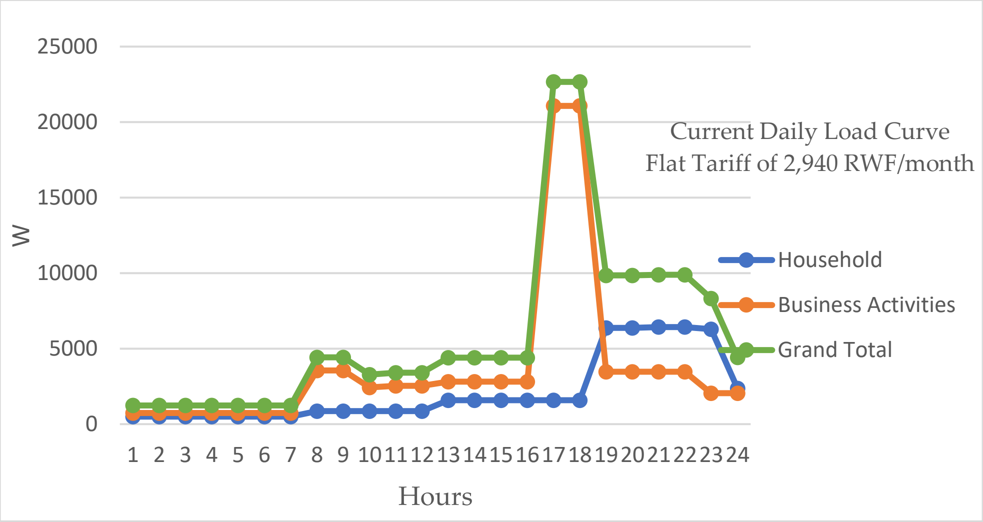


Figure 3-4: Current daily load curves. Source: own elaboration

The estimation of current average consumptions and expenditures for electricity substitutes represent two key indicators of the energy need assessment since consumptions are the basis for profiling the energy load curves and expenditures are crucial for evaluating the willingness to pay and, consequently, the electricity tariff plan as well as the level of service quality.

With respect to literature references, [79] mainly reporting on linear regression method and inverse matrix calculation which needed a comparative case study, the novelty here is based on the analytical calculation of the current average energy consumptions of a typical user per each customer group. This approach considers each source used differentiating the exclusive use of a source and the mixed use of different sources.

4. Technology integration

Small-scale generation systems based on renewable energy sources are increasingly gaining importance within power supply services of both developing and developed countries. Indeed, in DCs they can play a pivotal role in the electrification process of rural areas, while in developed ones they are gradually integrating within the main centralized grid in order to reduce the dependence (and its consequences) on fossil fuels.
In addition to the major positive features that stimulated such growing interest, it is worthwhile to mention also the main issues to be addressed when implementing this option. Specifically, these issues stem from the features of renewable energy sources:

(i) they are intermittent and seasonal and
(ii) short/medium term forecasts are quite difficult due to their high unpredictability.

When dealing with rural electrification based on off-grid power systems and mostly with hybrid mini-grids, the decision process as regards systems components sizes is not straightforward:

- it means matching a number of renewable sources with an uncertain load demand while providing the most favourable conditions in terms of reliability and cost;
- it often includes a storage systems which has to be sized according to provide proper system reliability, low costs, long life-time, etc. ;
- when a traditional system is employed (i.e. diesel generator set), despite reliability is more easily addressed, further economic (i.e. high O&M costs) and environmental (i.e. emissions) constraints may arise;
- multiple power systems, storage systems, load and energy sources uncertainty require complex control logics and advanced power electronics.

Within the process of system design all these issues cannot be tackled at the same step of the analysis. Nevertheless, in both cases, the identification of the main components sizes is preparatory to complete a proper design, implementation and operation of a system within a specific scenario.

Indeed, focusing on the scenario of developing countries, once developed the Energy Need Assessment and Load Profiling, the following step deals with carrying out the identification of the proper mix of energy sources and of the system components sizes.

4.1. Mini grid architecture

Coupling an energy system perspective with a local context perspective, mini-grids have been considered as systems: (i) composed by autonomous units where conversion and distribution have no interaction with other units, (ii) often based on local energy sources (i.e. renewables), (iii) sized for specific local energy needs of several consumers, and (iv) embracing a distribution system.

Moreover, hybrid mini-grids have been considered as systems: (i) composed by several conversion units, (ii) based on several different energy sources, (iii) often embracing energy storage systems, and (iv) supplying electricity to several consumers.

Figure 4-1: Smart village layout. Source: Res4Africa Foundation

Nevertheless, considering an electric perspective the following general features can be also associated to mini-grids:

- they are an aggregation of power generation systems which are locally controlled;
- they operate with a local low (≤ 1kV) or medium voltage distribution network;
- the EMS defines the set-point of active and reactive power for the different power sources in order to match the load profile, properly set the dispatch strategy, and to perform voltage regulation. In this case the EMS has to evaluate/estimate the available power and accordingly could connect or disconnect the loads.

In this case, the reference signal of the frequency must be provided by one power source among those available within the mini-grids. This generator works in *grid-forming* mode, while all the other work in *grid-following* (i.e. they inject power at the frequency they "read" on the grid);
Focusing on applications in DCs, according to the users connections, the type of loads, and the way the mini-grids are operated, three main system layouts can be identified: (i) systems with functioning in series, (ii) systems with functioning in parallel, (iii) systems with commutator functioning.
Figure 4-2 shows the typical configuration of systems functioning in series. This configuration requires that all generators, including all the rotating machines (i.e. traditional generators, hydro-turbines, etc.), are connected in parallel via a DC bus which is further connected also to the storage system. This approach allows simple management logics, but integrating several power sources (mainly in case of multiple rotating machines) brings about complexity as regards power electronics interfaces and the DC bus.

Indeed, the AC network is generated by means of a *grid-forming* inverter while rectifiers are needed to interface the power sources with the DC bus. This requires a data bus to integrate the rectifiers and define the active and reactive power set points of each power sources in order to control the DC voltage. This also results in difficulties in connecting *ex-post* further sources, thus limiting the Micro-Grid expansion.

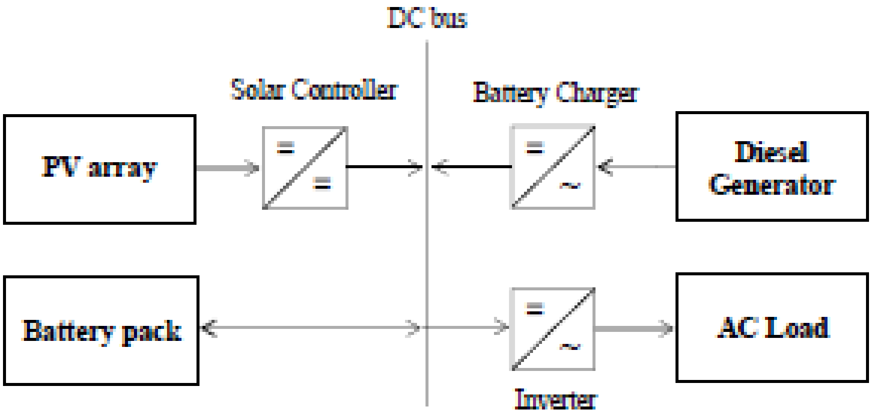


Figure 4-2 Hybrid Micro-Grid with functioning in series

In order to increase the reliability and the efficiency of the previous configuration, the commutator functioning can be employed (Figure 4-3). In this case all generators are still connected in parallel through a DC bus. Nevertheless a rotating machine (typically a traditional generator) can also directly supply power to the AC loads by the change-over switch. This allows supplying power to the load even in case of inverter failure with higher conversion efficiency. However, complexity in integrating several power sources and expanding the mini-grid remain.

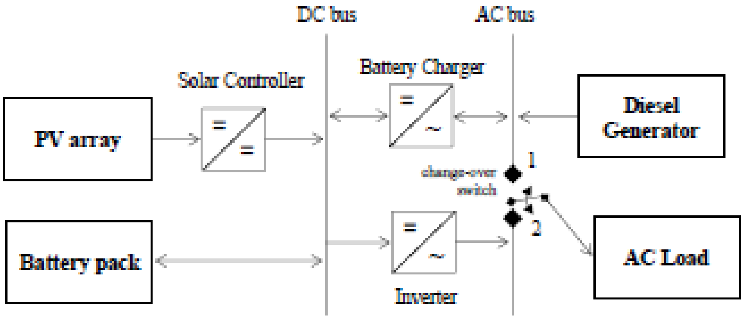


Figure 4-3 Hybrid Micro-Grid with commutator functioning. Source [1]

A different approach is employed for the functioning in parallel (Figure 4-4). This configuration provides that the generators can be connected in parallel via the DC bus (which is also connected to the accumulation system) or by means of the AC bus. Typically the rotating machines (i.e. traditional generators, hydro turbines, etc.) are connected to the AC bus, while PV, wind turbine, and storage are connected to the DC bus. The AC grid can be generated by means of a rotating machine connected to the AC bus, thus leading the other power sources and the bi-directional inverter to work in *grid-following* mode. Besides, the bi-directional inverter can also be operated in *grid-forming* mode if failures or unavailability of energy resources occur for the rotating machines.
In this case, the frequency on the AC bus works as reference signal to set the power injections of the bi-directional inverter. Moreover, on the AC side, if several generators are available they can be managed according to the typical control approaches of meshed grids. This allows avoiding the data bus and results in easier integration of further power sources thus expanding the Micro-Grid. On the contrary, more adequate management logics (e.g. to share the power among several different power sources, to control frequency and voltage) are required as well as more sophisticated inverters.

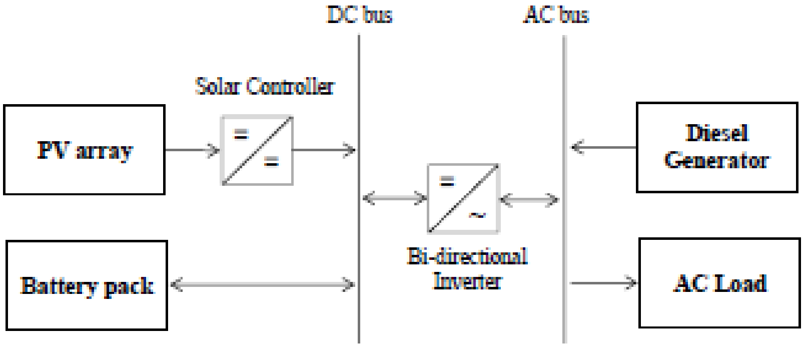


Figure 4-4: Hybrid Micro-Grid with functioning in parallel

In addition, new implementations of PV array and electrochemical batteries can be connected to a DC bus and then to the AC one thanks to a bi-directional inverter. Finally, this configuration can easily allow integrating further power sources on the AC grid, i.e. a petrol generator is already available at the school and clearly the required energy is expected to grow in the future.

The proposed architecture of the hybrid mini-grids provides for the parallel functioning of (i) the turbine/synchronous generator/dump load group and (ii) the PV/battery pack combination. This solution can limit the dissipated energy; nevertheless, it creates issues as regards the control of the system as well as the life-time performances of the battery pack. Indeed the battery pack can be operated in order to absorb part of the power on the dump load thus minimizing the dissipated energy and increasing the system efficiency. On the other hand this may increase the charge/discharge cycles of the battery pack (probably with shallower but more frequent cycles) thus decreasing its lifetime. Therefore it is necessary to analyse the functioning conditions of the battery pack, as regards the energy flows, in order to optimize the system control logics aiming at the longest life-time.

Nonetheless, the control logics that coordinate the operations between the battery pack and the dump loads can compromise the system real time control. Indeed dealing with the energy flows in order to optimize the battery pack/dump loads functioning can come into conflict with the energy flows control for the proper system frequency regulation.

Therefore it is necessary to analyse the control logics with regard to the system components reaction times, the rates of change in the power flows that can occur during the system functioning, the system inertia, etc.

4.2. Generation

A microgrid is a set of electricity generators and, possibly, energy storage systems interconnected to a distribution network that supplies the entire electricity demand of a localized group of customers. Mini-grids may have different possible generating sources such as Micro or Mini-hydro, Solar PV, Wind, Biomass or a combination of any or all of them.

Among these technologies, Mini-hydro are mature technologies with the lowest levelized cost of energy (LCOE) but the availability of the hydro resource is very site-specific. Solar PV is suitable for any location and easy to install, however, it requires a higher capital investment, while the wind resource is also site-specific, it requires detailed resource monitoring, and the technology is thus far less efficient or reliable at a small scale. Since they are not available at all times, solar PV and wind require storage in the form of a battery or a diesel generator to meet the demand reliably. The battery is a major part of the cost of solar PV and wind MGs and minimising this cost component while maximising reliability requires optimisation.

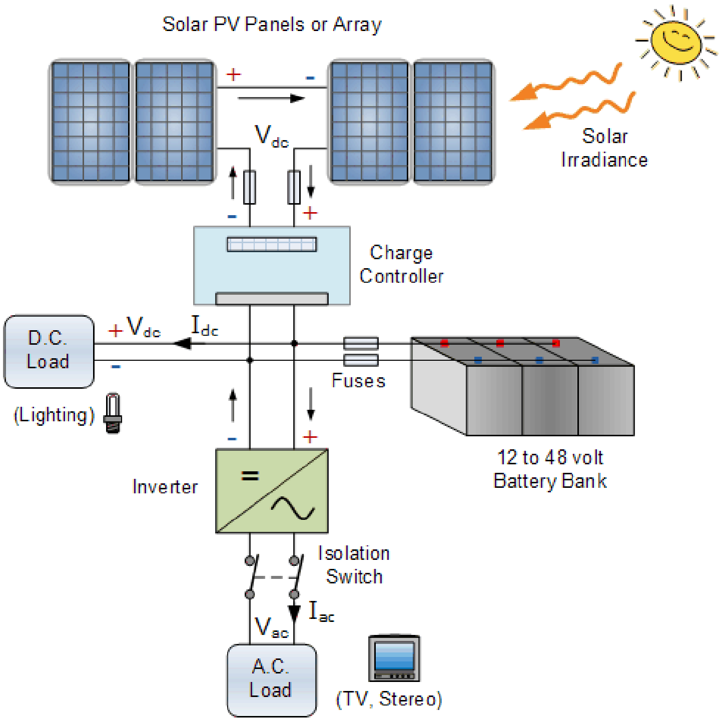


Figure 4-5: Off-grid PV generation system general electric scheme

Mini-grids may be in Alternating Current (AC) or Direct Current (DC) depending on the distance to be covered and types of loads. If the users are nearby to the generating plant the DC supply might be a feasible option if the voltage drop is within the limit

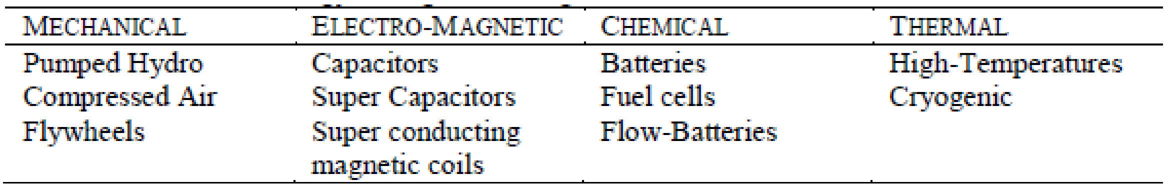
4.3. Storage

In the past, the storage of electrical energy was not convenient because of lower system efficiency: it was better to consume electricity when produced. Today, the emerging of new needs and applications, are changing the framework making valuable the storage choice.

Battery Energy Storage Systems (BESS) are just one of the possible storage options. They belong to the broader family of Electrical Energy Storage (EESs), which collect all those technologies that are used to store electrical energy. ESS technologies can be classified, according to literature [80] , following different methods based on their function, response time and suitable storage duration. However, the most widely used method is based on the form of energy stored in the system (Table 4-1)

- Mechanical Energy storage (MES) to which belong flywheels (FES), pumped hydro plants (PHS) and compressed air systems (CAES);
- Chemical Energy storage (CES) that include batteries (BES), fuel cells storage systems (FC) and Flow-batteries (FB)
- Electric or Magnetic storage (EMES) that include supercapacitors (SCES), Super conducting magnetic coils (SMES);

- Thermal Energy storage (TES) to which belong hot-thermal (HTES) and cryogenic (CrES) energy storages.



MECHANICAL	ELECTRO-MAGNETIC	CHEMICAL	THERMAL
Pumped Hydro Compressed Air Flywheels	Capacitors Super Capacitors Super conducting magnetic coils	Batteries Fuel cells Flow-Batteries	High-Temperatures Cryogenic

Table 4-1- Electrical Energy Storage technologies classification- Source [80]

After a brief review of all the available technologies, this work focuses on BESS options, with specific attention on Chemical and Mechanical Storage system and their possible integration.

4.3.1. Lead-acid Batteries

Lead-acid battery is the most mature, well known and widely used BESS type [81]. Lead-acid batteries are used in all industrial applications, from telecommunications system to automotive but also in naval and submarine applications.

There are different types of lead-acid batteries, each appropriate for specific applications. Although all types of lead-acid batteries follow the same basic chemical reaction, they can vary widely in terms of cost, method of manufacture and performance. The main components are: cathode made of PbO_2, anode made of Pb, electrolyte that is sulphuric acid. Lead-acid batteries have fast response times, small daily self-discharge rates (<0.3%), low capital costs and a service life which can reach up to 6-15 years [82] . However, they have a relatively low cycling times (1500 cycles at 80% of DoD), very low gravimetric and volumetric energy density (25-50 Wh/kg, 50-90 Wh/L) and very poor performance at a very low temperature .

There are two main categories of lead-acid batteries: flooded or vented types (VLA), in which the electrodes are immersed in reservoirs of excess liquid electrolyte; and sealed or valve-regulated types (VRLA), in which electrolyte is immobilized in an absorbent separator or in a gel. These two types are significantly different in terms of design, manufacturing, operating characteristics, life expectancy, and cost.

- VLA batteries are the traditional form of lead-acid batteries and continue to form the bulk of the market, due to their use in automotive sector and in most industrial applications. There are three general types of VLA: starting, lighting and ignition batteries, deep-cycle or traction batteries, and stationary batteries.
- VRLA batteries are constructed and operated quite differently from VLA, due to their starved electrolyte design. The electrolyte is contained within an absorbent separator or a gel to prevent migration out of the cell. VRLA batteries typically have shorter service life than conventional flooded lead-acid designs. These batteries have found application in portable electronics, power tools, and uninterrupted power supplies (UPS), and in a few large applications such as forklift batteries. There are two types of VRLA batteries, depending on how the electrolyte is immobilized, the absorbed glass mat (AGM) VRLA and the gelled electrolyte VRLA (often known as gel cells).

In order to improve lead-acid battery performances, while maintaining their low systems cost, new innovating materials are under R&D. For instance, carbon-enhanced electrode is increasing the energy density up to 150 Wh/kg and the coupling with carbon supercapacitor is creating new advanced hybrid lead-acid batteries [83] .

4.3.2. Lithium-based battery

Nowadays, Li-ion based BESS are dominating the market of portable devices and currently are a pivotal technology for the development of several industrial sectors (e.g. electric vehicles).

Overall, lithium-ion BESS present better performances if compared to competing technologies as Ni-Cd, NiMH and lead-acid technologies. The main features of Li-ion cells are: high operating voltage (3.7 V on average), high gravimetric and volumetric energy density, no memory effect, low self-discharge rate (less than 20% per year) and operation in a wide range of temperature [73]. As well-known, the main drawback is represented by its high cost. However, a relevant cost reduction is ongoing, boosted by the automotive sector.

4.3.3. Sodium Nickel Chloride battery

Sodium nickel chloride battery is also known as the ZEBRA battery, because it was invented in 1985 by the Zeolite Battery Research Africa Project (ZEBRA) group at the Council for Scientific and Industrial Research (CSIR) in Pretoria, South Africa.

During the charging phase, salt (NaCl) and nickel (Ni) are transformed into nickel-chloride (NiCl2) and molten sodium (Na). The chemical reaction is reversed during discharge. The electrolyte is a fully dense ceramic material, similar to NaS battery, which provides fast transport of sodium ions and ensures the electrical insulation between anode and cathode. Cells are hermetically sealed and packaged into modules of about 20 kWh each.

ZEBRA batteries are high-temperature battery devices like NaS, they operate in a temperature range of 270°-350°C. They present moderate energy density and power density: 94-120 Wh/kg and 150-170 W/kg respectively. The main advantages of sodium nickel chloride battery are good pulse power capability, cell maintenance, very little self-discharge and relatively high cycle life.

4.3.4. Flow Batteries

FBs store energy in one or more electroactive species, which are dissolved in liquid electrolytes. The electrolytes are contained in external tanks and they can be pumped through the electrochemical cell that converts chemical energy directly to electricity and vice versa. The system is based on the reduction-oxidation reactions of the electrolyte solutions. The power capability of the FB system is dependent on the size and design of the electrochemical cell, while the volume of electrolytes determines the energy capability. An important feature of FB systems is the low self-discharge thanks to the electrolytes stored in separated and sealed tanks. Moreover, FB can release energy continuously at a high rate of discharge for up to 10 hours [84] . The main drawback is the low gravimetric energy density due to the massive plant configuration needed. FB are differentiated based on the electrolytes and onto the electrochemical reactions. The ones knows mostly are:

- Vanadium Redox Flow Batteries (VRB), which store energy using vanadium redox couples (V2+/V3+ in the negative half-cell and V4+/V5+ in the positive half-cell). These are stored in mild sulphuric acid electrolytes. During the charge/discharge cycles, H+ ions are exchanged through the ionic selective permeable polymer membrane. The cell voltage is about 1.4–1.6 V and the efficiency can be up to 85% . Main features of VRB are the quick responses (faster than 1 ms) and the possibility of operating for 10000-16000 cycles . However VRB presents low electrolytes stability and high operating costs .
- Zinc Bromine Flow Batteries (ZnBr) are based on zinc and bromine elements, which are the reactive component of aqueous electrolyte solutions stored in external tanks. The main characteristics of ZnBr batteries are: the relatively high volumetric energy density (30-60 Wh/l), the cell voltage (1.8 V), the estimated lifetime of about 10-20 years, the discharge duration up to 10h [85]. Nevertheless, ZnBr batteries present some disadvantages: material corrosion, dendrite formation, relatively low efficiency (65%-75%) and they operate in a narrow temperature range.

4.3.5. Flywheel energy storage (FES)

FES is a system that stores electrical energy in the form of rotational kinetic energy. It included five main components: a flywheel, a group of bearings, a reversible electrical motor/generator, a power electronic unit and a vacuum chamber (which helps to reduced self-discharge losses) [86] . The amount of energy stored is proportional to the angular velocity reached. FES operates in charging and discharging mode: during the charge mode, a motor is used to accelerate a big rotating mass (flywheel); during the discharge mode, the kinetic energy is extracted by a generator driven by the inertia of the flywheel, resulting in a deceleration of the rotating mass.

FESs can be classified in low speed FESs which rotate below 6×103 rpm[9], and high speed FES which can run up to about 105 rpm by exploiting advanced component material . The key features of FES are: limited maintenance cost, cycle stability, long life, high power density, wide operating temperature range and environmental compatibility. However, these systems have a very high rate of self-discharge due to air resistance and bearing loss. In about 5-10 hours up to 50% of stored energy can be lost . For this reason, flywheels perform well when used in applications which demand high power for short periods together with a high number of charging-discharging cycles.

4.3.6. Applications

In general, it is well accepted that no single ESS technology can meet the requirements for all possible applications. Selection of ESS is based on the assessment of the characteristics of the different ESS options against the requirements of the specific application.

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[9] http://watt-logic.com/2017/06/07/flywheel-energy-storage/

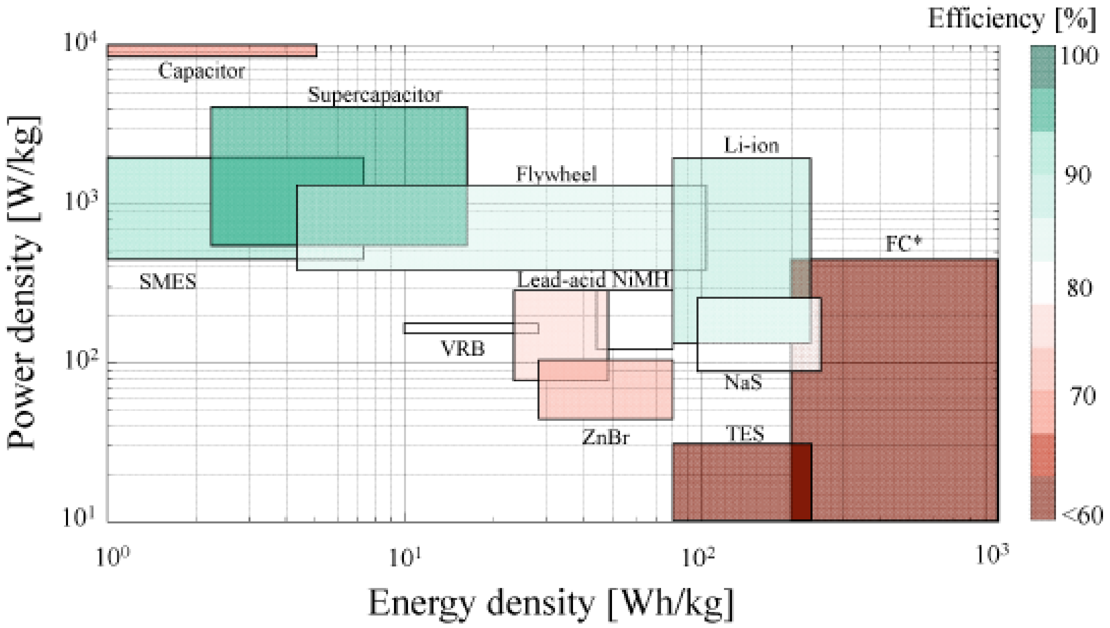

Figure 4-6: Comparison about energy density, power density and cycling efficiency for various EES technologies . Source [87]

Figure 4-6 compares ESS in terms of their typical energy densities, power densities and efficiencies. Energy densities and power densities are crucial when the size of ESS is of main concern. The higher the two indicators are the lighter and performant the BESS will be. Li-ion technology is the most positioned to the top-right of the graph: they have the best combination of energy/power performance available in the market to date. Good cycle efficiency is fundamental when the application is very stressful and prolonged in time. Efficiency has been continuously improved in time for all available technologies. As regards of BESS technologies, Li-ion batteries occupy the first position (η > 90% in standard conditions) followed by Nickel-based batteries (η > 85%), Molten-salt batteries (η > 80%) and lead-acid batteries (η > 75%).

Within these categories, it is possible to highlight some key stationary applications that represent actual opportunities for ESS [88]:

- Renewable integration: to minimize intermittency of RES by time-shifting production and dispatching. The storage is used to optimize the RES production in terms of supply quality and value. The typical size of application can be from hundreds of kW (distribution networks) to tens of MW (Transmission level). The discharge duration can be in the range of some minutes to some hours.
- Load levelling: to balance the large fluctuations associated with electricity demand and to smooth intermittent generation. The energy is stored during off-peak periods and used for the application. The capacity is typical at the MW level and it requires high energy efficiency since the charge/discharge periods can last several hours.
- Spinning reserve: to reduce requirements on idle generators that are dedicated to take over of any sudden failure of major generator. Reserve capacity used to keep the system

balanced. The installations are usually in the range of MW. The chosen technology must respond immediately (few seconds) and have the ability of maintaining the outputs for up to few hours.

- Customer-side peak shaving: to reduce the customer maximum (peak) energy demand level by exploiting EES at local level. Energy demand can be also shifted in order to assist the integration of local RES. This application is very similar to load levelling but at the customer level. The only difference is the typical size that can vary from kW to hundreds of kW.
- Primary Control Reserve (frequency regulation): to support the balancing of continuously shifting supply and demand (frequency regulation). In this case the requirements are the ability to react in some seconds and to maintain the service for several minutes. Typical size of application goes from hundreds of kW to tens of MW.
- Voltage support: to inject or adsorb reactive power to maintain voltage levels in the transmission and distribution systems under normal conditions. Discharge duration is very short (seconds) and the energy/power ratio of the installations can be very low.
- Arbitrage/storage trade. This involves storing low-priced energy during period of low demand and subsequently selling it during high-priced periods within the same market. This application requires EESs that have high round-trip efficiency and can achieve long storage duration (hours to days).
- Off-grid: storage is deployed in conjunction with local generation (mostly RES) to ensure reliability by filling the gaps between production and demand. The aim could be to electrify rural areas and/or to be independent from the main-grid. Installations might vary in terms of energy/power ratio according to the available resources (RES, genset, PV, wind or hydro turbines, etc.). Generally, they can range from tens of kW (small system) up to tens of MW (big islanded systems). Discharge phases can last up to days because they might have to sustain the loads even in the worst-case scenario of no energy production (e.g. RES+EES plants).

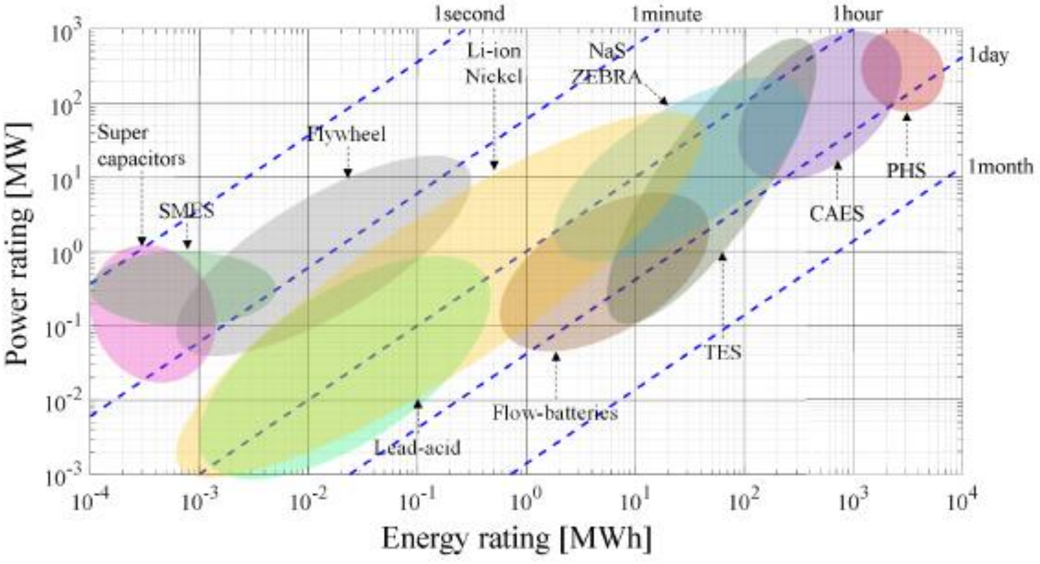

Figure 4-7: Comparison of Power/Energy ratings with discharge time at power rating for various EES technologies

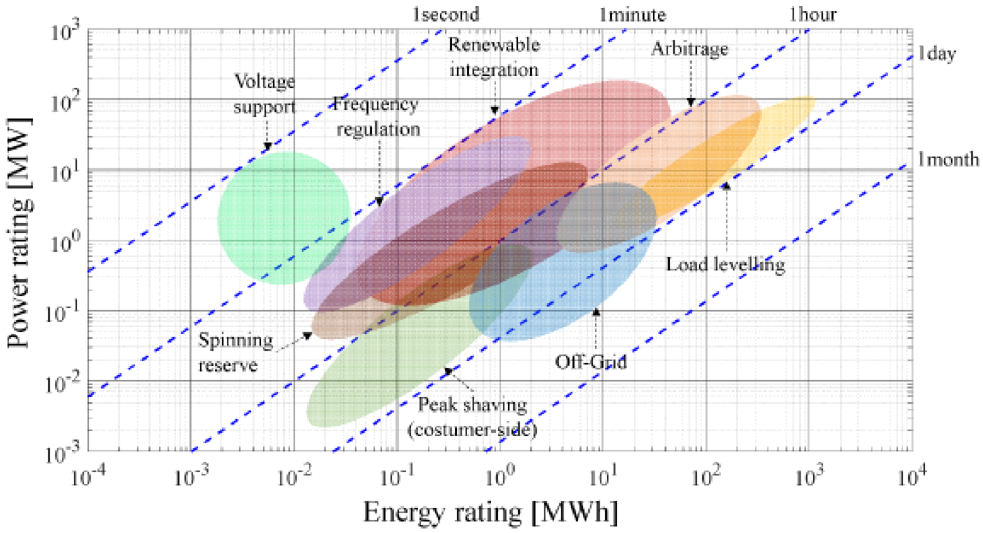

Figure 4-8: typical Power/Energy ratings requested to EES technologies by various stationary applications. Source: Deloitte 2015

Among BESS, lithium-ion appears to be the most suitable technology for stationary applications: its characteristic area overlaps almost the whole application area of Figure 4-8 . However, lithium-ion BESSs cover less than 30% of current stationary installations around the globe [89] . The main motivation is represented by the high cost of installation if compared with the other EES technologies. In 2019 the specific cost of lithium-ion BESS was the highest one (except for flywheels) with an average value of 450€/kWh, 3 times higher than lead-acid BESS. Nevertheless, much attention from researchers, producers and system integrators is given to this technology since a huge cost decrease is forecasted in the next decades. Projections to 2030 show that lithium-ion BESS will be interested in the highest cost reduction of nearly 60% [90] that will drive its specific cost to be quite comparable with all the other EES technologies This fact, together with the best overall performances as detailed above, will put Li-ion in a probable monopolistic position for stationary applications.

4.4. Hybridization simulation. *Ref. Paper PA-2*

Regarding technologies hybridization, the coupling of flywheels with conventional batteries for microgrid applications is able to extend the life of electrochemical storage systems, drastically reducing replacement costs associated with the latter. Specifically, in [91] accelerated aging tests, performed over lithium cells operated both in hybrid and non-hybrid configurations, result in a one third reduction in the internal resistance increase in case of hybridization over three years of operation, thus demonstrating that a relevant battery life extension is possible through flywheel-battery coupling. Flywheel energy storage systems (FESS) are capable to cope with highly oscillating power fluctuations [92] and therefore can be used as short-term storage devices [93]; reducing dangerous power spikes meanwhile increasing battery lifetime in hybrid configurations. FESS main characteristics are a high cycle life (hundreds of thousands), long calendar life (more than

20 years) independently from the depth of discharge, fast response, high round trip efficiency, high charge and discharge rates, high power density, high energy density [7,9] and low environmental impacts as described in [94]. Moreover, they present very low operational and maintenance requirements. According to the classification reported in [94], low-speed mechanical FESS (< 10,000 rpm) and high-speed composite FESS (up to 100,000 rpm) technologies are available.

In the present study a low-speed flywheel with a steel cylindrical rotor, low-friction mechanical bearing and housing under vacuum is taken into account for costs reduction. The extension in battery lifespan is determined for different flywheel/battery configurations under relevant operating conditions; moreover, the correlated positive economic effects are evaluated by implementing battery replacement in the LCOE index calculation procedure. To this aim single technologies and hybrid storage configurations have been investigated starting from the data gathered, for what concerns both PV production and users load request, at a Ugandan MG (Kitobo island) chosen as representative of remote areas in developing countries. Moreover, different load profiles typical of industrialized countries, have been considered for further evaluation of MG performance within future more developed scenarios.

For what above, energy storage is the key to deploy intermittent and non-dispatchable RES such as solar and wind in MGs while minimizing the dependency on fuel and guaranteeing reliability and high standards of quality of service, minimizing energy curtailment [95].

A case study of a Ugandan microgrid has been used to compare various battery technologies employed on their own and in a combination with a flywheel in terms of their durability and overall LCOE of the plant. Simulations show how the hybrid storage configurations result in a lower LCOE for the current load profile of the microgrid and even more so for two reference residential and industrial load scenarios, suggesting it would remain the best solution even accounting for future socio-economic development. The resulting LCOE for hybrid storage configurations is lower than the average values reported for microgrid projects and represents a promising solution to speed up the development of such electrification initiatives.

4.4.1. Kitobo Microgrid description

Lake Victoria is the second largest freshwater lake in the world, shared between Kenya, Tanzania and Uganda, which possesses 43% of its shoreline. It’s estimated that it’s an essential water source for about 30 million people in the area, and that over 3 million people depend on the its fish catch and processing value chain [96]. Kitobo is an island located 33 km from the mainland and the national grid, and is part of the Ssese Islands, an archipelago of 84 islands located in the northwestern part of Lake Victoria. In 2016, Kitobo had about 2000 inhabitants divided in 600 households, mostly engaged in fishing activities (tilapia, nile perch and Lake Victoria silverfish). In November 2016, a MG was commissioned by the project "Sustainable Energy Services for Kitobo Island", promoted by the investment platform Absolute Energy Capital, in partnership with CIRPS (Interuniversity Research Centre For Sustainable Development) and the AVSI Foundation NGO.

Before the construction of the plant, only 30 villagers were connected to a private diesel generator, facing high expenditures to buy gasoline, while others where using other traditional energy sources for lighting. At the time of writing, an ice machine has just started operations: availability of ice directly in the island will prevent higher expenses and losses experienced by the fishermen that need to buy ice from the mainland. Access to electricity is creating other income generating activities, helping increase the resilience of the population which is at the present time vulnerable, due to the seasonality of fishing.

The photovoltaic field consists of 880 PV panels with a nominal power of 260 Wp, adding up to a nominal power of 228.8 kWp, combined under eight inverters of 25kW each. There is a back-up three-phase diesel generator, with an 80 kVA rated power, to be used in cases of high demand not completely satisfied by the energy coming from the photovoltaic field, of prolonged periods without sun or in the case of extraordinary maintenance. The plant includes also vanadium redox flow batteries (VRFB), ensuring a total capacity of 520 kWh, each equipped with off-grid inverters able to modulate the power adequately. Since the village is densely populated and located at a reduced distance from the plant (200 m), a low-voltage distribution system is enough to reach the off-takers.

The generation and electric load data from Kitobo microgrid used in the present study cover the months from July to December 2017. The data represent the first six months of operation of the MG and, as expected, in the first months of operations the energy demand is low: the design choices have to be evaluated in consideration of the future ramp-up of energy demand, the diversification of economic activities and the modernization of current ones, even if this represents a slow process that takes places over years.

The case study presented has been used as a reference to investigate the potential benefits of H-ESS in increasing the financial feasibility for the replicability of the project in similar contexts, considering plant layouts that differ from the one actually in place, and are best suited to serve the electricity demand measured at the site.

For this purpose, the actual measured load profile has been used as an input to depict the actual needs of similar remote communities, but also two load profiles that reflect more "advanced" user cases have been derived from it, as explained in the following section.

As for the PV generation, the monitoring system registered a generation peak of 112 kW in the timespan considered, due to the fact that the inverters automatically curtail the production if there is a lack of request or the batteries are already charged. The output PV profile available has been used in the scenarios considered without doing further simulations, but for the LCOE calculations a PV power of 112 kWp (as reported in Table) instead of the nominal rating of 228 kWp has been used. This assumption, justified by the very low average PV power generation in comparison with the 112 kW peak, allows to evaluate comparatively the LCOE of various energy storage configuration in a generalizable scenario where generation capacity is appropriate for the load to be served.

Accordingly, as it can be seen in Table-Table, the storage sections considered for the investigated scenarios are significantly smaller than the VRFB capacity actually installed at Kitobo. Likewise, the power rating of the auxiliary generator is sensibly lower.

4.4.2. Methodology

The preliminary work carried out moves from the annual profiles of electrical load ($\boldsymbol{L_{Kit}}$ profile) and PV production gathered at the Kitobo island microgrid. Since the available dataset covered only 6 months of data, the annual profile was obtained by duplicating the available load profile data, in consideration of the low seasonality of consumption patterns in the island. First, taken into account the acquired PV production and load profiles, the preliminary sizing of the energy storage devices (Li-ion, Lead-gel, also in hybrid flywheel/battery configurations, and VRFBs technologies are applied) is performed through the simulation code presented in [91], providing as output also the State of Charge (*SoC*) trend throughout the year (in terms of angular velocity for flywheel modules). Second, for conventional batteries the *SoC* trend made it possible to estimate for each storage configuration the number of annual cycles and the relative lifespan in years, through the application of the Rainflow algorithm and the specific "Cycles to Failure" curve of the technology analyzed. Finally, the set of such data is then used for the implementation of the *LCOE* index calculation together with further parameters as indicated below.

This procedure is followed for several storage architectures and, moreover, considering also different users load profile, characterized by a greater oscillating behavior (in the following $\boldsymbol{L_{Kit_{res}}}$ and $\boldsymbol{L_{Kit_{ind}}}$ profiles) at parity of yearly energy consumptions, aiming to evaluate a possible future scenario consequent to the socio-economic development of the Kitobo community. $\boldsymbol{L_{Kit_{res}}}$ and $\boldsymbol{L_{Kit_{ind}}}$ profiles were determined on the basis of measurements performed at residential and industrial users respectively, located in industrialized countries. These acquired load profiles were scaled to have the same overall annual consumption measured at Kitobo, but maintaining their specific fluctuating character. To highlight differences in fluctuation among the three investigated load profiles, Figure 4-9, as example, depicts their trends for a limited period of a week. .It must be emphasized how $\boldsymbol{L_{Kit_{res}}}$ and $\boldsymbol{L_{Kit_{ind}}}$ have higher power peaks, due to the use of appliances and industrial electric loads respectively. So that, a possible future socio-economic development can also increase the LCOE difference between hybrid (flywheel-battery) and non-hybrid (only battery) storage systems, with an increasing advantage provided by the H-ESS thanks to the greater exploitation of FESS peak-shaving function towards the battery.

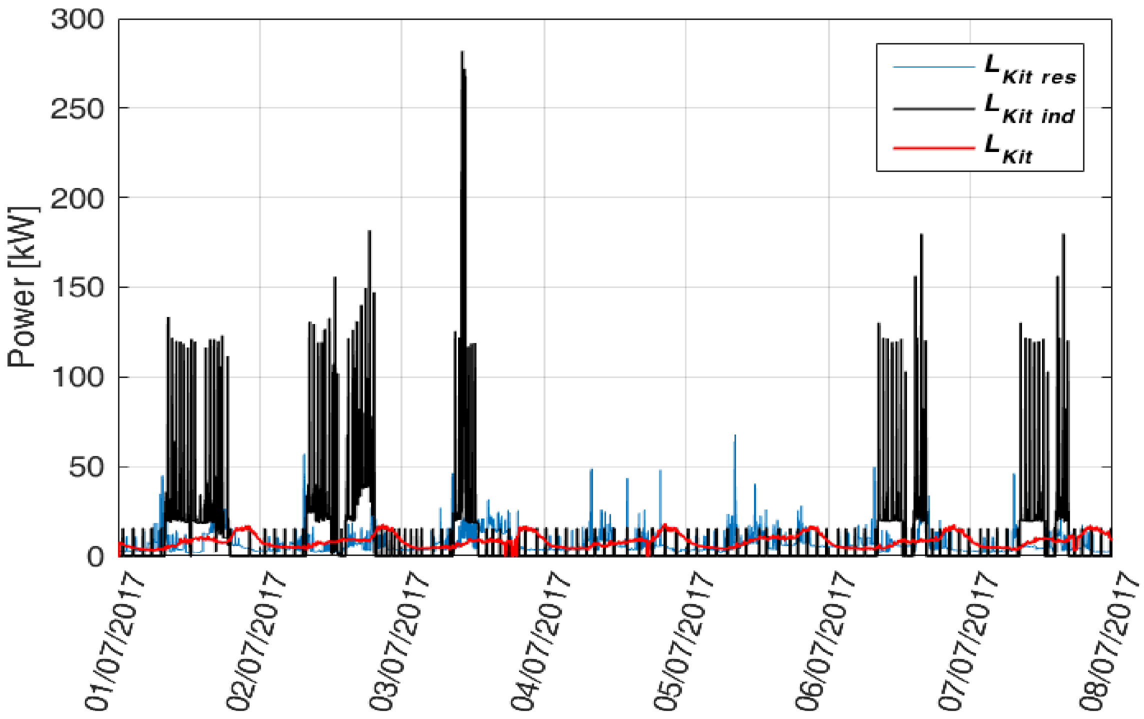

Figure 4-9 - (L_{Kit}, $L_{Kit_{res}}$ and $L_{Kit_{ind}}$) electric load profiles shown for a time interval of 1 week (1 minute time step)

4.4.3. Storage system annual operation assessment

Kitobo microgrid represents an example of an off-grid system. Therefore, it is mandatory to maximize the self-consumption of energy produced by the PV plant and to minimize the diesel auxiliary generator operation, used to provide energy whenever requested.

MG energy performance is evaluated by means of the MG simulation code developed in Matlab environment for batteries [97] and flywheel/battery hybrid storage sections [91], [92]. The code performs a power flows management, with 1 minute time step, based on PV production and load profiles. It provides as outputs the trends of energy exchanges among the PV plant, the auxiliary generator, the load and the storage section, as well as the corresponding global yearly amounts. Thus, it is possible to evaluate the overall yearly amount of self-consumption due to the storage system as output.

The developed software requires the following input data:

- RES production and load profiles with 1 min. time step;
- Storage battery capacity;
- Battery depth of discharge;
- Battery maximum charge/discharge power;
- Battery round trip energy efficiency;
- Presence or absence of flywheel storage system, including its technical features (inertia momentum, minimum/maximum rotational speed, round trip efficiency);

- State of charge of the storage devices at the beginning of the simulation.

When production is greater than demand, the surplus energy is used to charge the storage system. On the other hand, the storage system provides energy to the load when higher than the PV production. In case of battery/flywheel hybrid architectures, a complex management algorithm is used, as presented by the authors in [91], [92], implementing the flywheel peak-shaving functionalities on the basis of the difference values (*Diff*), the current and the one relative to the previous calculation step, between production and load. Specifically, on the basis of two consecutive *Diff* values, two step-profiles (i.e. consisting of consecutives step variations), characterized by a slow variation and approximating the *Diff* trend by excess or defect respectively (with reference to absolute values), are determined in real time. In accordance with the particular operating mode (surplus or lack of renewable energy, full charge, complete discharge, power saturation of storage devices), the current value of one of the step-profiles is chosen as the power accumulated/delivered by the battery pack in the time step (or the auxiliary generator in case the storage system can't be operated), while the oscillation (i.e. the difference between such parameter and the current *Diff* value) is processed by the flywheel. The algorithm consists of two main sections corresponding to the case of lack and surplus of PV production, each one structured in several sub-cases identified according to flywheel rotational speed, battery state of charge and absence/presence of PV production as detailed in [91]. It is remarked that the code is developed to characterize the energy exchanges in grid connected MG. However, it is applied to the present study, considering that the potential extra energy amount can be provided by the diesel auxiliary generator.

The battery state of charge, which is continuously updated during the simulation, is used as input for the Rainflow algorithm, in order to evaluate battery lifetime. The main outcomes of the annual microgrid simulation together with results of the Rainflow battery and further input parameters (see Table), are implemented in the next sections for the LCOE calculation.

4.4.4. Rainflow cycle counting algorithm

As described in [98], the rainflow algorithm is a widely used model [99]–[108], usually applied to evaluate battery lifetime when subjected to complex cycles, as in the case of present investigation. Even if it is not accurate, generally providing an overestimated lifespan evaluation, this strategy is here implemented for a lifespan comparison among several storage configurations rather than to achieve an absolute estimation of battery useful life.

This method is based on counting the charge/discharge cycles Z_i corresponding to each range of Depth of Discharge (*DoD*), split in m intervals, for a year. A number of Cycles to Failure (CF_i) corresponds to each *DoD* interval. Comparing the number of cycles performed during the year at a certain depth of discharge with the Cycle to Failure curve of the considered battery, it is possible to estimate the useful life of the battery, according to Equation. 4-1), as reported in [98]:

$$Life_{batt} = \frac{1}{\sum_{i=1}^{m} \frac{Z_i}{CF_i}}$$

Equation 4-1

4.4.5. LCOE evaluation model

This section presents the calculation model for the LCOE index, here implemented in order to evaluate in economic terms the most convenient energy storage solution among the various investigated alternatives for the Kitobo microgrid.

As described in [109], LCOE is a measure of costs which attempts to compare different methods of electricity generation. LCOE corresponds to the minimum cost at which electricity must be sold to achieve break-even point over the considered lifetime of the project. In [110], IEA provides an analytical definition of LCOE as following:

$$LCOE = \frac{\sum_{i=1}^{n}(I_i + M_i + F_i)/(1+r)^i}{\sum_{i=1}^{n} E_i/(1+r)^i}$$

Equation 4-2

Where:

I_i	investment costs during year i;
M_i	operation and maintenance costs during year i;
F_i	fuel costs during year I due to the auxiliary diesel generator;
E_i	generation during year i;
r	discount rate;
n	lifetime of the project.

In the discussed analysis, investment, maintenance and replacement costs are referred to the procedures discussed in [111].

In detail, equations 4-3) - (4-6) show the ***investment costs*** (in €) of: *i)* the energy generation system (PV panels, eq. (4-3) and diesel auxiliary generator, eq. (4-6)); *ii)* the energy storage systems, in particular batteries (4-4) and flywheel accumulator (4-5).

$$C_{cap,PV} = C_{PV} * P_{PV} \tag{4-3}$$

$$C_{cap,batt} = PCS * P_{batt,disch} + C_{storage} * E_{batt} + BOP * P_{batt,disch} \tag{4-4}$$

$$C_{cap,FW} = C_{storage} * E_{fw} + PCS * P_{fw} + C_{inst} \tag{4-5}$$

$$C_{cap,aux.gen.} = C_{aux.gen.} * P_{aux.gen.} \tag{4-6}$$

Equation 4-4,5,6

Where:

$C_{storage}$	Cost of storage section [€/kWh]
PCS	Cost of power conversion system [€/kW]
C_{PV}	Cost of photovoltaic section [€/kWp]
P_{PV}	Photovoltaic peak power [kWp]
$P_{batt,disch}$	Maximum battery discharge power [kW]
$P_{batt,ch}$	Maximum battery charge power [kW]
E_{fw}	Installed flywheel capacity [kWh]
P_{fw}	Maximum flywheel power [kW]
$C_{cap,PV}$	Total capital costs for PV section [€]
$C_{cap,Li-ion}$	Total capital costs for li-ion battery [€]
$C_{cap,Lead-gel}$	Total capital costs for lead-gel battery [€]
$C_{cap,VRFB}$	Total capital costs for vanadium redox flow battery[€]
$C_{cap,FW}$	Total capital costs for flywheel [€]
C_{inst}	Flywheel installation costs [€]
E_{batt}	Maximum battery storable energy [kWh]
BOP	Cost of balance of plant [€/kW]
$C_{cap,aux.gen.}$	Total capital costs for Diesel generator [€]
$C_{aux.gen.}$	Cost of Diesel generator [€/kW]
$P_{aux.gen.}$	Diesel generator peak power [kW]

It is highlighted as for the FESS (Flywheel Energy Storage System) technology, capital (eq. (4-5)) costs consider:

as regards the costs depending on the size (C_{FW}): cost of the rotor divided into the cost of the forging stock (it grows with the mass of the raw material) and the cost of the mechanical work on the piece (it grows with the mass of the forging raw because at working hours); housing cost, related to the size and weight of the contained components, and cost of the adjustment system, related to the size of the rotor.

as regards the costs depending on the maximum power (P_{FW}): cost of the linear machine depends on its volume (increasing costs of laminations, winding, resin and magnets with height and diameter of the machine); housing cost, related to the size and weight of the contained components; cost of the electrical system and its main sub-components, linked exclusively to the power of the electric machine.

Regarding the operation and maintenance costs of the aforementioned technologies, eqs. (4-7)-(4-9) refer respectively to the different storage solutions, the PV system and the diesel auxiliary generator.

$$C_{O\&M-storage,a} = C_{FOM} * P + \frac{C_{VOM}}{1000} * E_{storage,a} \tag{4-7}$$

$$C_{O\&M-PV,a} = C_{fom_{pv}} * P_{PV} \tag{4-8}$$

$$C_{O\&M-aux,a} = FC * C_{fuel} + C_{FOM,aux} * P_{aux.gen.} + \frac{C_{VOM,aux}}{1000} * FC \tag{4-9}$$

Equation 4-7,8,9

Where:

C_{FOM}	Fixed operational and maintenance costs for the considered storage technology [€/kW-year]
C_{VOM}	Variable operational and maintenance costs for the considered storage technology [€/MWh]
$C_{fom_{pv}}$	Fixed operational and maintenance costs for PV $\left[\frac{€}{\mathrm{kWp-yr}}\right]$
$E_{storage,a}$	Annual stored energy in the battery/flywheel unit $[\frac{\mathrm{kWh}}{\mathrm{year}}]$
P	$P_{batt,disch}$ in the case of battery; P_{fw} in the case of flywheel
$C_{O\&M-storage,a}$	Operational and maintenance costs for storage section [€/year]
$C_{O\&M-PV,a}$	Operational and maintenance costs for PV [€/year]
C_{rep}	Replacement cost [€]
$C_{O\&M-aux,a}$	Annual fuel and operative costs for generator [€/year]
FC	Annual energy production from auxiliary diesel generator [kWh/year]
C_{fuel}	Fuel cost (Diesel) for generator [€/kWh]
$C_{FOM,aux}$	Fixed operational and maintenance diesel generator costs [€/kW-year]
$C_{VOM,aux}$	Variable operational and maintenance diesel generator costs [€/MWh]
P_{PV}	PV installed power [kW]

Replacement costs are expressed by eq. (4-10) in case of Li-ion and lead-gel technologies, while in case of VRFB they are mainly due to the membrane replacement, as described in [112]-[113].

$$C_{rep} = C_{storage} * E_{batt} \tag{4-10}$$

Equation 4-10

A mathematical model is shown in the following equations in order to evaluate membrane replacement costs, on the basis of the installed stack power and considering a replacement time of 8 years and 250 €/m^2 as membrane cost ([112]). The current density (*CD)* and internal resistance (R_{cell}) for the single cell are set at 50 mA/cm^2 and 1.5 Ω*cm^2 ([113]) in order to evaluate the cell voltage v_{cell} according to eq. (4-11). Once the cell voltage has been determined, the nominal current I_{nom} is calculated, as described by eq. (4-12), considering a stack voltage of 48 V and a specific stack number.

Subsequently, from eq.(4-13) it is identified the necessary number of cells, N_{cell}. Finally, the total surface of the membranes ($S_{membrane}$) is deduced from eq. (4-14), while the replacement costs concerning VRFB technology results from eq.(4-15).

$$v_{cell} = 1.35\,[V] - CD\left[\frac{A}{cm^2}\right] * R_{cell}[\Omega \cdot cm^2] \tag{11}$$

$$I_{nom}[A] = \frac{P_{nom}\,[W]}{v_{stack}[V] * N_{stack}} \tag{12}$$

$$N_{cell} = \frac{v_{stack}}{v_{cell}} * N_{stack} \tag{13}$$

$$S_{membrane}[m^2] = 1.1 * S_{electrode} = 1.1 * \frac{I_{nom}[A]}{CD[\frac{A}{cm^2}]} * \frac{N_{cell}}{10000} \tag{14}$$

$$C_{rep,membrane} = S_{membrane} * \; C_{membrane} \tag{15}$$

Equation 4-11,12,13,14,15

Where:

CD	Current density fixed at 0.05 A/cm^2
R_{cell}	Cell internal resistance [Ω*cm^2]
v_{stack}	Stack voltage [V]
N_{stack}	Number of stacks [-]
v_{cell}	Cell voltage [V]
I_{nom}	Rated current [A]
P_{nom}	VRFB rated power [W]
$S_{membrane}$	VRFB effective membrane area [m^2]
$S_{electrode}$	Electrode total area [m^2]
$C_{membrane}$	Membrane cost [€/m^2]

Finally, it is highlighted as FESS technology has a significantly higher lifetime with respect to electrochemical accumulators, compatible with the analysis scenario. Hence, it implies no substitutions are needed during the considered LCOE time horizon.

It is emphasized that all costs (capital, O&M and replacement) must be discounted. The discounting is carried out considering the Weighted Average Cost of Capital (WACC) discount rate, which is the weighted average between the cost of equity and the cost of debt capital (the chosen numeric value is indicated in **Table**). Considering all eqs. (3)-(15), the calculating formula concerning LCOE index implemented at the aim of the present study can be expressed by eq. (4-16).

$$LCOE = \frac{C_{cap,storage} + C_{cap,PV} + C_{cap,aux.gen.} + \sum_{t=1}^{T} \frac{C_{O\&M-storage,a} + C_{O\&M-aux,a} + C_{O\&M-PV,a}}{(1+WACC)^t} + \sum_{k=1}^{s} \frac{C_{re}}{(1+WACC}}{\sum_{t=1}^{T}(FC + E_{PV} * (1-d)^t/(1+WACC)^t)} \tag{16}$$

Equation 4-16

Where:

$LCOE$	Levelized Cost of Electricity [€/kWh]
T	Time horizon for LCOE calculation [year]
$WACC$	Nominal discount rate [%]
d	Annual photovoltaic degradation factor [%]
LT_{batt}	Battery lifetime [year]
s	Number of replacements [-]
E_{PV}	Annual amount of energy generated by the photovoltaic system $[\frac{\text{kWh}}{\text{year}}]$
$C_{cap,storage}$	Total capital cost for storage section [€]
C_{rep}	Replacement costs [€]

4.4.6. Analysis of alternative configurations

Target of this work is the evaluation of the effectiveness of H-ESS integrating a flywheel coupled with conventional chemical storage devices, in terms of improved LCOE index with respect to batteries devices. Since the general purpose of the study is to evaluate if H-ESS can provide sufficient flexibility and competitiveness to islanded MGs fed by renewable sources in the context of developing countries, also VRFBs are considered as further comparative technology, due to the possibility of independent power and capacity sizing. Therefore, the following energy storage technologies are considered:

- Lead-gel battery (Lead-gel);
- Li-ion battery (Li-ion);
- Vanadium redox flow battery (VRFB);
- Flywheel (FESS).

Li-ion and Lead-gel batteries are widely widespread nowadays. Lead-gel batteries (which represent an improvement of conventional lead batteries since the electrolyte is like a gelatinous compound, instead of liquid one) are particularly suitable for bulk heavy storage, thanks to their relative low cost per kWh. Li-ion batteries are largely used in small and medium storage systems, thanks to their high energy to weight ratio, no memory effect, high levels of efficiency and reliability and low self-discharge; however, they present a high price compared to other storage technologies and critical issues concerning lithium and cobalt availability, as described in [97].

Vanadium redox flow batteries are one of the most promising storage systems, specifically for stationary applications, as they are characterized by a high capacity to storage power ratio. [114] lists the main advantages of VRFB technology, such as independent sizing of power (which depends on cell area) and energy (which depends on electrolyte volume), high round-trip efficiency, 100% DoD, long durability, fast responsiveness and limited environmental impact. However, the high cost of membranes involves an economic disadvantage when high powers are required. Regarding flywheel storage systems, they have fast responsiveness, high efficiency, long cycling life and high power densities [115].

On the other hand, standing losses are non-negligible. It implies that flywheels are usually applied for power modulation (short term energy storage). In hybrid configurations, as in the present study, their application range can be extended. Hybridization allows multi-operation modes of the ESS, merging the positive features of base-technologies. Therefore, in this study a low-speed flywheel with a steel rotor is devoted to peak-shaving function towards Li-ion and lead-gel batteries, in order to extend their lifespan as already proved in [91]. Different flywheel sizes are considered. Flywheel capacity can be increased acting on mass and geometry, which determine the rotational inertia of the object. Ramping capability during transients is affected by the same parameter; however fast response is determined by the torque curve of the electric machine – that in turn is related to the power. Table 4-2, which reassumes main simulation parameters, includes also technical and economic parameters relative to the considered storage devices.

Furthermore, as already discussed, three different load profiles (i.e. $\boldsymbol{L_{Kit}}$, $\boldsymbol{L_{Kit_{res}}}$ and $\boldsymbol{L_{Kit_{ind}}}$) have been used in order to evaluate the LCOE index taking in consideration a different oscillating behavior of the electric load profile according to the envisaged development of the community.

Energy Production Technology	**Photovoltaic – PV**
$P_{PV}[kWp]$	112
d [%]	0.05%
$C_{fom_{pv}}\left[\frac{€}{kWp-yr}\right]$, from [116]	8
$C_{PV}\left[\frac{€}{kWp}\right]$, from [117]	1200
$T\ [year]$	30
$E_{PV}\left[\frac{kWh}{year}\right]$	110643.1
$WACC$[%][1]	8,74%
Inflation [%]	0%
C_{fuel} [€/kWh], from [118]	0.17
$C_{FOM,aux}\left[\frac{€}{kW-yr}\right]$, from [119]	13.2
$C_{VOM,aux}\left[\frac{€}{MWh-yr}\right]$, from [119]	13.2
$C_{aux.gen.}\left[\frac{€}{kW}\right]$, from [119]	572

[1] Weighted Average Cost of Capital, referred to Uganda case [120].

Table 4-2: Specifications and costs for the photovoltaic system

4.4.7. Results

For each load profile, several ESS are investigated considering different technologies (Li-ion, Lead-gel, VRFB) and, for each technology, the variation of main sizing parameters. Also H-ESS, consisting of conventional batteries coupled to a flywheel, are considered and compared to a battery of equivalent capacity equal to the sum of flywheel and battery installed ones. Moreover, in case of hybrid configurations different flywheel features are investigated once battery capacity values are chosen.

First, assessments of the MG annual operation are determined by means of the code above presented. Specifically, for all investigated ESS architectures, one-year simulation is performed with 1-minute time step to determine the profile of all energy fluxes among MG components and their operating status. Among these parameters the cumulated amount of energy provided by a diesel auxiliary generator is determined to characterize the MG energy independence.

Second, lifetime expectation results are presented for Li-ion and lead-gel technologies on the basis of the simulated yearly SoC profile. Finally, LCOE analysis is realized according to the procedure presented above to compare all the different investigated configurations.

Table4-3 reports only the most performing configurations in terms of the LCOE index among the investigated ones based on Li-ion and Lead-gel technologies, included hybrid flywheel/battery systems. Sizing features characterizing the investigated configurations are chosen aiming to guarantee a sufficient energy independence of the microgrid (close to 90% and anyway greater than 85% with respect to the yearly amount of the users request measured in about 65.000 kWh/y), thus limiting the exploitation of the auxiliary diesel generator, with reduced values of installed storage capacity and power. It summarizes installed capacities for Li-ion, Lead-gel, as well as flywheel's power and capacity values for the hybrid configurations. With regard to Li-ion and Lead-gel technologies, installed capacity values correspond for each configuration (#1,3,5) to the same useful capacity considering *DoD* values of 90% and 40% respectively. Moreover, for non-hybrid configurations (#2,4,6), battery capacity is the equivalent capacity of the flywheel/battery corresponding architecture.

Same procedure is followed in the VRFB case considering different power values for a certain capacity. Table4-4 shows VRFB installed power values for the different investigated load profiles. It is highlighted how the installed power increases moving from configuration #7 to #9 accordingly to the higher peak power of the load profiles (an analogous consideration can be done in reference to the flywheel power sized for the H-ESS in case $\boldsymbol{L_{Kit_{ind}}}$ is adopted with respect to other load profiles).

Table reports the auxiliary generator installed power values and the yearly amounts of produced energy (in the range 5.000-9.000 kWh/year for all reported configurations) implemented in the LCOE index evaluation as requested in the case of $\boldsymbol{L_{Kit_{res}}}$ and $\boldsymbol{L_{Kit}}$ load profiles. The sizing of the auxiliary diesel generator and its functioning is assessed, for each of the several investigated cases, to guarantee a continuous operation time at each start-up compatible with the technology features, so not satisfying peak requests. For this reason, in the case of the industrial load profile, withdrawals from diesel generator are neglected because of the characteristic instantaneous high power peaks.

Configuration	$E_{Li-ion}[kWh$	$E_{Lead-gel}[kWh$	$P_{FW}[kW]$ $L_{Kit_{res}}, L_{Kit}$	$E_{FW}[kWh]$ $L_{Kit_{res}}, L_{Kit}$	$P_{FW}[kW]$ $L_{Kit_{ind}}$	$E_{FW}[kWh]$ $L_{Kit_{ind}}$
1 (hybrid)	120	270	50	30	150	22
2	150/142[1]	300/292[1]	-	-	-	-
3 (hybrid)	150	337.5	50	30	150	22
4	180/172[1]	367.5/359.5[1]	-	-	-	-
5 (hybrid)	180	405	50	30	150	22
6	210/202[1]	435/427[1]	-	-	-	-

[1] First equivalent battery capacity values are referred to $L_{Kit_{res}}$ and L_{Kit}, while the second ones to $L_{Kit_{ind}}$.

Table 4-3: Analyzed ESS configurations for Li-ion and Lead-gel technology

Configuration	$FC_{Kit}[kWh/year]$			$FC_{Kit_{res}}[kWh/year]$		
	Li-ion	***Lead-gel***	$P_{aux.gen.}[kW]$	***Li-ion***	***Lead-gel***	$P_{aux.gen.}[kW]$
1 (hybrid)	5402	5415	5	8200	8243	10
2	6845	6860	5	6700	8078	15
3 (hybrid)	5368	5368	5	7923	7934	10
4	6845	6845	5	6460	7764	15
5 (hybrid)	5368	5368	5	7846	7856	10
6	6845	6845	5	6460	7695	15

Table 4-4: Installed power of the auxiliary generator and yearly energy production

Configuration	$E_{batt}[kWh]$	$P_{batt}[kW]$	$FC_{Kit}[\frac{kWh}{year}]$	$FC_{Kit_{res}}[\frac{kWh}{year}$	$P_{aux.gen.}[kW$
7 (L_{Kit})	250	80	6571	-	5
8 ($L_{Kit_{res}}$)	250	110	-	6550	15
9 ($L_{Kit_{ind}}$)	270	210	-	-	-

Table 4-5: Analyzed VRFB configurations

Table4-6 reports the values of useful battery life, estimated for the different configurations by means of the rainflow algorithm, in the case of the L_{Kit} load profile. It can be seen as the useful life of the batteries extends in the presence of the flywheel. The high values of expected lifespan are due to the overestimation provided by the rainflow algorithm (as it does not consider self-discharge phenomena, degradation due to thermal stresses, etc.) and, significantly, to the very flat load profile measured at the Kitobo MG.

Configuration	***Li-ion lifetime***	***Lead-gel lifetime***
1 (hybrid)	21.7	11
2	20	9
3 (hybrid)	-[2]	13
4	29	10
5 (hybrid)	-[2]	17
6	-[2]	13

Configuration	***VRFB lifetime***
7	24[1]

[1] VRFB lifetime reported in [113] is assumed.

[2] In these configurations evaluated expected lifetime exceeds life of the plant.

Table 4-6. Expected battery lifetime - $\boldsymbol{L_{Kit}}$ *load profile*

This is evident from the battery lifespans indicated in Table 4-7 when the more oscillating residential load profile $\boldsymbol{L_{Kit_{res}}}$ is considered. Also, in this case it is evident as flywheel hybridization extends the battery useful life.

Configuration	***Li-ion lifetime***	***Lead-gel lifetime***
1 (hybrid)	14	4.2
2	8.8	2.5
3 (hybrid)	17.2	4.5
4	10.3	2.7
5 (hybrid)	20.5	4.7
6	12	2.8

Configuration	***VRFB lifetime***
7	24[1]

[1] VRFB lifetime reported in [113] is assumed.

Table 4-7: Expected battery lifetime - $\boldsymbol{L_{Kit_{res}}}$ *load profile*

Table4-8 lists battery lifespans resulting in case the $L_{Kit_{ind}}$ industrial load profile is considered. In this case high peak power requests are smoothed through the peak-shaving function of the flywheel. Therefore, thanks to flywheel operation mode, hybrid configurations present a significant increase in battery lifetime.

Configuration	***Li-ion lifetime***	***Lead-gel lifetime***
1 (hybrid)	13.5	4.3
2	4.8	1.6

Configuration	***VRFB lifetime***
9	24[1]

3 (hybrid)	14.1	4.5
4	5.2	1.6
5 (hybrid)	15	4.7
6	5.6	1.7

[1] VRFB lifetime reported in [113] is assumed.

Table 4-8: Expected battery lifetime - $\boldsymbol{L_{Kit_{ind}}}$ *load profile*

Moreover, it can be noted as the advantages achievable in terms of battery life extension increase with the fluctuating character of the considered load profile. To this regard, it is worth of interest to highlight as the battery charge / discharge pattern is modified, for the investigated storage sections, by the presence of the flywheel varying the adopted load profile. As example for each investigated load, the state of charge profile assessed through simulation for the specific Li-ion battery pack in hybrid configuration 1 to the one determined for the corresponding non-hybrid configuration 2. Moreover, it is highlighted that: *i)* the SOC profile of configuration 1 is always more stable than the one related to configuration 2; *ii)* the gap between the hybrid and non-hybrid SOC profiles increases with the fluctuating character of the load, thus with a greater impact of the flywheel on the battery lifespan.

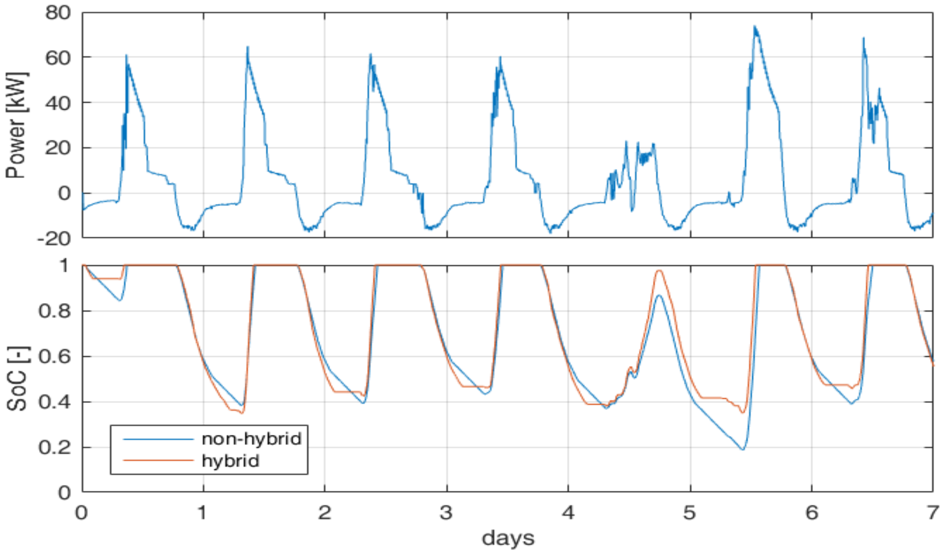

Figure 4-9: SoC trends assessed for configurations 1 (hybrid) and 2 - in reference to the power difference between PV production and $\boldsymbol{L_{Kit}}$ *load profile*

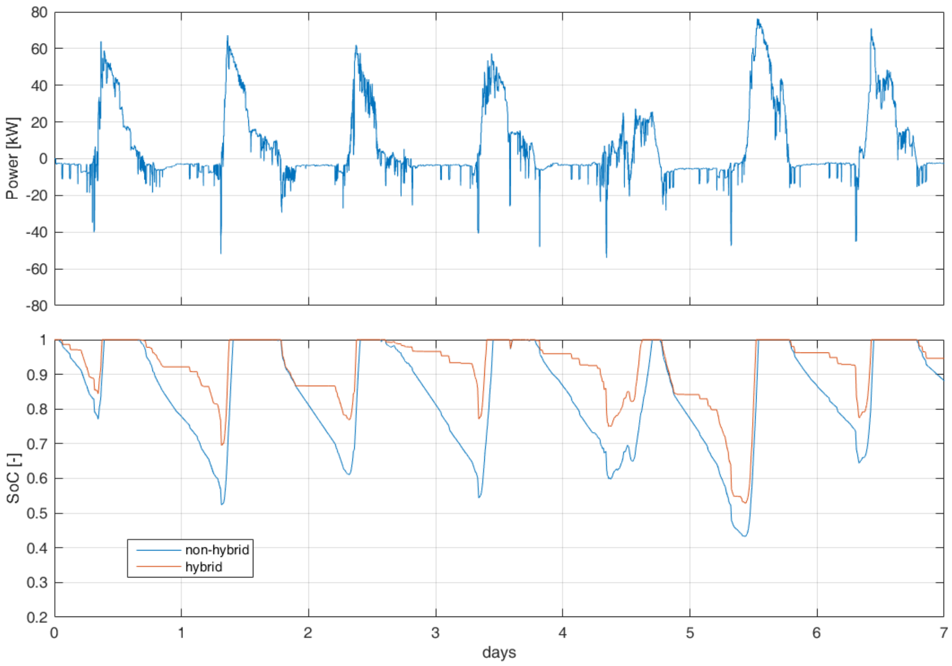

Figure 4-10: SoC trends assessed for configurations 1 (hybrid) and 2 - in reference to the power difference between PV production and $\boldsymbol{L_{Kit_{res}}}$ *load profile*

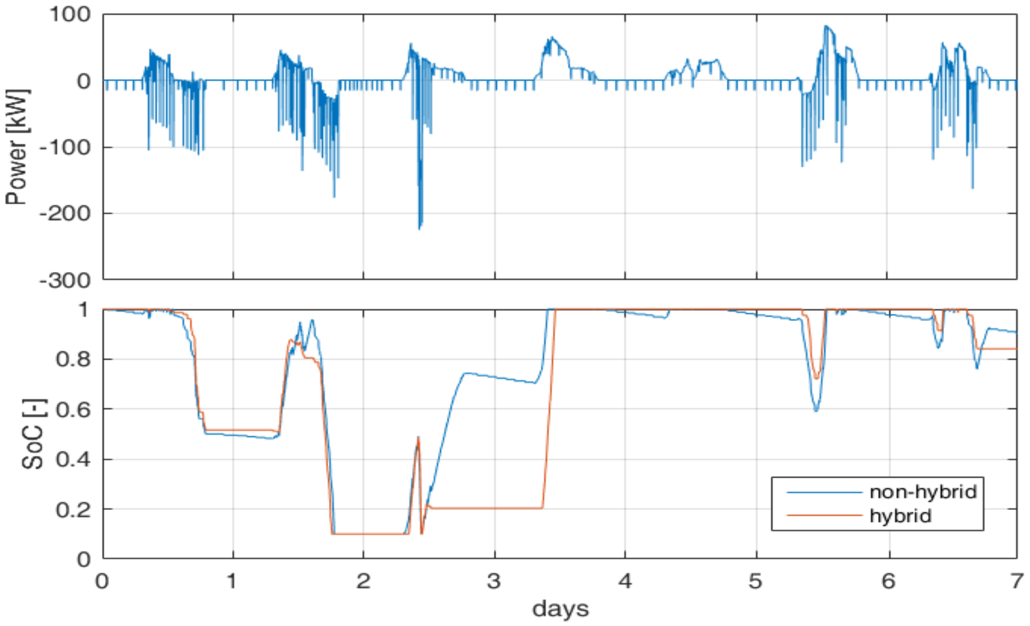

Figure 4-11: SoC trends assessed for configurations 1 (hybrid) and 2 - in reference to the power difference between PV production and $\boldsymbol{L_{Kit_{ind}}}$ *load profile*

4.4.8. LCOE results

Table4-9 reports LCOE results related to all investigated configurations in case the L_{Kit} load profile is considered. Lead-gel batteries exhibit a high value of LCOE, due to a greater replacements number because of short lifetime of this solution.

Moreover, their higher installed capacity (due to the imposed 40% *DoD*) with respect to Li-ion and VRFB technologies implies a higher investment cost nevertheless the lower technology specific cost (€/kWh). The hybrid Li-ion/FESS configuration (#3) seems to be the best solution for the Kitobo microgrid, thanks to the extended lifetime due to the flywheel peak-shaving function towards the battery.

Low LCOE values for hybrid Li-ion/FESS architectures are ascribable to the particular battery management implemented in case of flywheel installation. It implies that oscillations are provided by the flywheel; at the same time, as evident in Table 4-2*: Specifications and costs for the photovoltaic system*

, operating charge and discharge battery powers are strongly limited with respect to the technological thresholds. This results in a significant reduction of battery exploitation to satisfy power requests. Nevertheless, VRFB is a competitive alternative for energy storage in Kitobo, thanks to its long lifetime compared to the other technologies and the possible power and capacity independent sizing. The VRFB results in a LCOE index lower than all not-hybridized Li-ion batteries.

Configuration	***LCOE Li-ion [€/kWh]***	***LCOE Lead-gel [€/kWh]***
1 (hybrid)	0.3567	0.5088
2	0.4182	0.6406
3 (hybrid)	**0.3422**	0.6279
4	0.5313	0.6178
5 (hybrid)	0.3696	0.5794
6	0.4652	0.7807

Configuration	***LCOE VRFB [€/kWh]***
7	0.3715

Table 4-9. LCOE related to the different investigated configurations - $\boldsymbol{L_{Kit}}$ *load profile*

Accordingly to the fluctuating residential ($\boldsymbol{L_{Kit_{res}}}$) and industrial ($\boldsymbol{L_{Kit_{ind}}}$) load profiles, as shown in Table 4-10-Table 4-11*:*, Li-ion-FESS technology (specifically configurations #3 and #1 respectively) seems to be still the best solution among the analyzed ones. Hybridization reduces LCOE costs making of interest flywheel coupling to Li-ion batteries, since it makes this technology competitive with the VRFB one. It is highlighted as VRFB configurations always exhibit performance (in terms of LCOE index) higher than the not-hybridized Li-ion technology. Moving from $\boldsymbol{L_{Kit}\ to\ \ L_{Kit_{res}}}$ and $\boldsymbol{L_{Kit_{ind}}}$, the increasing oscillating behavior of the electric load profile (at parity of annual amount of consumed energy) implies higher LCOE index values. This is due for configurations based on Li-ion and lead-gel technologies to a greater battery exploitation, while for VRFB cases to the higher installed power (from 80 kW up to 210 kW as evident in **Table**). In the case of $\boldsymbol{L_{Kit_{ind}}}$ adoption, also the installed power of the flywheel triples to satisfy the high-power peak requests.

Configuration	***LCOE Li-ion [€/kWh]***	***LCOE Lead-gel [€/kWh]***
1 (hybrid)	0.4029	0.8132
2	0.5085	1.0373
3 (hybrid)	**0.3758**	0.8417
4	0.5052	1.3448
5 (hybrid)	0.4227	1.0059
6	0.5895	1.3927

Configuration	***LCOE VRFB [€/kWh]***
8	0.408

Table 4-10: LCOE related to the different investigated configurations - $L_{Kit_{res}}$ *load profile*

Configuration	***LCOE Li-ion [€/kWh]***	***LCOE Lead-gel [€/kWh]***
1 (hybrid)	**0.4325**	0.75
2	0.624	1.5073
3 (hybrid)	0.4937	0.9106
4	0.6407	1.823
5 (hybrid)	0.4383	1.0865
6	0.7633	2.0665

Configuration	***LCOE VRFB [€/kWh]***
9	0.4752

Table 4-11: LCOE related to the different investigated configurations - $L_{Kit_{ind}}$ *load profile*

Finally, the obtained results, proving that specific hybrid configurations are more convenient with respect to VRFB varying the considered load profile, are analyzed again taking into account a possible battery calendar aging. Specifically, at this regard a maximum battery duration of 15 years is considered. It results that:

- in the case the L_{Kit} load profile, all hybrid configurations result more convenient (lower LCOE) than the VRFB (Table), but for all a duration greater than 15 years is determined. Analyzing configurations “3(hybrid)” and “1(hybrid)”, since characterized by the lower LCOE values, substituting the battery pack at the 15th year, we achieve:
    - for the storage configuration “3(hybrid)”, originally with the lowest LCOE value of 0.3422 €/kWh, the LCOE increases at 0.3713 €/kWh (considering 1 substitution at the 15th year instead of no replacement). It is remarked as this value is still no greater than the one determined for the VRFB (0.3715 €/kWh).
    - For the configuration “1(hybrid)”, the LCOE decreases from 0.3567 €/kWh to 0.3381 €/kWh. This is due to the fact that, at parity of total investment cost (since it is still required 1 replacement), the cost

related to the battery pack substitution is amortized over 15 years instead of 8 years (from year 22nd to year 30th)

- In the case the $\boldsymbol{L_{Kit_{res}}}$ load profile is considered, two configurations have a LCOE index lower than the VRFB and, for the "1(hybrid)" one, a battery duration lower than 15 years is assessed. So the final conclusion about the greater convenience exhibited by hybrid storage section in terms of LCOE with respect to VRFB can be considered not affected by calendar aging.
- Finally, under the $\boldsymbol{L_{Kit_{ind}}}$ load profile, two configurations result more convenient of the VRFB and for both a battery lifespan lower or equal to 15 years is evaluated. Therefore we can consider also this result not affected by calendar aging.

4.4.9. Conclusions

Ensuring financial sustainability is still a challenge because of the relevant costs of energy storage systems. To this regard IRENA has evaluated that only in 2035, thanks to the expected reduction in storage costs, the related LCOE would decrease from the current 0.47-0.92 USD/kWh (0.41-0.81[10] €/kWh) to 0.19-0.35 USD/kWh (0.17-0.31 €/kWh), making renewable MGs potentially competitive with grid extension.

With regards to this scenario, the present study demonstrates, through an organic analysis which considers energy storage technologies usually applied for applications up to hundreds of kW, that technologies hybridization can significantly accelerate this process. Specifically, in the case of Li-ion battery hybridization with mechanical flywheel, the peak-sheaving function of the flywheel towards the battery allows to largely extent the battery lifespan with relevant positive effect on replacement costs.

Consequently, LCOE lowers, from estimations included in the range variation indicated above for conventional solutions, down to about 0.34 €/kWh in case of hybrid configurations implementing SoA devices (Li-ion battery, flywheel) to the real load and PV production profiles measured at the Kitobo MG, considered representative of the East African scenario.

It is also proved that considering more oscillating residential and industrial load profiles, typical of European developed countries, the Li-ion battery/flywheel hybrid configuration still exhibits the lowest LCOE values among the investigated solutions, thus confirming the convenience of this strategy also in case of the expected socio-economic development of the African communities.

It is also remarked as the use of low-speed flywheel technology is suitable for the applications in developing countries and in the framework of renewable MGs, since it

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[10] An exchange €/USD =1,14 was considered

significantly improves the quality of energy sent to users, as well as it is characterized by low needed maintenance and independence from climate conditions typical of the installation.

5. System design

Once selected the energy sources and determined the components sizes, the System Design process should address the optimization of the system functioning. This refers to analyses coping with the real interactions of all the system components (i.e. power sources, storage systems, power electronics, control systems, etc.) during the system working.

This chapter and the following one present the specific architecture of the hybrid Micro-Grid that will be implemented by the project "Sustainable Energy services for Rural DRC", in both generation and distribution sides.
It is worthwhile to mention that this chapter collects the results of the research developments carried out in the final part of the PhD activities. Specifically, the addressed topic allows opening this thesis also to electrical engineering aspects for off-grid power systems which are pivotal when moving from capacity planning and system sizing to real implementations. The proposed approach and relating models still require further developments and analyses in order to be fully recognized as a novel approach which can deeply contributes to improve the design process of off-grid systems. Nevertheless, the early results obtained are worth to be presented since they are quite promising.

5.1. Methods and softwares

System design refers to the identification of the proper mix of energy sources and of the main power system components sizes (i.e. rate powers, storage capacities). This presumes that at least one energy source (typically renewable one) is locally available and relating data and end-uses consumptions data are also available or have been properly estimated. Given this information, planning of energy systems generally refers to the solution of the energy balance between energy sources and consumer loads in order to identify the most suitable system components sizes according to a specific objective function. Different accuracy in the analyses mainly results from the length of the time-step the balance is solved for, the degree of detail in the energy sources data, in the load data, in the mathematical modelling of the system components, and from the approach employed to look for the optimal solution. Usually time-step can vary from monthly- to hour-basis and analyses can be performed throughout a day, a year or several years.
In the following a short selection of energy planning approaches available in the scientific literature is presented. The objective is to highlights the main general features of available planning methods and models in order to highlights the peculiarities of the new procedure described in this chapter:

- ❖ in [121] the capacity planning for a stand-alone PV systems coupled with batteries has been accomplished by employing estimation of daily energy consumption of residential devices and availability of solar radiation. The main components sizing is based on a single daily energy balance, on assumed autonomy days and on simple components modellings;

- in [122] a hybrid Micro-Grid (wind, PV, batteries, diesel) is considered, and different power sources sizes and storage capacity are analysed by means of energy indicators (i.e. renewable production, diesel production, etc.) in order to identify the best option to supply power to a household. Solar, wind data, and technical features of PV panels, wind turbines and batteries are considered. The energy balance is solved for a year and on monthly basis with simple components modelling.
- in [123] different energy systems options (i.e. traditional systems, off-grid systems, on-grid electrification) are compared according to energy indicators which are computed for different consumption scenarios of a rural village. The analyses within a scenario evolve throughout 15 years and are accomplished with daily energy balances. For each system option, data about the whole supplies chains (i.e. a set of energy systems which describe the different steps of energy conversion from primary sources to final uses) are employed. In this case, optimization of the energy supplies chains (both thermal and electrical power) is performed according to the constraints considered in a scenario (i.e. electrification rates, emission limits, renewables penetrations, etc.). Trends of targeted indicators throughout the considered timespan (i.e. TFC by sources and uses, emissions, etc.) are employed to analyze the different solutions;
- in [124] the optimum sizes of different power sources are identified by minimizing the overall life-time systems cost. Thermal and electrical consumptions are met by local available renewable resources thanks to mathematical constraints which work with yearly energy balances and consider simple components modelling.

These few examples have been considered since they allow identifying further specific features of energy planning approaches which can be summarized as follows:

(i) those which particularly address the computation or identification of components sizes in order to properly and precisely match the actual required loads within a *constant* scenario and

(ii) (ii) those which consider the sizing of the system components as parameters or variables which contribute in analyzing an energy scenario in a global (also evolving) context (e.g. [125]). The former ones better address the sizing issue, the latter ones the planning issue;

Also dedicated software tools have been developed to address the issue of energy planning and also in this case they show the same features that have just been recognized for specific methods and models:

- HOMER Energy[11] employs economic variables to perform life-cycle sizing of systems components within a constant scenario.

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[11] https://www.homerenergy.com/products/pro/index.html

- RETScreen[12] employs economic variables to compare different energy systems solutions within evolving scenarios.
- LoadProGen [126] is a tool devoted to formulate daily load profiles, properly describing users' energy consumptions uncertainty (i.e. properly representing the stochastic nature of the load profiles). LoadProGen is based on a bottom-up approach: load profiles are built from users' electric needs and habits that can be estimated or collected by interviews, audits, etc. . To do this, users are divided into different classes so that within each class users have the same type and number of appliances, and they use them with a similar behaviour. Considering the coincidence behaviour of the appliances, the tool defines the switching on instants for each appliance within each class and it obtains a daily load profile for the single user class; repeating this process for each user class, at the end it sums the profiles of the classes to find the total load profile
- Reference Electrification Model (REM) supports large-scale electrification planning and local (smaller-scale) electrification projects [127]. Required information about building locations, solar irradiance, topography, grid extent and reliability, expected consumer demand, fuel costs, and infrastructure costs are input into the model. After running a series of clustering and optimization algorithms specifically designed for electrification planning, REM produces lowest-cost system designs. A user can then tune input parameters to enable sensitivity analyses and derive policy-driven insights or entrepreneurially-driven plans. When building location data not available, we can provide inferences using satellite imagery and deep learning-powered building extraction systems.
- PVsyst is a project design tool for sizing, simulation and data analysis of PV systems. PVsyst is a software package which presents results in the form of a full report, specific graphs and tables, and data can be exported for use in other softwares like Homer Pro

5.2. Appropriate techno-economic approach

At this stage input data only refer to energy consumption patterns and energy resources availability. Moreover, selection and components sizing have been performed by means of indicators and performances parameters which only refer to energy quantities. In this case, these approaches, which can be identified as *Techno-Economic System Sizing*, can work as further analyses following and refining system capacity planning.

A quite common tool which exemplifies Techno-Economic System Sizing is the software HOMER Energy. It performs steady-state energy simulations throughout a year of all the possible system configurations considered by the designer. Beside energy models of the system components, it also embraces capital and O&M costs. These two aspects lead to

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[12] https://www.nrcan.gc.ca/maps-tools-publications/tools/data-analysis-software-modelling/retscreen/7465

perform system design by minimizing the life-time cost given targeted energy performances.
Minimization of life-time costs is often employed as objective function for system sizing since it leads also to minimize the cost of electricity. This is quite appropriate for rural electrification actions. Nevertheless, the typical Techno-Economic System Sizing approaches for off-grid power systems follow a design process which can be considered inappropriate as regards the features of the rural areas.

In the context of RESs, off-grid PV systems are those which probably will contribute the most to rural electrification in the near future. Indeed, solar energy is the most available RES in DCs [128] and, as expected, PV systems are becoming more and more popular in rural areas thanks to a growing market that benefits from an appreciable decreasing of components costs, from the integration of PV technology in rural electrification programs, and from an increasing commitment of multinational players due to the huge potential market.

Sizing techniques are a main research topic when addressing off-grid PV. In fact, sizing off-grid PV systems is not straightforward since it means matching an unpredictable energy source with an uncertain load demand while providing the most favourable conditions in terms of system reliability and cost. Sizing techniques are based on the solving of the balance between solar radiation and load demand, taking into consideration the features of the system components. Differences mainly result from the length of the time-step the balance is solved for, and from the methods employed to look for an optimal solution: a short time-step and a great complexity of the solver are accompanied by a high degree of detail in the solar and load data and in the mathematical modelling of the system components.

Khatib et al. [129] have recently reviewed Techno-Economic System Sizing techniques for off-grid PV systems. In accord with this review it can be stated that, except for the simple intuitive sizing methods, whatever techniques are employed, they ultimately search for an optimal combination of system reliability and cost. In fact, system reliability is proportional to system cost, and hence the greater the reliability the higher will be the cost and vice versa (Figure 5-1 and 5-2Figure **Errore. L'origine riferimento non è stata trovata.**). Therefore, any technique aims at optimizing the system by analysing the relationship between reliability and cost in order to find the best trade-off [130] .

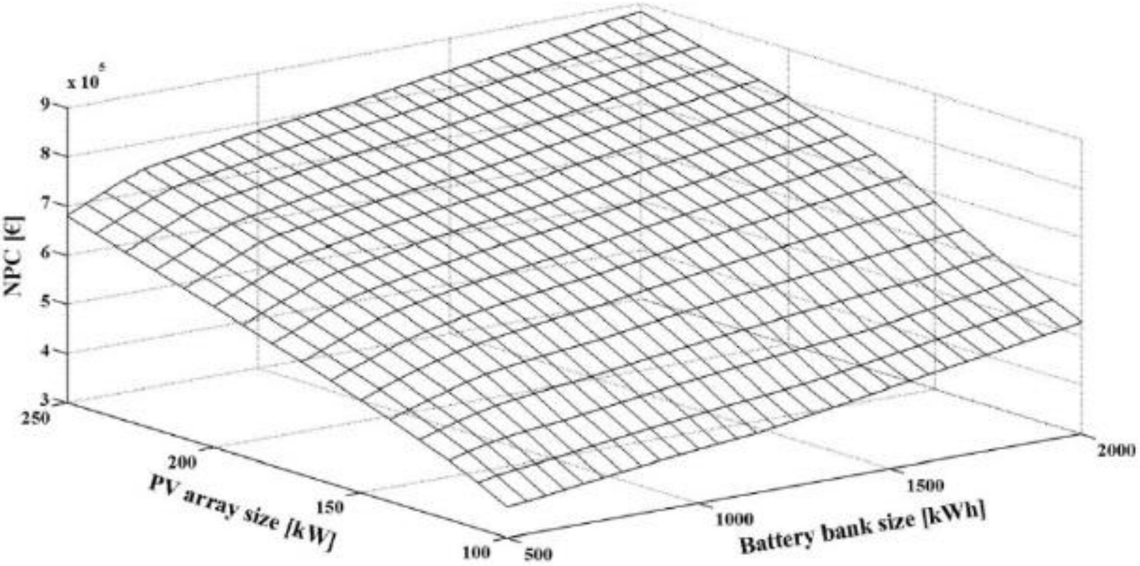


Figure 5-1: Net Present Cost values for different size combinations of solar array and battery [1]

System reliability can be identified with the Loss of Load Probability (LLP), which is the share of the electricity demand not fulfilled by the power system over a certain period [131].

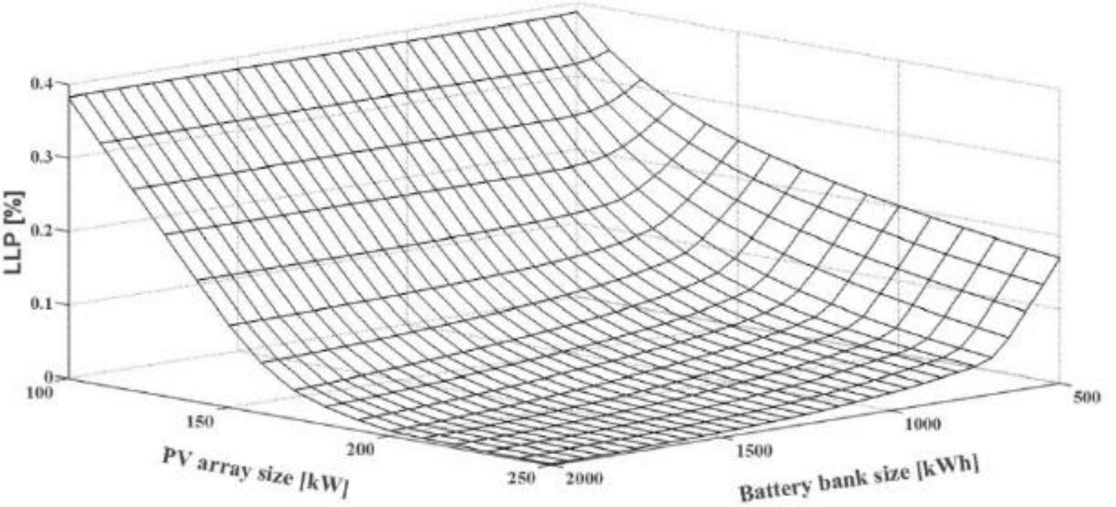


Figure 5-2: Loss of Load Probability values for different size combinations of solar array and battery

As final remarks, it can be state that the main peculiarity of the new sizing methodology is the capability, given an economic value of the electric energy unit at local level, to optimize the off-grid PV system in order to minimize to overall expenditure that targeted consumers face in meeting the electric energy needs. This comprises the cost associated with the renewable energy power plant, but also those associated with compensating the Loss of Load with traditional energy systems.

5.3. Stand-alone PV-battery sizing – *Ref. Paper PA-1 and Projects PR -1,2,3*

Based on the load profile output from the case study presented in Chapter 3 (3 villages in Rwanda, Eastern Province), a PV-Battery mini-grid plant could be sized. HOMER Pro Microgrid Analysis Tool 3.11.6 [132] is the simulation tool adopted for the optimization of the plant. This simulation tool assists in the planning and design of renewable energy based multi-source generation systems.

Power plant configuration, life-cycle cost (excluding dismantling) and the energy and economic comparison were carried out using the two main operations of the software: Simulation and Optimization.
In the Simulation area, HOMER Pro determines technical performance, feasibility and life-cycle cost of a system for every hour of the year.
In the Optimization section HOMER displays each feasible system and its configuration in a search space sorted by the least cost depending on the total net present cost. In this way, we can find the optimal configuration which satisfies the constraints imposed in the model. The description of economic output is set out in the following paragraph[133].

Solar irradiation has been considered as the only renewable source available. The solar irradiation and surface annual solar radiation data have been obtained from an average of 20 years of NASA data, which interpolate data of available weather stations to infer specific location [134]. The average annual of daily solar radiation in this region is 5.02 kWh/m2. The average clearness index is 0.50. Based on these data, assumptions for the different months are represented in Figure 5-3.

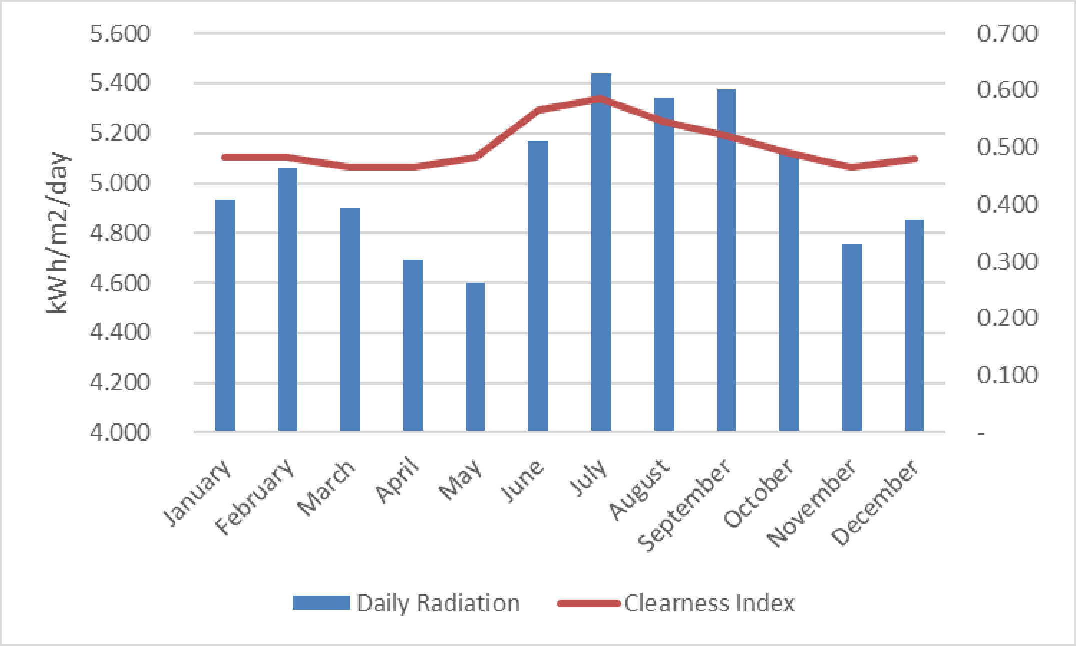


Figure 5-3: Assumed average daily solar irradiation and clearness index for the plant location.

It was assumed to size a hybrid mini-grid composed by a PV plant, a Battery Energy Storage System (BESS) and a diesel generator as in Figure .

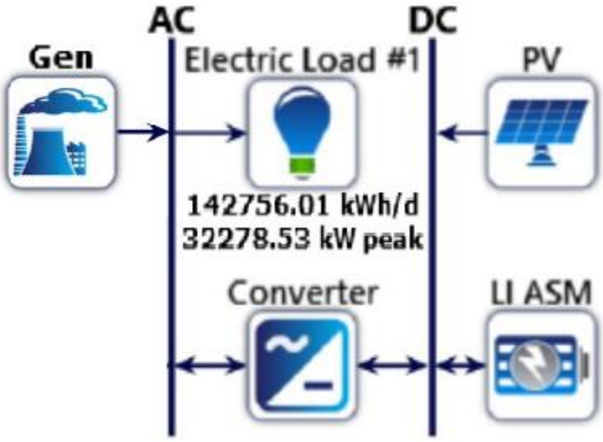


Figure 5-4: Scheme of the Hybrid mini-grid. Source: Own elaboration

The considered PV system and replacement cost is 2,200 $/kWp. The O & M cost is set to 10 $/kWp/year. The solar module type is a polycrystalline PV panel with efficiency 15%. Costs include purchase, transportation and installation of modules, all balance of system components like cables and structures (excluding the inverter) and the security system.
The cost of the inverter is set to be 300 $/kW, and the efficiency is assumed to be 95%.
For the BESS the authors consider a Li-Ion battery, with round trip losses of 8%, an estimated cost of 600 $/kWh, an O & M cost of 10 $/kWh/year, and a connection on the DC bus [133].
The cost of the diesel Generator is set to 500 $/kW and the fuel price is set to 1.4 $/l, data collected during the site visit.
The optimal configuration proposed by Homer is formed by 29.4 kWp PV generator, with a 15 kW converter, a 110 kWh BESS, and a 36 kW diesel generator.
The PV total energy production would be 59.3% of the total annually energy needs, with a Levelized Cost of Energy of 0.447$/kWh (382.53 RWF/kWh) with a project lifetime of 25 years, it should be noticed that this value, excluding bar and barber shops, is under the Average cost of electricity paid by villagers.

5.4. Multi-source generation modelling – *Ref. Project PR-4*

5.4.1. Project description

"Sustainable Energy services for rural DRC" is an international cooperation projects promoted by the Italian Ngo AVSI Foundation and Democratic Republic of Congo's Ministry of Energy and Environment Conservation.

The initiative is aimed at proving the environmental and economic viability offered by off-grid solutions to sustainably promote access to electric power generation from renewable energy sources and to achieve the electrification targets in DRC

Over the second semester of 2018 AVSI and MECNDD surveyed different locations in eastern Congo to identify a viable site where to run a pilot intervention aimed at providing access to clean, reliable and affordable electricity, through a Stand-alone Smart mini-grid with renewable energy generation, and at promoting community development through productive use of electricity. Based on these criteria the island of Idjwi in Lake Kivu was identified as feasible location since it is not in the national electrification plan for the next 10 years, it is safe, it has a lively economic activity and a number of densely populated towns/villages. Moreover, according to the ATLAS, a potential of 400 kWh from hydropower are available on the island.

The project foresees to provide access to electricity to the entire target communities of Kashara and Kimomo, on the island of Idjwi.

In order to amplify the impact of energy access in the community, to increase the community resilience to climate change and improve the economic sustainability of the action, as part of the strategy the project will be based on the virtuous energy consumption cycle, with a focus on the productive use of electricity. The model will ensure the project's sustainability by actively supporting productive demand and replacing CO2 intensive supply. The success of this project will strongly impact local productivity, contributing to the reduction of poverty as well as population's vulnerability to climate change, for a real sustainable economic development of the local community.

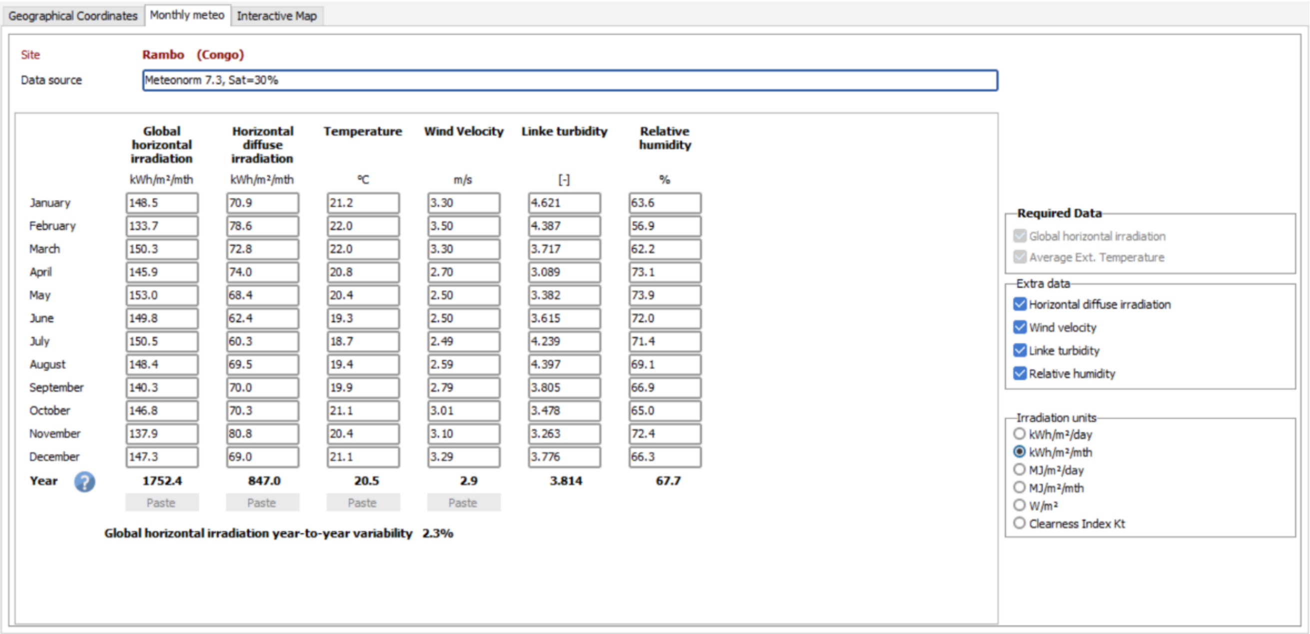
The author's role within this project was the basic engineering of the electric systems, including load profiling, generation plant and distribution grid sizing.

"PVsyst" is the software used to perform this energy flow simulation. This software is an energy modelling tool that helps in analysing how much solar energy can be harvested into an electrical energy from a site or location.

5.4.2. Data input and PV simulation

The first step of the procedure was the identification of the installation site. Once the location was defined it has been possible to access different databases (e.g. Meteonorm 7.3, NASA-SSE, PVGIS TMY) to obtain the most accurate meteorological data available in a specific place.

In our location the database “Meteonorm 7.3” results to have the most accurate data to simulate the behaviour of the system with different configuration to demonstrate the relevance of a back-up system in a stand-alone mini-grid. A summary of the main meteorological data is shown in Figure 5-5



Site: Rambo (Congo)

Data source: Meteonorm 7.3, Sat=30%

	Global horizontal irradiation kWh/m²/mth	Horizontal diffuse irradiation kWh/m²/mth	Temperature °C	Wind Velocity m/s	Linke turbidity [-]	Relative humidity %
January	148.5	70.9	21.2	3.30	4.621	63.6
February	133.7	78.6	22.0	3.50	4.387	56.9
March	150.3	72.8	22.0	3.30	3.717	62.2
April	145.9	74.0	20.8	2.70	3.089	73.1
May	153.0	68.4	20.4	2.50	3.382	73.9
June	149.8	62.4	19.3	2.50	3.615	72.0
July	150.5	60.3	18.7	2.49	4.239	71.4
August	148.4	69.5	19.4	2.59	4.397	69.1
September	140.3	70.0	19.9	2.79	3.805	66.9
October	146.8	70.3	21.1	3.01	3.478	65.0
November	137.9	80.8	20.4	3.10	3.263	72.4
December	147.3	69.0	21.1	3.29	3.776	66.3
Year	**1752.4**	**847.0**	**20.5**	**2.9**	**3.814**	**67.7**

Global horizontal irradiation year-to-year variability 2.3%

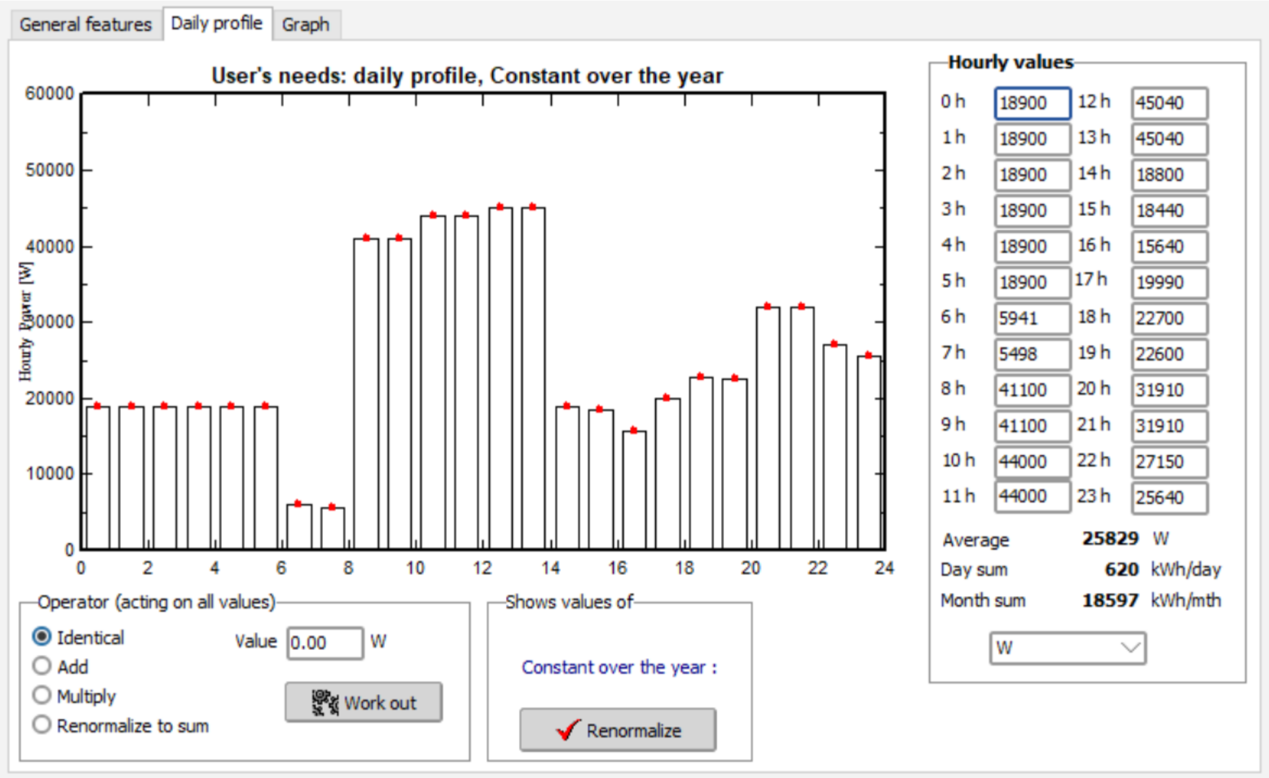
Required Data
- ☑ Global horizontal irradiation
- ☑ Average Ext. Temperature

Extra data
- ☑ Horizontal diffuse irradiation
- ☑ Wind velocity
- ☑ Linke turbidity
- ☑ Relative humidity

Irradiation units
- ○ kWh/m²/day
- ● kWh/m²/mth
- ○ MJ/m²/day
- ○ MJ/m²/mth
- ○ W/m²
- ○ Clearness Index Kt

Figure 5-5: Idjwi island monthly irradiation data

Following step was the energy demand forecast: a constant daily profile has been assumed for the simulation, as output from the energy need assessment, since only small seasonal effects have been reflected on energy usage.



Hourly values

0 h	18900	12 h	45040
1 h	18900	13 h	45040
2 h	18900	14 h	18800
3 h	18900	15 h	18440
4 h	18900	16 h	15640
5 h	18900	17 h	19990
6 h	5941	18 h	22700
7 h	5498	19 h	22600
8 h	41100	20 h	31910
9 h	41100	21 h	31910
10 h	44000	22 h	27150
11 h	44000	23 h	25640

Average	**25829**	W
Day sum	**620**	kWh/day
Month sum	**18597**	kWh/mth

W

Operator (acting on all values)

● Identical
○ Add
○ Multiply
○ Renormalize to sum

Value 0.00 W

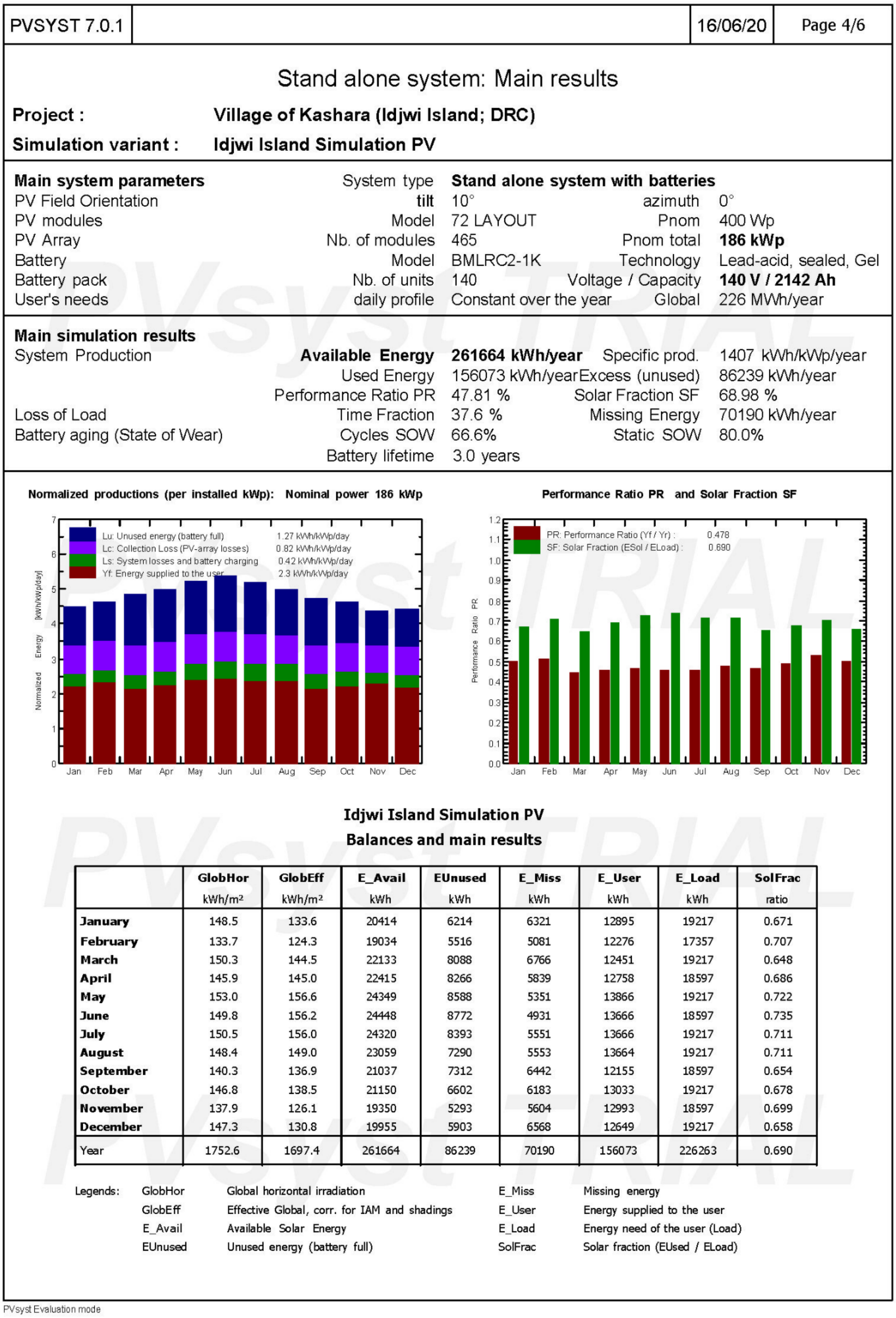
Shows values of

Constant over the year :

Figure 5-6: Daily load profile used for simulations.

The software allows to build-up the photovoltaic system configuration, a large database with different models of PV modules, inverters, batteries is available in order to simulate precisely the behaviour and the compliance of main components. With this tool is possible to optimize the PV layout (e.g. Orientation, String distribution) to meet the requested input parameter of the chosen power electronic devices.

The first simulation has been performed considering an array nominal power (STC) of 186 kWp and a Lead-Acid BESS with a stored energy capacity of 240 kWh.



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Stand alone system: Main results

Project : **Village of Kashara (Idjwi Island; DRC)**

Simulation variant : **Idjwi Island Simulation PV**

Main system parameters	System type	**Stand alone system with batteries**		
PV Field Orientation	tilt	10°	azimuth	0°
PV modules	Model	72 LAYOUT	Pnom	400 Wp
PV Array	Nb. of modules	465	Pnom total	**186 kWp**
Battery	Model	BMLRC2-1K	Technology	Lead-acid, sealed, Gel
Battery pack	Nb. of units	140	Voltage / Capacity	**140 V / 2142 Ah**
User's needs	daily profile	Constant over the year	Global	226 MWh/year

Main simulation results				
System Production	**Available Energy**	**261664 kWh/year**	Specific prod.	1407 kWh/kWp/year
	Used Energy	156073 kWh/year	Excess (unused)	86239 kWh/year
	Performance Ratio PR	47.81 %	Solar Fraction SF	68.98 %
Loss of Load	Time Fraction	37.6 %	Missing Energy	70190 kWh/year
Battery aging (State of Wear)	Cycles SOW	66.6%	Static SOW	80.0%
	Battery lifetime	3.0 years		

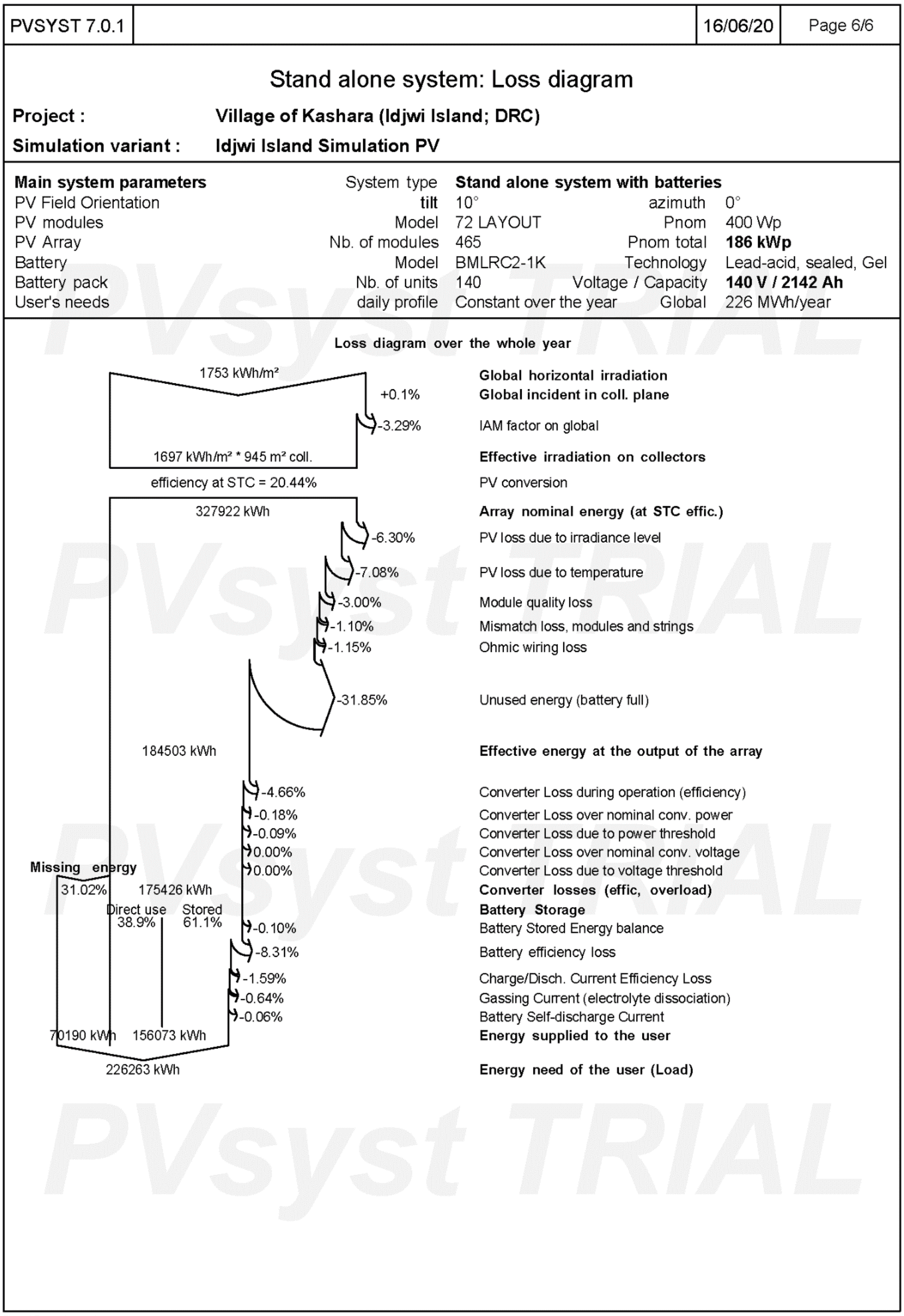
Idjwi Island Simulation PV

Balances and main results

	GlobHor kWh/m²	GlobEff kWh/m²	E_Avail kWh	EUnused kWh	E_Miss kWh	E_User kWh	E_Load kWh	SolFrac ratio
January	148.5	133.6	20414	6214	6321	12895	19217	0.671
February	133.7	124.3	19034	5516	5081	12276	17357	0.707
March	150.3	144.5	22133	8088	6766	12451	19217	0.648
April	145.9	145.0	22415	8266	5839	12758	18597	0.686
May	153.0	156.6	24349	8588	5351	13866	19217	0.722
June	149.8	156.2	24448	8772	4931	13666	18597	0.735
July	150.5	156.0	24320	8393	5551	13666	19217	0.711
August	148.4	149.0	23059	7290	5553	13664	19217	0.711
September	140.3	136.9	21037	7312	6442	12155	18597	0.654
October	146.8	138.5	21150	6602	6183	13033	19217	0.678
November	137.9	126.1	19350	5293	5604	12993	18597	0.699
December	147.3	130.8	19955	5903	6568	12649	19217	0.658
Year	1752.6	1697.4	261664	86239	70190	156073	226263	0.690

Legends:				
	GlobHor	Global horizontal irradiation	E_Miss	Missing energy
	GlobEff	Effective Global, corr. for IAM and shadings	E_User	Energy supplied to the user
	E_Avail	Available Solar Energy	E_Load	Energy need of the user (Load)
	EUnused	Unused energy (battery full)	SolFrac	Solar fraction (EUsed / ELoad)

Figure 5-7: First simulation output



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Stand alone system: Loss diagram

Project : **Village of Kashara (Idjwi Island; DRC)**

Simulation variant : **Idjwi Island Simulation PV**

Main system parameters	System type	**Stand alone system with batteries**		
PV Field Orientation	**tilt**	10°	azimuth	0°
PV modules	Model	72 LAYOUT	Pnom	400 Wp
PV Array	Nb. of modules	465	Pnom total	**186 kWp**
Battery	Model	BMLRC2-1K	Technology	Lead-acid, sealed, Gel
Battery pack	Nb. of units	140	Voltage / Capacity	**140 V / 2142 Ah**
User's needs	daily profile	Constant over the year	Global	226 MWh/year

Loss diagram over the whole year

Figure 5-8: First simulation Loss diagram

From the loss diagram over the whole year is easy to verify that this configuration is not able to meet the community energy demand, even though the sizing procedure has been performed considering the whole daily load curve.

This is caused by mismatch between the load curve and the production curve of the generation system, the peak shaving operation performed by the management system is not enough to deal with this mismatch, resulting in a 31.85% of unused energy incurring during BESS 100% State of Charge (SOC); consequently, a huge amount of energy is missing, 31.02% of the total energy needs of the community, probably due to long rainy season or cloudy conditions.

These inefficiencies affect the system's Performance Ratio (PR) which has a very low average annual value of 0.478. The PR is a measure of the quality of the system, this parameter is independent of location and represents the ratio between the actual and theoretical energy output of a PV plant.

5.4.3. Hydropower integration analysis

A multi-source configuration of the mini-grid with a combined production of both photovoltaic and hydroelectric has been investigated to increase system global performances: mini-hydropower is basically constant throughout the day, with seasonal excursion in terms of energy production and in the reference village, hydropower potential has been assessed having an output of 11.7 kW.

$$E_{Hydro,daily} = P_{Hydro,nominal} * 24h = 280.8\ kWh$$

$$E_{PV,daily} = E_{Load,Daily} - E_{Hydro,daily} = 620 - 280.8 = 339.2\ kWh$$

Equation 5-1, 5-2

Assuming a PV equivalent hours equal to 4.2 and a system efficiency of 0.8 the reduced Nominal Power of the photovoltaic system needed to meet the community demand results to be:

$$P_{NET,2} = \frac{E_{PV,daily}\left[\frac{kWh}{d}\right]}{PV_{OUT}\left[\frac{kWh}{kWp * d}\right]} = 80.76\ [kWp]$$

$$P_{Nominal,2} = \frac{P_{Net}\ [\,kWp]}{PV_{Efficiency}} = 100.95\ [kWp]$$

Equation 5-3, 5-4

However, the presence of the hydroelectric system, which unlike the photovoltaic system is characterized by a 24/7 power production, allows to reduce the size of the BESS.

The energy produced by the hydroelectric system during the night is equal to:

$$E_{Hydro,night} = P_{Hydro}[kW] * 12\ [h] = 140.4\ kWh$$

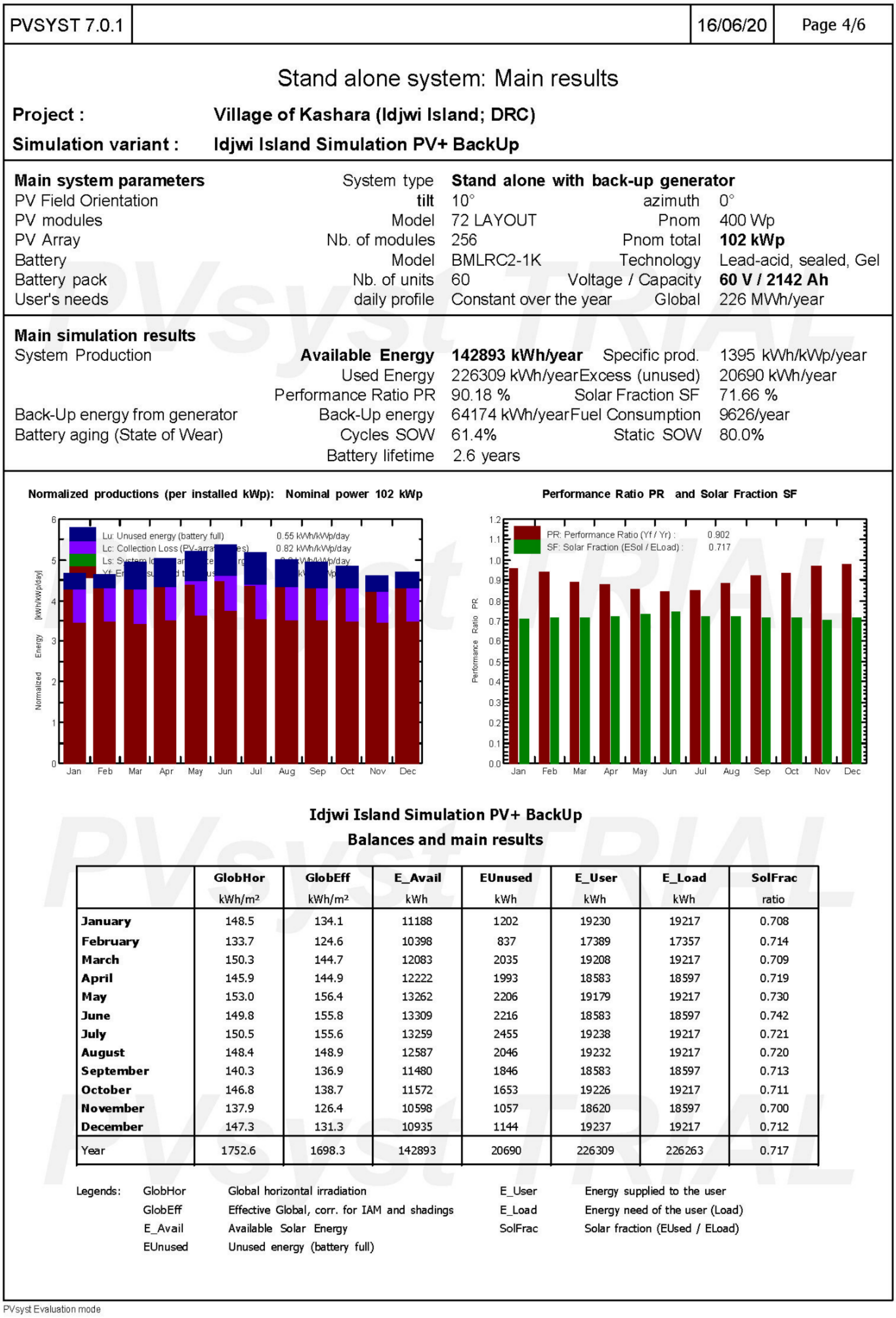
Equation 5-5

Decreasing the BESS total capacity to:

$$E_{ESS} = E_{Load,night}[kWh] - E_{Hydro,night}[kWh] = 240 - 140.4 = 99.6\ kWh$$

Equation 5-6

The average minimum power demand of the community during the night is equal to 5.49 kW according to our previsions, a lower value than the potential production of the hydroelectric system, estimated at 11.7 kW. This situation may represent an inefficiency in the case in which the BESS is completely full; in this condition the exceeding energy must be dissipated though dump loads; however, this condition only occurs between 5 and 6 a.m. or rather the last hours of night in which the BESS will be able to store energy. This energy will be used during the first hours of the morning when the community requires the maximum amount of energy. This configuration therefore allows a complete exploitation of the power generated by the hydroelectric system (Since PVsyst is not able to simulate the presence of a hydroelectric system, the second simulation has been performed assuming a diesel generator as a back-up component with the same behaviour of a hydroelectric system).



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Stand alone system: Main results

Project : **Village of Kashara (Idjwi Island; DRC)**

Simulation variant : **Idjwi Island Simulation PV+ BackUp**

Main system parameters	System type	**Stand alone with back-up generator**		
PV Field Orientation	tilt	10°	azimuth	0°
PV modules	Model	72 LAYOUT	Pnom	400 Wp
PV Array	Nb. of modules	256	Pnom total	**102 kWp**
Battery	Model	BMLRC2-1K	Technology	Lead-acid, sealed, Gel
Battery pack	Nb. of units	60	Voltage / Capacity	**60 V / 2142 Ah**
User's needs	daily profile	Constant over the year	Global	226 MWh/year

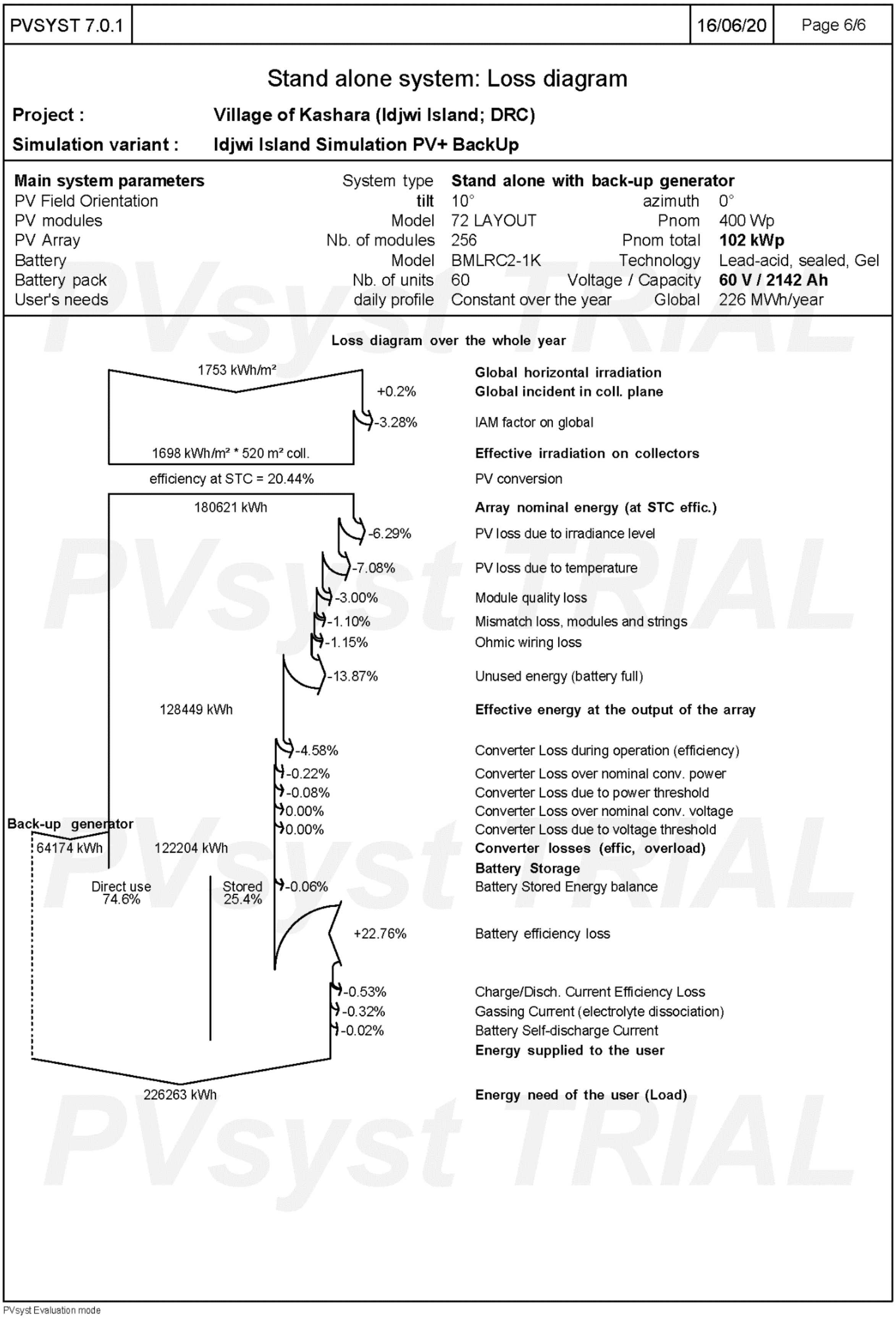
Main simulation results				
System Production	**Available Energy**	**142893 kWh/year**	Specific prod.	1395 kWh/kWp/year
	Used Energy	226309 kWh/year	Excess (unused)	20690 kWh/year
	Performance Ratio PR	90.18 %	Solar Fraction SF	71.66 %
Back-Up energy from generator	Back-Up energy	64174 kWh/year	Fuel Consumption	9626/year
Battery aging (State of Wear)	Cycles SOW	61.4%	Static SOW	80.0%
	Battery lifetime	2.6 years		

Idjwi Island Simulation PV+ BackUp
Balances and main results

	GlobHor kWh/m²	GlobEff kWh/m²	E_Avail kWh	EUnused kWh	E_User kWh	E_Load kWh	SolFrac ratio
January	148.5	134.1	11188	1202	19230	19217	0.708
February	133.7	124.6	10398	837	17389	17357	0.714
March	150.3	144.7	12083	2035	19208	19217	0.709
April	145.9	144.9	12222	1993	18583	18597	0.719
May	153.0	156.4	13262	2206	19179	19217	0.730
June	149.8	155.8	13309	2216	18583	18597	0.742
July	150.5	155.6	13259	2455	19238	19217	0.721
August	148.4	148.9	12587	2046	19232	19217	0.720
September	140.3	136.9	11480	1846	18583	18597	0.713
October	146.8	138.7	11572	1653	19226	19217	0.711
November	137.9	126.4	10598	1057	18620	18597	0.700
December	147.3	131.3	10935	1144	19237	19217	0.712
Year	1752.6	1698.3	142893	20690	226309	226263	0.717

Legends:				
	GlobHor	Global horizontal irradiation	E_User	Energy supplied to the user
	GlobEff	Effective Global, corr. for IAM and shadings	E_Load	Energy need of the user (Load)
	E_Avail	Available Solar Energy	SolFrac	Solar fraction (EUsed / ELoad)
	EUnused	Unused energy (battery full)		

Figure 5-9: Second simulation output



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Stand alone system: Loss diagram

Project : **Village of Kashara (Idjwi Island; DRC)**

Simulation variant : **Idjwi Island Simulation PV+ BackUp**

Main system parameters	System type	**Stand alone with back-up generator**		
PV Field Orientation	**tilt**	10°	azimuth	0°
PV modules	Model	72 LAYOUT	Pnom	400 Wp
PV Array	Nb. of modules	256	Pnom total	**102 kWp**
Battery	Model	BMLRC2-1K	Technology	Lead-acid, sealed, Gel
Battery pack	Nb. of units	60	Voltage / Capacity	**60 V / 2142 Ah**
User's needs	daily profile	Constant over the year	Global	226 MWh/year

Loss diagram over the whole year

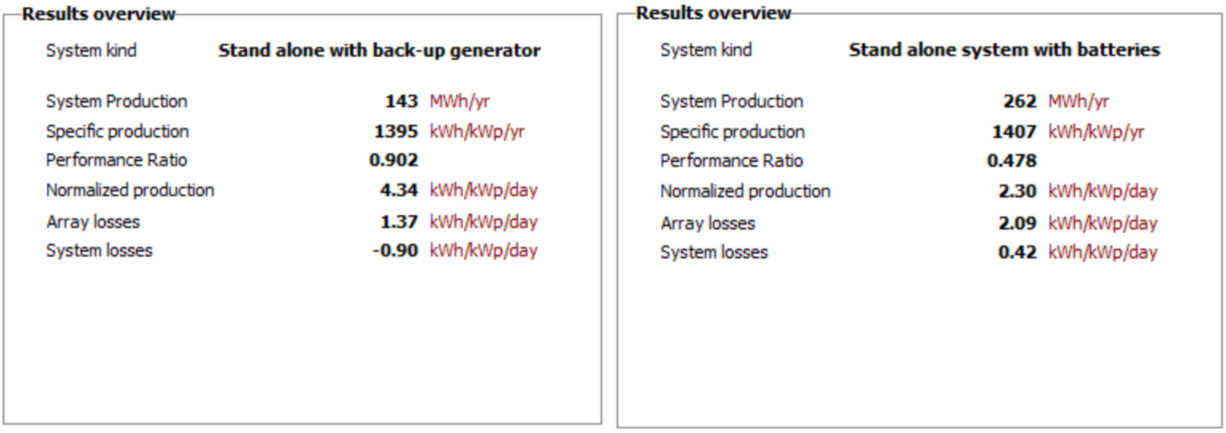
Figure 5-10 Second simulation Loss Diagram

5.4.4. Results

The fundamental role of a back-up element is clear visible, with the PR of the photovoltaic system rising up to an excellent value of 0.902 and the unused energy decreased from 31.85% to 13.87%.

By means of a small back-up element of 10 kW, the size of the PV capacity strongly reduces and the generation system can meet the whole community demand increasing drastically the quality of the system by reducing strongly the cost.

Here a comparison of the main results of the simulations.



Results overview

System kind	**Stand alone with back-up generator**	
System Production	**143**	MWh/yr
Specific production	**1395**	kWh/kWp/yr
Performance Ratio	**0.902**	
Normalized production	**4.34**	kWh/kWp/day
Array losses	**1.37**	kWh/kWp/day
System losses	**-0.90**	kWh/kWp/day

Results overview

System kind	**Stand alone system with batteries**	
System Production	**262**	MWh/yr
Specific production	**1407**	kWh/kWp/yr
Performance Ratio	**0.478**	
Normalized production	**2.30**	kWh/kWp/day
Array losses	**2.09**	kWh/kWp/day
System losses	**0.42**	kWh/kWp/day

Table 5-1: Simulation outputs comparison

6. Distribution

Systematic distribution planning is a key success factor of any electrification programme on local or national scale. The process includes the collection and analysis of consumption data or load estimation through the Energy Need Assessment tool, information on unelectrified areas, migration to a GIS platform where possible, and carrying out network analyses to determine the most appropriate technology to be used for network development.

For many unserved rural areas in sub-Saharan Africa, it is technically not possible to provide the needed service by extending MV national grid, due to the large distances involved. Consequently, it would also not be cost effective to extend the transmission system and build grid substations using traditional standards. However, various cheap options are available to enable grid extensions to reach such locations at the required technical standards and at acceptable cost.

Another key aspect is that reliability levels needed should not be confused with system voltage. In fact, the reliability of a low cost transmission extension will be greater than the alternative of MV extensions over long distances. Hence, serious consideration should be given wherever possible for low cost transmission extension to feed areas not feasible by MV extensions.

6.1. Off-grid vs. on-grid electrification

In planning rural electrification development, an important consideration is the decision between the overall technology options of:

- National main grid extension;
- Local mini-grids;
- Stand-alone solutions such as Solar Home Systems.

The appropriateness of each of these options for a particular area will depend on a number of factors: proximity to grid supply, availability of local generation resources, load density, expected development of productive use and anchor loads, etc. The growing demand to serve the rural populations can be met from a variety of resources, both grid and off-grid.

In some areas, where the load densities are extremely low and motive power for machines is not yet required, Solar Home Systems (SHS) will probably be the best solution. For larger communities and in areas where renewable energy sources such as hydroelectric and wind power are available, renewable or hybrid mini-grids may be the optimal choice for electrification.

In areas with larger electricity demands and close distance to the grid however, the technology of choice would be extensions from the national grid. Grid-based alternatives have the singular advantage of being able to meet additional loads, particularly linked to industrial, irrigation and agricultural demands, which normally develop over time.

Such options can be complementary to each other and should not be treated as competing alternatives. In many cases the first stage of electrification of an area is provided by a low power resource, e.g. Solar Home Systems. As demand for electrical power grows, the need may arise for an upgrade to a system that can provide more power.

6.2. Rural Technologies

When a grid based development is considered to supply a particular area, a further consideration is whether to use standards appropriate for urban or rural areas.

In urban areas, both the economic value of power outages is high. Alternative stand-by diesel generation plants with high capital and operating costs are employed in many establishments, such as commercial buildings, industry and office complexes. The costs of such alternative or stand-by supplies can be minimized with higher reliability of the grid supply. Even where such alternative stand-by arrangements are not used, the enhanced willingness to pay for lower outages in urban areas justifies designs at higher reliability levels. Increased reliability requirements in urban areas should thus be met with suitable network designs, which enable greater switching flexibility by providing a number of alternative supply options. This also requires enhanced conductor sizes to meet higher load carrying capabilities when network changes are made.

For rural networks, such stringent conditions do not need to be adhered to, enabling simpler network designs at lower cost [135]. Rural networks have significantly lower load densities than in urban areas (usually measured in kW per unit area or kW per km of line). The lower loads on the distributors enable the designer to choose from a greater array of options, thus allowing lower cost technologies to be used.

Compared to urban areas, requirements for reliability of supply are also usually lower in rural areas; as well as the willingness to pay for increased reliability of supply. Taking into account these considerations, substantial costs savings can be achieved by applying standards appropriate for rural areas – enabling increased electricity access rates with the same budget.

Significant advances have already been made in developing and applying alternative low cost technologies for rural electrification in several countries, listed in the following paragraphs.

6.2.1. Single Phase Reticulation

In many sub-Saharan African countries, network expansion to rural areas was the direct application of the technology used for the urban loads. These consist of MV networks (usually 33 kV / 11 kV), large capacity transformers (50 kVA to 500 kVA), and long LV lines often extending to over 2 km in length. While single phase LV lines are only sometimes used for by-lanes, the main LV network is usually of three phase construction.

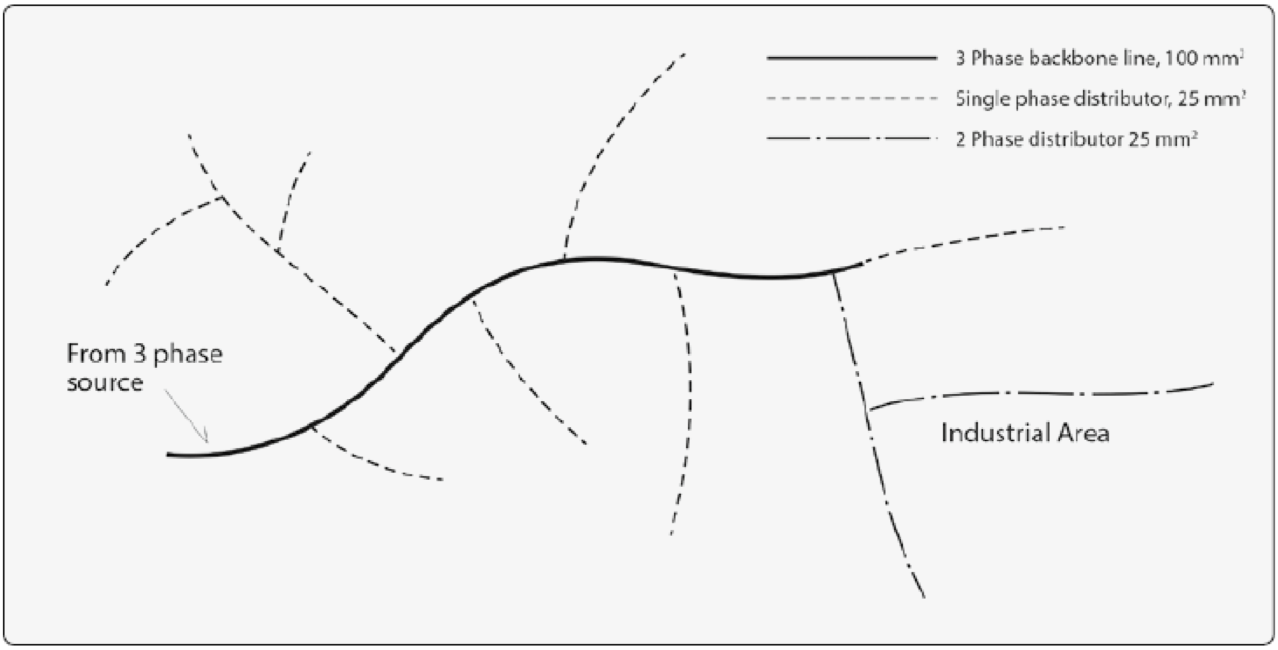
The use of single phase lines at MV can however result in substantial cost reductions, as applied in the USA and successfully adopted in several countries. The main features of such power systems include:

- three phase, four wire MV lines which serve as the system backbone,
- single phase to neutral MV laterals that extensively cover the supply area,
- single phase to neutral small capacity transformers to feed small clusters of consumers, and
- very limited or hardly any LV lines.


Figure 6-1: Single phase transformer used in Bangladesh

The main function of this system is to cover the supply area with an extensive network of single phase MV distributors bringing the MV power virtually to the doorstep of the consumer. These single phase lines are fed from the three phase backbone system which carries the combined loads of the distributors. The single phase transformers are of low capacity from 5 kVA to 37.5 kVA and constructed with cylindrical steel sheets and thus considerably cheaper to manufacture than the rectangular frame transformers used for three phase transformers. Single phase transformers are used both on the three phase and single phase lines.

When three phase supply is needed at a three phase line, three single phase transformers are symmetrically mounted on a single, often wooden, pole. The service connection is often directly from the transformer pole or within a couple of additional poles. Thus, there is a larger number of transformers along the MV line. There is no continuous LV coverage and gaps with no houses are left without any LV coverage. This practice substantially reduces the LV network; power is transferred to the LV system in small quantities close to the consumer. The ratings of the LV conductors are therefore much smaller.



Note: The industrial area is fed off a phase-phase line which allows three phase LV supply to be provided via open wye – open delta transformations.

Figure 6-2: example of a network with backbone line and lateral arrangement. Source: ESMAP

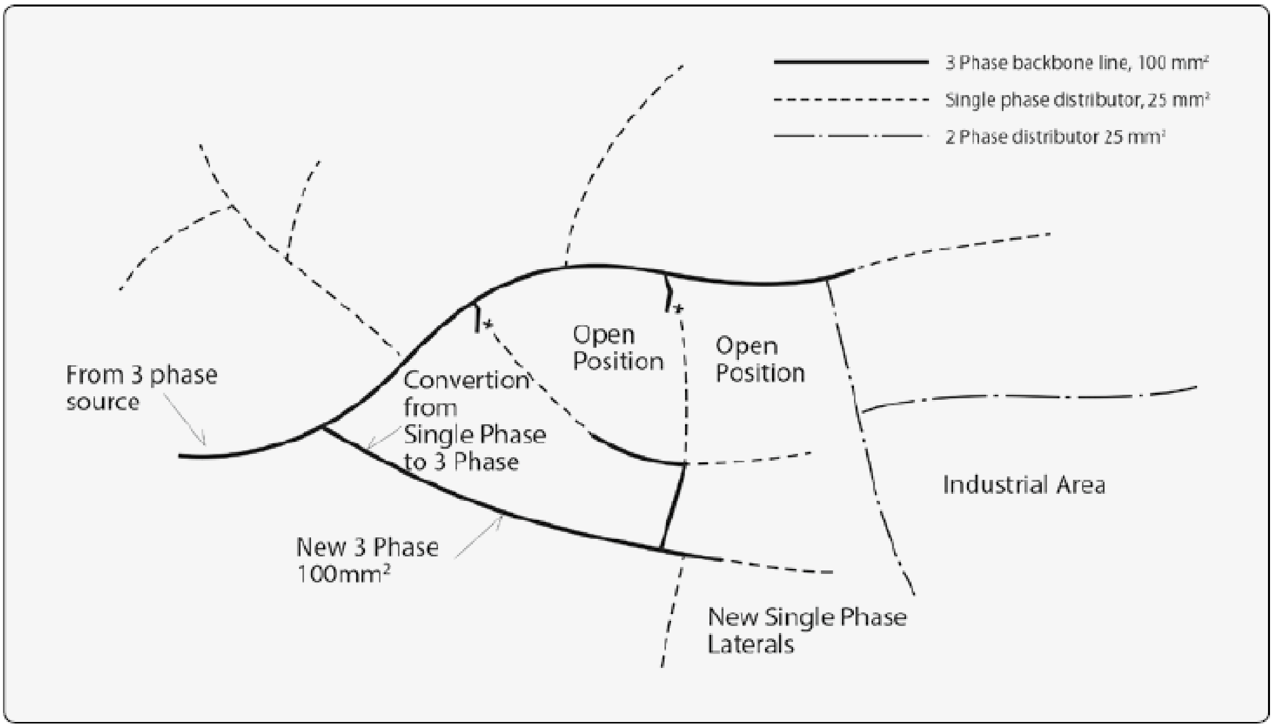


Figure 6-3: Subsequent augmentation of the network to meet additional distribution loads. Source: ESMAP

Figure 6-2: gives an example of a network with backbone line and lateral arrangement. In Figure 6-3 additions are made to this network to meet additional loads. The strategy adopted is to convert a single phase portion to a three phase backbone line thereby changing the manner of feeding the laterals, thus enabling a greater power flow.

<u>Advantages</u>

The reduction in cost of using single phase4 at MV compared to traditional three phase settings arises due to (i) the lower cost of MV reticulation and (ii) the elimination of the extensive LV line coverage: The cost of a four wire (three phase) LV line is of the same order as that of a three phase MV line. Depending on the terrain, unit costs of MV lines is sometimes even cheaper than an LV line due to the longer spans possible, resulting in lesser number of poles and pole top hardware (which is more costly for MV).

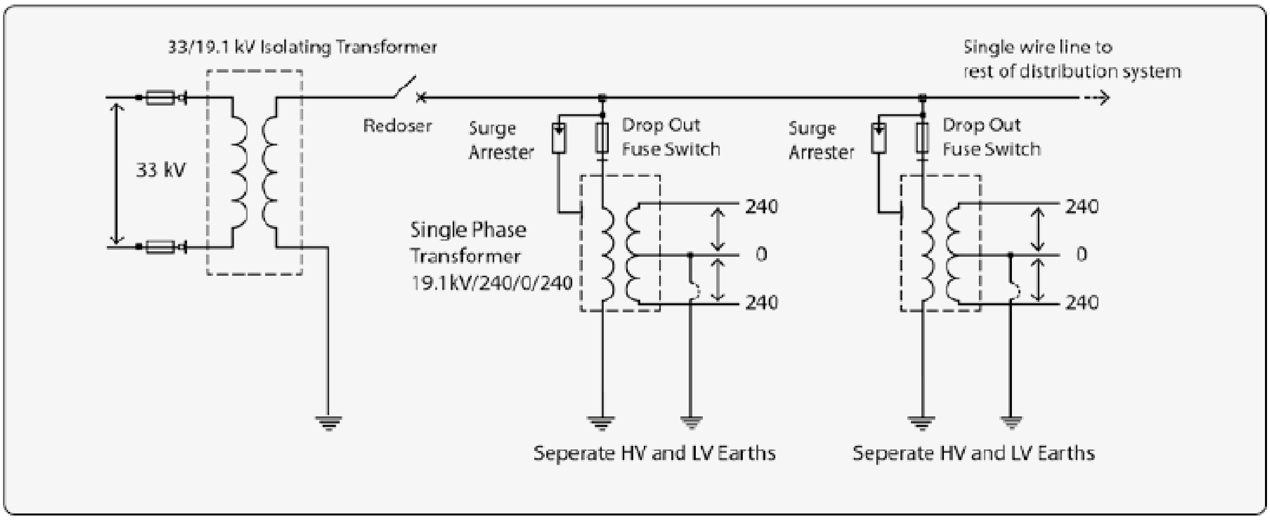
When the loads are widely dispersed, the advantage of the single phase reticulation becomes more pronounced. In such locations the single phase laterals can conveniently be erected with small capacity single phase transformers supplying small clusters of consumers. The alternative of having a three phase arrangement will require the coverage area per transformer to be enhanced and the erection of more extensive LV lines.

6.2.2. Single Wire Earth Return (SWER)

The Single Wire Earth Return (SWER) system is basically a single phase distribution system at MV using the earth as the return conductor. There are two basic types of SWER systems in use: (i) using an isolating transformer at the tap-off from the main supply line (Figure 6-46-4), and (ii) tapped directly from the main supply line (“direct SWER”, Figure 6-5).

The SWER system is usually combined with the North American practice of having a number of dispersed single phase transformers to feed small load clusters rather than having a centralized transformer with substantial LV lines. Thus the LV network is substantially reduced, similar to the case of single phase reticulation (see previous chapter).

The single wire MV phase line, which is extended to the load sites, uses single phase distribution transformers in the order of 5 kVA, 10 kVA, 15 kVA and sometimes up to 37.5 kVA. The voltage used depends on the supply voltage available and the requirements of the system to carry the expected load.

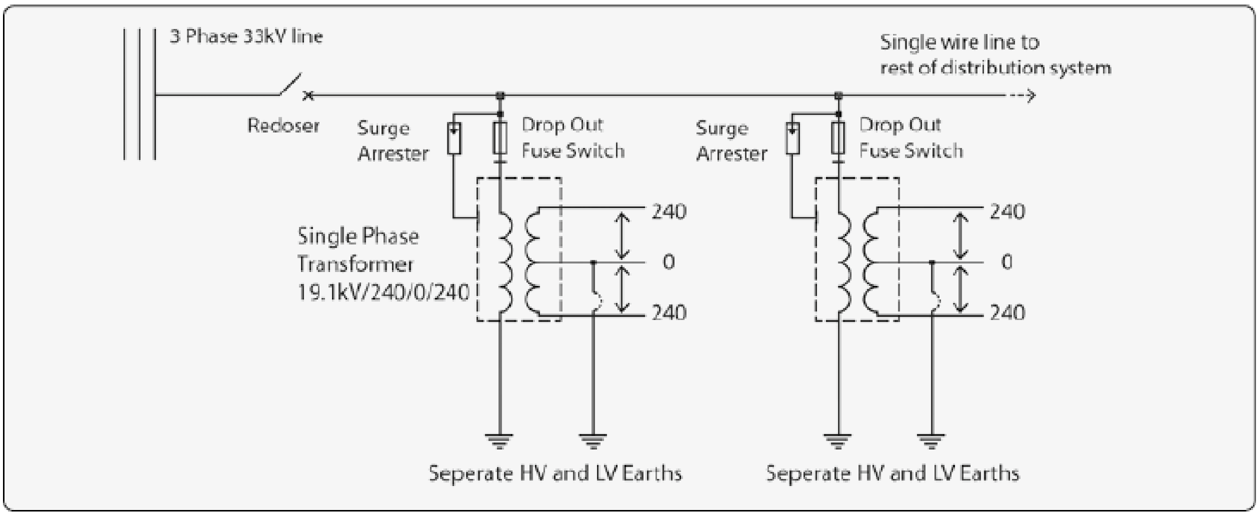


Note: The distribution transformers are indicated as bi-voltage +/- 240 V. However, the single phase LV transformers, 19.1 kV/240 V can also be used instead.

Figure 6-4: SWER System with isolating transformer. Source: ESMAP

Technical considerations

The advantages of using isolating transformers are primarily associated with the ability to limit earth fault currents to the area of the SWER system: The earth return current will flow back to the earthed terminal of the isolating transformer and the rest of the network is unaffected. Any difficulties caused by the earth current will not be felt outside of the SWER supply area. Isolating transformers are essential on systems employing neutral grounding reactors at the HV/MV supply substations unless the grounding reactance is very small. They will also enable the use of sensitive earth fault protection schemes on the feeders emanating from the supply substation.



Note: The distribution transformers are indicated as bi-voltage +/- 240 V. However, the single phase LV transformers, 19.1 kV/240 V can also be used instead.

Figure 6-5 Direct SWER system

Another advantage of direct SWER is the reduced costs due to the omission of the isolating transformer. However, if the source substation is situated in an area of considerable telecommunication activity ground currents may cause interference, once again reiterating the need for careful balancing of various SWER lines from different phases.

Multiwire Systems

A number of variations can be used when a simple SWER system is unable to meet the expected loading conditions:

The isolating substation may use two isolation transformers and supply two separate SWER lines. In this case the earth currents can be minimized by cross-connecting the primary windings of the transformers so that the earth-return currents are in phase opposition.

- A centre tapped single phase isolating transformer
- can be used to give 19.1–0–19.1 in a 33 kV system or 12.1–0–12.1 in a 22 kV system with the centre tap grounded. As in the previous case, the earth-return currents will be in phase opposition. The two phase wires can be used as a backbone SWER network and single wire direct tapped SWER lines can be taken as laterals; alternatively, each phase wires can go in different directions as single wire SWER lines.
- A three phase SWER backbone system can be provided by using a single delta-star transformer.

As before the three lines can be used as a backbone to supply single wire SWER laterals or strung in different directions to feed separate areas. If the three SWER lines have identical currents and phase angles, the resultant earth return current at the isolating transformer will be zero.

When computing earth electrode resistance for limiting EPR, the faulted line condition should be considered where the earth-return currents will not balance each other.

Advantages

The main advantages of SWER systems may be summarized as follows:

Substantial cost savings are realized from the use of only one MV wire to cover the supply area. Thus SWER systems have a substantially lower initial investment costs than that of other alternatives.

The design simplicity results in less pole top hardware and no crossarms.

- ✓ Substantially longer spans can be used as the wind loading is much less than for three conductor or two conductor lines, and there is also no issue with respect to conductor clashing. In New Zealand, hilltop to hilltop spans of over 1 km have been used providing substantial cost savings. With an appropriately designed line route, the usual routing along road ways can be avoided resulting in a line length much lower than for a standard line.
- ✓ The ability to use longer spans also eases out interference with vegetation.
- ✓ Due to the simplicity of design the construction is also much easier and can be carried out by less skilled personnel in normal terrain.
- ✓ The reliability of the network is improved due to fewer components to breakdown. Field experience has in fact confirmed this in many countries and it is observed that the SWER systems have a record of less breakdowns and unplanned outages than standard systems.
- ✓ Maintenance costs are also substantially reduced due to the fewer components in the system.

6.2.3. Shield Wire System (SWS)

The Shield Wire System (SWS) of transporting MV power over long distances was developed many years ago by Professor Francesco Iliceto of Rome University [136]. It is characterized by the use of the shield wire of transmission lines to transport Medium Voltage (MV) power along the transmission route to a convenient location and then extending the supply from there, by normal pole lines up to the supply area. For this purpose, the shield wire/s (which is normally grounded) need to be insulated up to the MV level. The SWS allows electricity to be made available at MV to communities located along HV transmission lines, with an installation cost that can be as low as 10–15 % of cost of independent MV lines on the same right-of-way.

If the insulation of the shield wire is carried out along with the transmission line construction, the costs are minimized, with practically only the cost of the additional MV insulators and arching horns being incurred for most of the line length. If the insulators are to be attached retroactively i.e. on existing transmission lines, the costs increase substantially as it would involve live line working on a transmission line, or alternatively requiring outages on the transmission line.

The MV supply is derived from the substation where the transmission line commences and is usually between 20 to 34.5 kV depending on the MV system used in the country.

The SWS system utilizes the physical infrastructure of the high voltage (HV) transmission line and enables the transport of the MV power over long distances at minimal cost. It is particularly useful to supply power to many communities situated along or close to the transmission line. Distance of these communities from the closest HV/ MV transformer station may be quite substantial (often exceeding 100 km) and the load demand considerably low, so that it is uneconomical to provide supply by normal means.

The main features of SWS are:

× Shield wire(s) insulated from the transmission line towers for MV operation (20–34.5 kV)
× Shield wire(s) energized from the HV/MV transformer at the main supply substation
× MV network extended along pole lines (when the line route moves away from the transmission line)
× MV/LV transformers installed to feed the supply area SWS can be used in the following configurations:
× with a single insulated shield wire with earth return providing a single phase MV;
× with two shield wires used providing a two wire single phase MV; or
× with two shield wires used with earth return providing the third phase.

Three phases SWS

In the case of three phase SWS [135], the phases are balanced by using a grounding resistor-reactor (R-L circuit) along with unsymmetrical power factor correction capacitors. The ohmic resistance of earth path is low, only 0.05 ohm/km at 50 Hz. The voltage drop in the R-L circuit adds to the low resistive voltage drop of the earth return circuit and the total voltage drop is made about equal to the drop in the shield wires. The unsymmetrical capacitors cancel out the voltage dissymmetry along the SWL, which are caused by the unsymmetrical induced voltages and leakage capacitive currents from the HV circuit. Capacitors also eliminate the risk of ferro-resonance over voltages.

The three phase SWL can be supplied by a dedicated tertiary winding of the HV/MV transformer. If a dedicated tertiary winding is not available, a MV/MV interposing transformer is used. It may be noted that a multiple earthing system is applied for achieving the low ground resistance required for the earth return of the current and for the safety of people. In the HV/MV substations supplying the SWS, the station ground mat is used for earth return of the current.

In the case of three phase MV, the voltage to ground of the two shield wire phases will be √3 (i.e.1.732) times higher than for a conventional three phase as the ground operates as the third phase. This requires an enhanced basic insulation level (BIL); thus a BIL of 200 kV is used instead of the usual 170 kV for 34.5 kV systems.

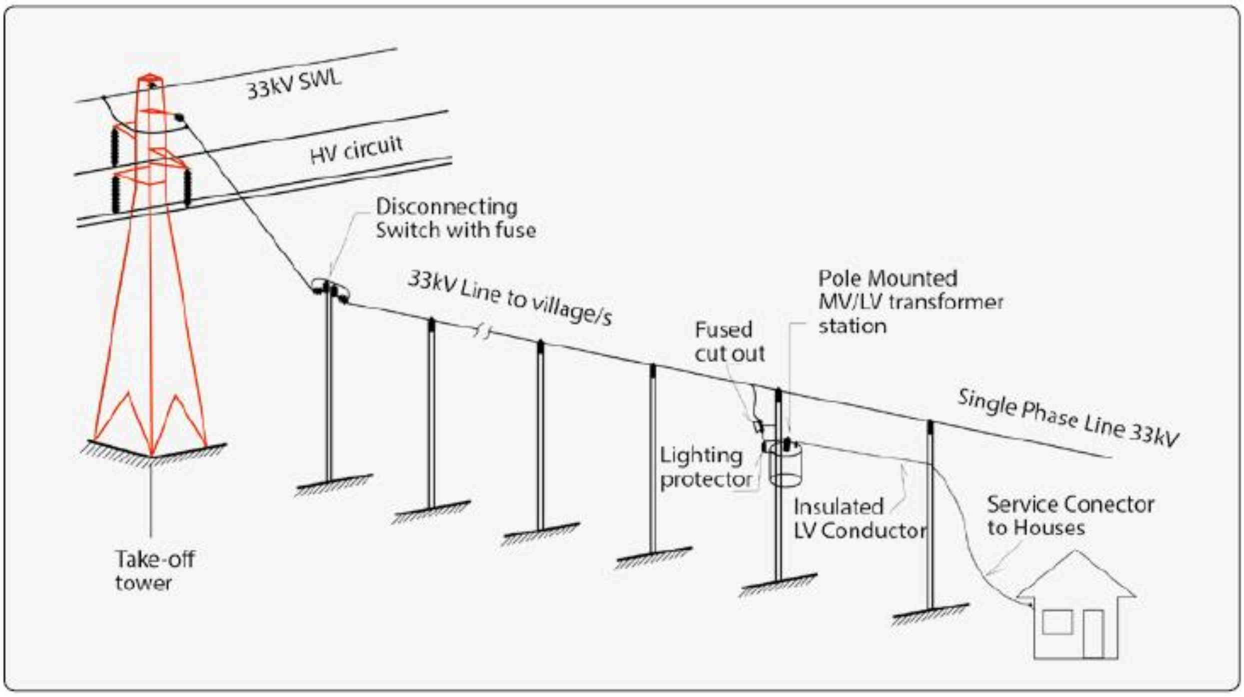


Figure 6-6: Shield Wire Scheme with one shield wire and single phase LV

6.2.4. Supplying Three Phase Loads

MV single phase networks enable rural areas to be supplied at optimum cost. However, in such situations the supply of three phase power to small industries has been a major challenge. This deficiency has been a major stumbling block to the widespread use of single phase lines in many developing countries. In some instances public authorities were forced to convert the single phase networks to three phase within a short time of the commissioning of the systems at considerable cost due to public protests and demand for three phase supply.

Many areas benefiting from rural electrification have seen the development of small industries, initially with the conversion of a few existing diesel engine powered industries to electricity and thereafter the gradual proliferation of a number of new industries. In fact the existence of a few diesel engine powered agricultural or industrial applications in a village indicates a higher economic level and a greater potential for an economically beneficent rural electrification scheme. The lower cost of grid-based power – compared to diesel-generated electricity – enables rural industries to become competitive and leads to the gradual economic development of the area. Hence all efforts need to be made to ensure that the power supply needs for productive use of energy are addressed.

There are large capacity single phase motors which can satisfy loads of 20 kW more. However, unless the demand reaches a sufficient critical mass, the facilities for securing such motors often remain out of reach of the rural industrialist in developing countries.

6.2.5. Distribution Options Comparison

A summary of the main characteristics along with the respective advantages and disadvantages of various options for distribution system development to feed low density rural loads are indicated below:

The selection criteria of low cost distribution alternatives for rural areas can be summarized as follows:

- ✓ SWER is best applied when the load density is sufficiently small and expected load growth rates are not high enough to need an upgrade of the system in a few years.
- ✓ SWS offer the best solution to reach remote areas where access through a transmission line is readily available.
- ✓ Single phase laterals (Phase-Neutral or Phase- Phase) are most suitable for application when the load density does not allow the lower cost MV distribution options described above. The new development may include a three phase backbone or the single phase laterals can be tapped from existing three phase lines.
- ✓ Three phase backbone and laterals is a standard technology; applicable when the load density is sufficiently high.

6.3. Last-mile connections

All too often lines are built, but household connections either take a long time to materialize or even remain unrealized over extended periods. This is mainly due to the high service connection charge levied on consumers, the requirement to pay the full costs upfront, restrictions imposed on housing types, and logistical difficulties faced by rural consumers.

The situation can be improved by (i) use of appropriate gauge conductors for service connections; (ii) arrangements for payment of the service connection charge over an extended period with instalments along with the monthly bills; (iii) community involvement, consumer mobilisation and education in all aspects of the electrification program; (iv) offering a 'group connections' programme to reduce the cost and eliminate difficulties in securing the services on an individual basis; and (v) developing norms and guidelines to enable service connections to be given to semi-permanent and temporary houses.

A key objective of any rural electrification scheme should be to connect as many households, commercial establishments and industrial users as possible in the electrified area – the final goal is increasing electricity access rather than building lines.

Barriers for increasing the number of connections in completed rural electrification schemes include:

- restrictions imposed on dwelling types;
- high investment costs of service connections;
- limited consumer access to financing needed for connection charges and internal wiring; and
- logistical hurdles faced by consumers in obtaining a service connection.

In many sub-Saharan countries, electricity connections are restricted to households constructed with permanent materials, such as brick and mortar, and often require permanent roofs. Low-income households usually apply less stable construction materials, such as mud walls and thatched roofs. This limits access to electricity for the poorest share of rural households, often the female headed households, due to substandard housing. The rationale often used for these higher standards is that providing electricity to such households can cause fire hazards from electrical short-circuits. This however ignores the hazards of alternatives normally used – kerosene and candles – which present a larger fire risk than from electricity supply.

Using appropriate technologies can guarantee the safe use of the electricity supply in such households. Supply can be provided by a safe ready board fixed securely to the inferior building materials or on a separate short pole inside the house (if the wall material is not dependable) without incurring undue risks.

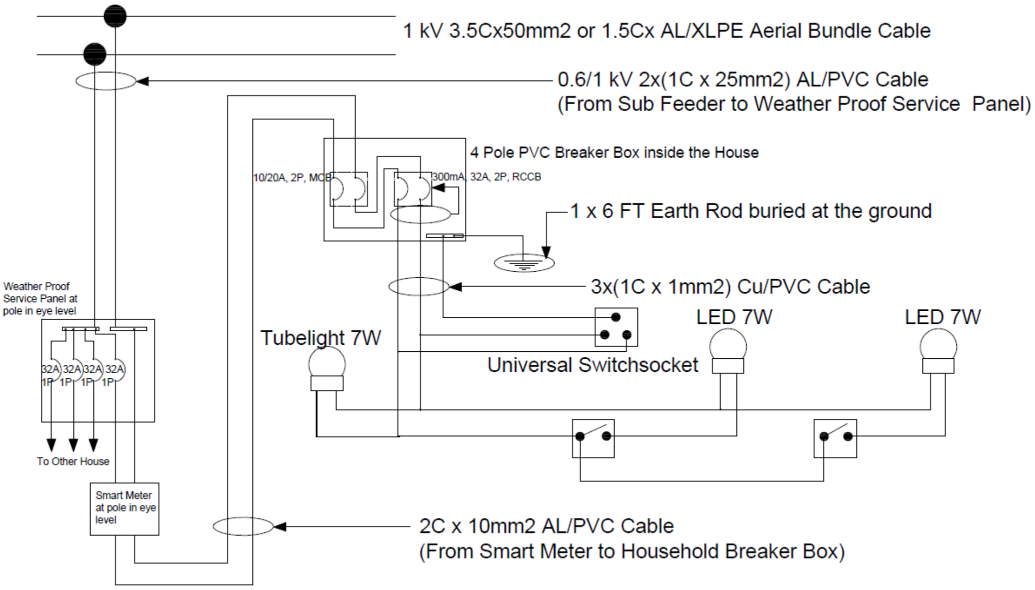


Figure 6-7: Electrical circuit diagram from sub feeder to household. Source : DRD Myanmar

The ready board could be a simple wooden board on which is mounted a Miniature Circuit Breaker (MCB), a plug outlet and one or two switches for lights. In some instances, utilities have been making this item complex leading to higher costs defeating the objectives of its use; hence particular care is needed in this respect. Also insulated conduits can be used for the service wire entry and along the sub-standard wall ensuring a safe system.

In many sub-Saharan African countries, charges for service connection in rural areas are disproportionately high and often constitute the main barrier for increasing the connection rate. A recent study carried out by the World Bank examined the relationship between service connection charge and access rates of a large number of countries. The cost for the smallest rated consumer service is often of the order of USD 100 to 300. These costs are in stark comparison to connection rates in South and East Asia and South America which range from about USD 10 to USD 75. The strong inverse relationship of the two variables is obvious from Figure 6-8 below.

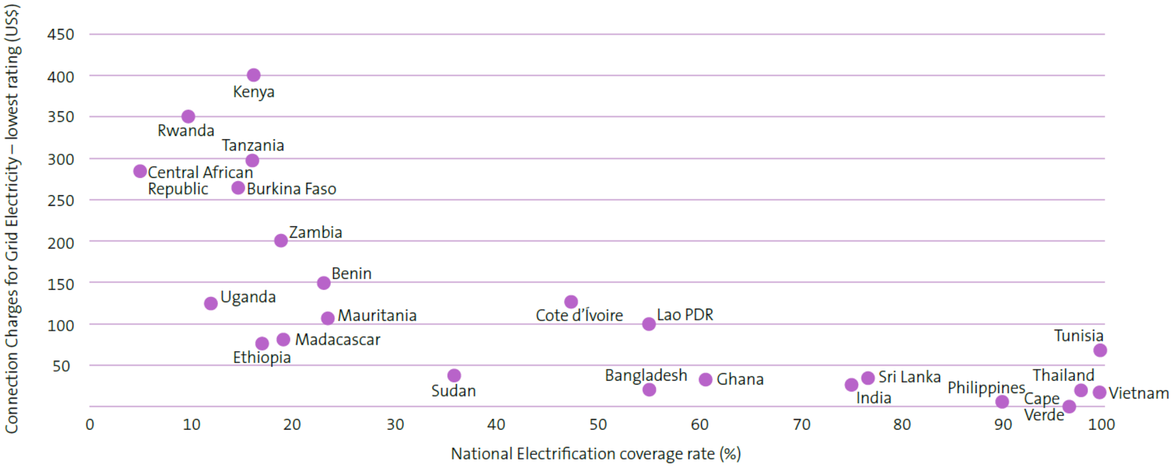


Figure 6-8: Connection charges vs. national electrification rates. Source: EUEI Energy for development 2016

The reasons for the high connection charges mainly include inappropriate sizing of service connection conductors, and addition of extra charges such as testing fees, travel and visit costs, and overheads which often exceed what could be incurred under a good practice scenario. In addition, the consumer has to incur the cost of wiring the premises which are also not optimized in most rural households.

6.4. Metering

Households with low consumption patterns can well be supplied off standard electronic or even electromechanical meters available at low cost. However, due to the reducing cost of the standard electronic meters the production of electromechanical meters has now greatly declined.

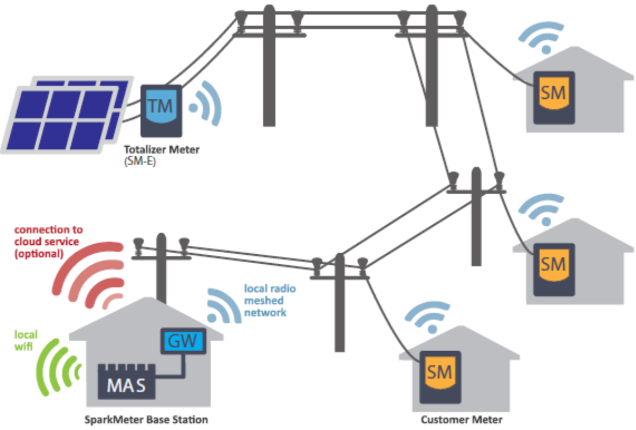


Figure 6-9: Pay as You Go meter. Source: EBS, Figure 6-10: Smart metering communication

Many sub-Saharan utilities have programmes to convert the consumer metering systems to pre-payment meters which address problems related to revenue collections. As the higher cost of pre-payment meters is passed on to the consumer, it may prevent some consumers from getting a service in the first place.

Common pre-payment meters will not offer a major safeguard against theft and non-technical losses – however, there are sophisticated ‘smart’ meters which provide an alarm in the event of tampering, which again involve higher costs. Further, it may be noted that much of the power theft occurs by bypassing the meter and this cannot be resolved by increasing meter complexity if the meter is located in the consumer’s premises.

This difficulty can be overcome by using split type prepayment meters with the meter fixed on the pole (to reduce any attempts at tampering) and the consumer console inside the house. Once again it may be noted that this will involve higher costs; a standard meter fixed on the utility pole outside the premises will offer a low cost solution to power theft.

The selection of meter types should therefore be made after an evaluation of logistical arrangements available for meter reading, the prevalent non-technical losses and the relative trade-offs – convenience of revenue collection vs. the added costs incurred.

6.5. Local Grid planning – *Ref. Project PR-4*

The following paragraph refers to the case study of Idjwi island, DRC, and presents the design approach and sizing scheme of the distribution system of the multi-source mini-grid powered by 100 kWp PV, 10 kW Hydroelectric and 100 kWh Carbon-Lead BESS.

The preliminary design of the grid configuration is performed by means of a mapping procedure carried out during the field mission in the target community, along with the data acquisition operations. With this procedure the GPS coordinates of the most energy-consuming users have been collected (red marks in Figure 6-11), in particular:

- Anchor Loads;
- Public Services;
- Small Business Activities;
- Borders of the community.

6.5.1. Stake Out and Mapping

These data were implemented with an in-deep analysis of the available satellite images of the area with which it was possible to estimate the number of households (light-blue marks in Figure) more quickly and accurately; 450 potential households were detected with this analysis.

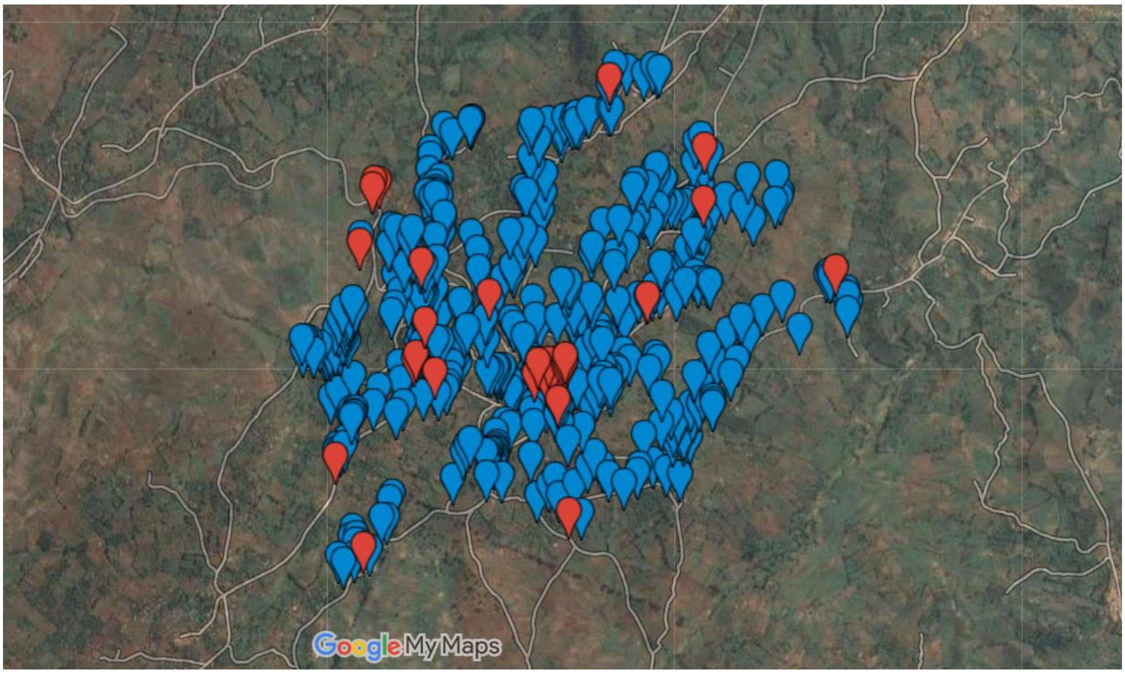


Figure 6-11: DR Congo project users' spatial distribution. Source: own elaboration

The GPS coordinates of the users have been imported in a virtual map of the area on which the model of the distribution line (DL) was built.

The DL has been designed to maximize the ratio between the number of connections and the length of the network, ensuring the connection of all public services.

The proposed layout shown in Figure has a total length of 11.135 km, develops along the main roads of the community and can serve about 500 users.

Figure 6-12: Distribution grid layout from Google Earth. Source: own elaboration

The distribution line will be developed throughout the community territory through an over-head line distribution system based on aluminium conductors (ABC cable).

The use of aluminium conductors has been preferred because it is a less expensive solution with respect to copper conductors, furthermore, Aluminium conductors are more easily available in the African market, facilitating in such a way the project's logistics.

The over-head line results to be the only cost-effective design solution in the rural context, particularly if the installation site is located on an island such as the community of Kashara.

The realization of an underground power-cable distribution line would involve unsustainable costs and time of installation. Furthermore, more complex O&M procedures are needed for underground lines, requiring earth-moving machinery and specialized personnel not present in the area and consequent longer time in case of failures for fail detection and for service restoration. This solution was consequently rejected in the pre-feasibility phase to ensure service continuity and power quality.

Since the anchor loads of the community of Kashara require a 3-phase connection, a multiwire SWER backbone System + lateral would be needed, thus minimizing the economic advantage of this technology over a traditional solution.

Since the power plant will be located in a barycentric plot, a MV transmission line is not required and the system will act basically as a distribution network with a radial geometry. This configuration makes it possible to have a distance between the power plant and the farthest user always lower than 2 km, making possible the realization of a low voltage distribution grid while maintaining an acceptable voltage drop. Furthermore, this configuration allows the connection of both single-ph and 3-ph users (e.g. Milling machines) which represent a significant amount of the community's load.

6.5.2. Conductor Sizing

Often standardizing on conductor sizes has unnecessarily increased costs in rural areas. By applying the maximum voltage drop criterion, the conductor sizing has been determined with careful consideration of the load to be carried (inclusive of future needs). Furthermore, the function of the line (i.e. backbone or lateral) has been considered.

In particular, the target was a maximum acceptable voltage drop of 5% at the user furthest away from the PV Generation Site. In order to consider future needs of the community the calculation is based on the maximum power consumption forecasted in the daily load profile (5-year forecast).

Since the user's distribution is not defined accurately in this preliminary phase, the first step of the sizing procedure was the determination of the distributed load under the above conditions. This calculation is made possible by the data collected for load profiling activity.

The maximum power consumption of the community takes place at 12 a.m. and it is characterized by an active power of 45kW.

The load is distributed among the users as shown in Table 6-1:1:

Loads	Un [V]	Sn [VA]	cosφ	In [A]	Ina [A]	sinφ	Inr [A]	P [W]	Q [VAr]
HHs	220	9485.3	0.95	43.1	41.0	0.31	13	9011.0	2961.8
BUS	220	10223.3	0.9	46.5	41.8	0.44	20	9201.0	4456.2
Anchor Loads	380	32812.5	0.8	86.3	69.1	0.60	52	26250.0	19687.5
Public Services	220	604.2	0.95	2.7	2.6	0.31	1	574.0	188.7
Street Lighting	220	0.0	0.9	0.0	0.0	0.44	0	0.0	0.0

Table 6-1:1 Load disaggregation per users' categories

The distributed parameters are determined according to the layout mapped on Google Earth, which total length is equal to 11.135km, the results are shown in Table 6-2:

Sn [VA/km]	P [W/km]	Q [VAr/km]	In [A/km]	In a [A/km]	In r [A/km]
1590.34	1348.18	817.07	5.35	4.62	2.59

Table 6-2: Linear load density

The user furthest away from the photovoltaic system was therefore identified thanks to the analysis of satellite images.

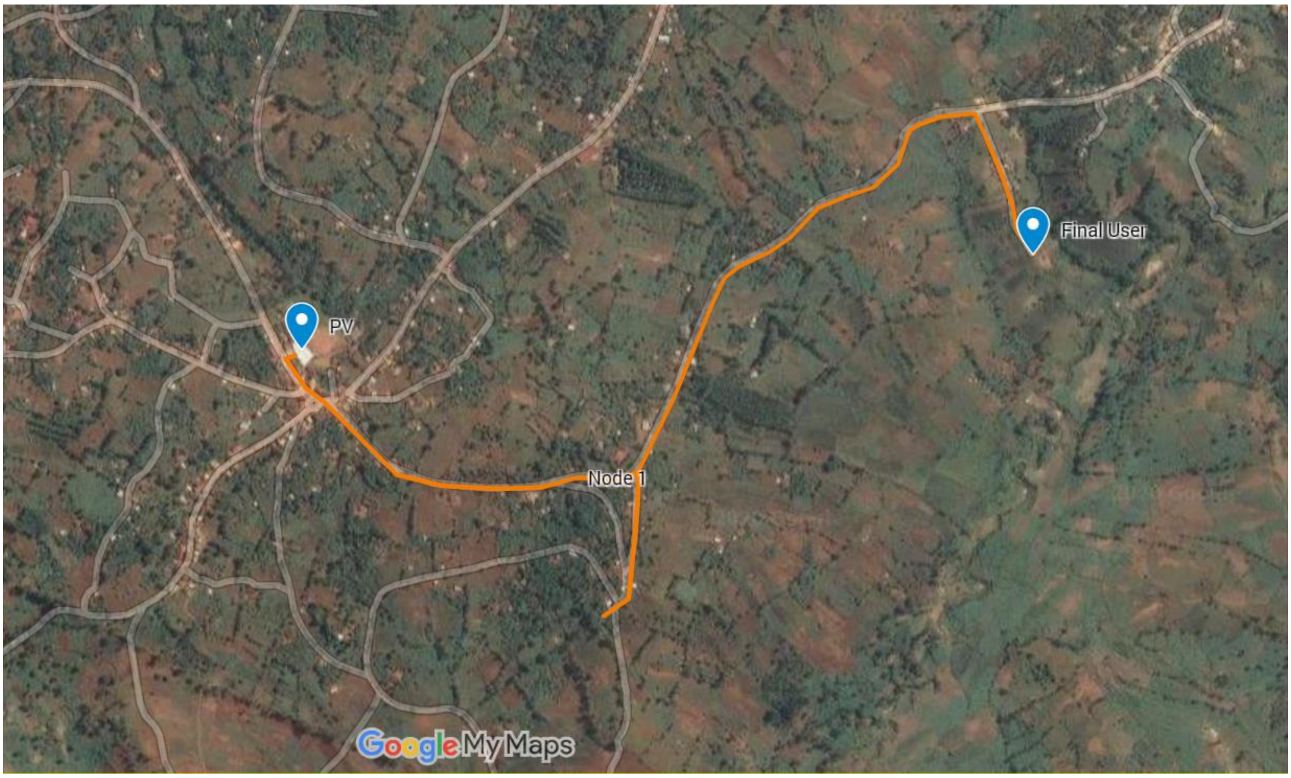


Figure 6-13: Longest branch between PV plant and farthest off-taker

The user is located at a distance of about 1.7 km from the photovoltaic system. The theoretical conductor cross-section to limit the voltage drop to 5% of the nominal value has therefore been calculated using the equivalent length method.

This method allows us to simplify a complex system into a simpler one with a similar behaviour.

The starting system as shown in Figure6-13 has two branches and one node and is characterized by a distributed load, thanks to the method of equivalent lengths we will obtain a simplified final system, characterized by a single branch feeding a single equivalent load, at its end.

The equivalent length method is iterative, it must be repeated at each node, which is why in our case it will be repeated twice.

The simplification process is shown in the next tables, where:

- N 1 is Node 1.
- B 1,2,3, eq2, eq1 are Branches;
  In particular:
  - B1, from PV to Node 1;
  - B2, from Node 1 to Farthest User
  - B3, from Node 1 southward

The method is based on the calculation of the amperometric moments of the loads i.e. quantities that take into account both the intensity of the current and the distance of the load from the point of origin of the power line, from the dimensional point of view they are equal [M] = m *A.

The formula for amperometric moment is as follows:

$$Mi = L_{PV-i}\ [m] * Ii\ [A] = [m * A]$$

Equation 6-1

Where:

- Mi is the amperometric momentum of a generic load I;
- Lpv-i is the distance between the generic load i and the PV system;
- Ii is the current absorbed by load i.

Once the amperometric moments of the loads have been determined, the equivalent length of the simplified system can be determined using the following formula:

$$Eq.Lenght\ = \frac{\sum_{i=1}^{n} M_i}{\sum_{i=1}^{n} L_{PV-i}} = [m]$$

Equation 6-2

The equivalent load of the simplified system will feed an equivalent load which is equal to the summation of all the loads of the branches composing the starting system.

- First iteration (At node 1):

Starting data are shown in Table 6-3:

Node 1	Length [km]	In [A]	Ia [A]	Ir [A]	Ma [A*km]	Mr [A*km]
Branch2	0.19	1.00	0.86	0.48	0.16	0.09
Branch3	1.06	5.67	4.90	2.74	5.20	2.91

Table 6-3: Stating data; 1st iteration

The equivalent circuit parameters of the equivalent branch 2,3 are shown in next table:

Equivalent Length B2 [km]	Ptot [W]	Qtot [VAr]	cosφ	It [A]	It a [A]	It r [A]
0.93	1681.18	1018.88	0.85	5.22	4.42	2.77

Table 6-4: Equivalent Circuit Parameters; 1st iteration

- Second iteration (At PV node):

Starting data :

PV Node	Length [km]	In [A]	Ia [A]	Ir [A]	Ma [A*km]	Mr [A*km]
Branch 1	0.60	3.21	2.77	1.55	1.66	0.93
Eq. Branch 2,3	0.93	5.22	4.42	2.77	4.11	2.57

Table 6-5: Starting data; 2nd iteration

The equivalent circuit parameters of the final simplified system are :

Equivalent Length [km]	Ptot [W]	Qtot [VAr]	cosφ	It [A]	It a [A]	It r [A]
0.80	2490.09	1509.13	0.85	7.73	4.42	4.10

Table 6-6: Equivalent Circuit Parameters; 2nd iteration

6.5.3. Validation

The last step of the conductor sizing procedure is the determination of minimum theoretical cross-section needed to contain the voltage drop at the final user at 5%. With this simplified geometry it is possible to apply the following formula to evaluate the theoretical cross-section:

$$S_{min,theo} = \frac{Eq.Lenght * \; I_t * cos\varphi}{\Upsilon * (\Delta E_{MAX} - \Delta E_r)} = 20.9 \; mm^2$$

Equation 6-3

Where:

- $S_{min,theo}$ is the minimun cross-section of the conductor required to contain the voltage drop;
- Eq. Length is the value calculated with the second iteration of the equivalent length method;
- It is the current absorbed by the equivalent load;
- ϒ is the electrical conductivity of Aluminium, equal to 0.028 [km/Ω*mm^2];
- ΔE_{max} is equal to the maximum l-n voltage drop, equal to 11V (5% of 220V);
- ΔE_r is the voltage drop due to the reactive power, equal to 1.05 V (considering an OHL's reactance equal to 0.3 Ω/km)

The first available commercial section is 25 mm^2.

By performing the reverse calculation, the expected voltage drop to the end user is equal to 9.4V (4.3%). Therefore, technical standards can be met.

7. Operation

In the scientific literature two main types of analyses are typically carried out in order to address the issues of Dispatch Strategy Optimization and Real Time Power Control, as Mandelli, S. [1] and Fioriti, D.[137] suggest in their literature review.

Optimum dispatch is typically carried out by means of analyses which deals with the flows of energy within the system [138] . The objective is to identify the best regulation algorithm for the interaction among various system components. The regulation strategy determines the energy flows from the various power sources, towards the user loads, and dump loads, including the charging and discharging of the energy storage systems, in such a way as to optimize system performance according to targeted objective functions (i.e. operating cost, battery life-time, etc.).
Dispatch analyses [139] are typically based on the steady-state solution of the energy balance between energy sources, storage, and consumer loads and employing mathematical modelling of the system components. Different accuracy in the analyses mainly results from the length of the time-step the balance is solved for the degree of detail in the load/energy source data, in the mathematical modelling of the system components, and from the approach employed to look for the optimal solution. Usually time-step can vary from day-to-day to one-minute and analyses are performed throughout a year, a week, a day of for particular functioning conditions.

Also system sizing methodologies often embrace dispatch strategies to perform system simulation and hence sizing the components. Nevertheless, in these cases dispatch strategies are defined before the analysis and hence they are not optimized for the specific case. Typically *cycle charging* and *load following* strategies are considered [140]. Recently, also in dispatch strategy optimization, multi-objective optimizations have been employed in order to embrace also environmental parameters in the system control [141];

Real time power control analyses [142] take into account that a power supply system is a highly nonlinear system that operates in a constantly changing environment (i.e. when considering mini-grids, loads and generators outputs can change continually). They address the study of frequency and electrical quantities control (e.g. current and voltage) and their main objective is to analyse the continuance of intact system operation following a disturbance. Specifically they can focus on observing the trend of system variables during a disturbance, on the size of the disturbance, and on the time span that must be taken into consideration in order to restore stability. These analyses are based on circuit models of the components and on the solving of the related equations within the continuous time-domain. They are typically carried out for short intervals (from few to tens of seconds) in order to study the development of frequency and voltage.

In this framework, and at the light of the example of the hybrid Micro-Grid under study for Idjwi Island in DR Congo, it is important to address some important aspects of the design process of off-grid systems that which are not appropriately addressed both by optimum dispatch strategy and real time power control analyses:

- concerning dispatch strategy analyses: (i) even when electrical quantities are employed in system components modelling, systems are studied with steady-state numerical simulations and hence trends of V and f are never analysed, (ii) typically the dispatch algorithm focuses on the energy balance without considering the consequences it has on system control and hence on V and f. These aspects can affect the size as well as the life-time of the components, especially when systems include rotating machines together with RE generators, power converters and electrochemical storage;
- concerning power stability analyses, they do not provide elements to optimize the flows of energy among the main system components and they are too heavy when addressing issues that occur over longer periods (i.e. battery charge/discharge cycle, computation of Loss of Load, Excess Energy, etc.).

A combination of all following strategies is required to effectively operate mini-grid systems, along with optimized planning described in the previous Chapters

7.1. Dispatch strategies

Mini-grids and hybrid systems have proven to provide a stable electricity supply although they meet loads using variable sources like photovoltaic and wind. The key component is the control unit that guarantees not only the optimal management of the dispatchable units, such as thermal plants or storages, but also supervising and monitoring activities by remote control [143].

In a rural mini-grid, typically no national grid supplies power, and the operator, be it the owner of the system or not, manages the entire system as a vertically integrated utility. For this reason, typically the objective of the management system is to keep the system stable and to minimize the operating costs from the operator point of view, which include fuel expenses, maintenance costs, and the economic value of the energy-not-served. However, the formulation has to comply with the control system available in such contexts, including both hardware and software constraints.

As first described in [144] , the simplest strategies to dispatch rural mini-grids are based on simple priority list rules that prioritize renewable sources, then storages, and finally fuel generators. The two main strategies, namely load-following (LFS) and cycle-charging (CCS), set the working point of the fuel generator in function of the State-Of-Charge (SOC) of the battery

However, more advanced techniques propose a rolling-horizon approach wherein the dispatching of the system is updated more frequently, like intra-daily, to cope with the unavoidable forecasting errors [125]. It is worth noticing that the time between two consecutive redispatches undertakes a key role because it impacts on the results of the methodology, but it has to comply with constraints like the availability of updated forecasts.

Despite being deterministic, this approach partially manages uncertainties, at the cost of increased computational requirements but still very suitable for short-term applications.

7.1.1. Load Following

The load-following strategy aims at prioritizing cheap sources related to renewable sources directly, or indirectly when the energy is stored like in batteries. Lastly, fuel generators are used. Those guidelines are translated in a number of rules that apply at every time step. Recent studies [137] suggested a slightly modified version of a load-following approach composed by the following rules. The main difference from the traditional approach is detailed in the 2nd rule, where the decision on whether to turn on the generator relates to the cheapest option between turning on the generator and curtailing part of the demand.

1) When the inverter can fully meet the load, the diesel is kept off and the battery balances the system. a) When the inverter cannot meet the entire load: evaluate the potential curtailment cost of the exceeding load.
b) When potential curtailment cost is higher than turning the diesel on at the minimum working point: turn on the diesel till required and do load curtailment if the diesel cannot meet the exceeding load.
c) When the potential curtailment cost is lower: do load curtailment.

2) When the renewable production cannot be fully exploited to meet the load and charge the battery, due to energy or power limits: do renewable curtailment.

A graphical example of a daily dispatching is depicted in Figure 7-1, where it is worth noticing that the diesel generator is turned on when the batteries reach the minimum SOC. Moreover, the generator keeps running to supply the load without recharging batteries until renewable production is available to supply the load and recharge batteries.

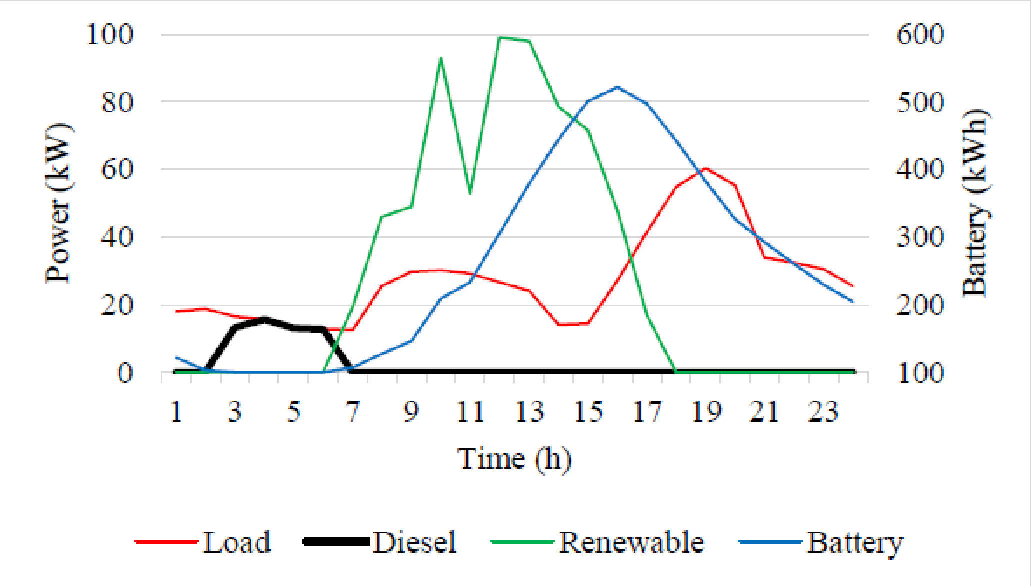


Figure 7-1: Example of load-following dispatching

7.1.2. Cycle Charging

As for the load-following strategy, also the cycle-charging prioritizes first renewable source, then the energy stored in batteries, and finally the fuel-based generators. Similarly, the generator turns on only when the energy stored in the battery goes down a fixed threshold. However, in this case, the generator supplies not only the load but also the batteries, recharging them up to another threshold. The developed [137] cycle-charging strategy is based on the following rules:

1) When the generator is shut off and the energy stored in the battery goes down to a fixed threshold ($SOC_{CC,start}$) or the inverter cannot fully meet the load due to power constraints: start the diesel generator at the specified power rate $P_{D,CC}$ (maximum efficiency point/rated power).
2) If the diesel was running in the previous time step, keep it running until the SOC in the battery reaches a fixed threshold ($SOC_{CC,end}=SOC_{CC,start}+\Delta SOC_{CC}$).
3) If the inverter is not able to meet the full load and the diesel is running: increase the dispatching of the diesel till required.

This modified version is more flexible than the standard one and it can be used with any design configuration of the mini-grid, contrarily to the standard CC strategy. In fact, the standard CC strategy only cares about the state of charge of the battery, but it might fail with inappropriate designs due to constraints in the installed capacity of some components, leading to inappropriate behaviour of the system. This strategy, instead, can manage also those designs. The generator is assumed to work always at the rated power. Moreover, when the average requested power of the generator is lower than the rated power, like when the battery has almost reached the pre-set threshold, the generator is assumed to be working for a fraction of the time at the specified rate; therefore, the efficiency of the specific cost of the generator production is constant. The maintenance cost is fully considered in every time step the generator operates.

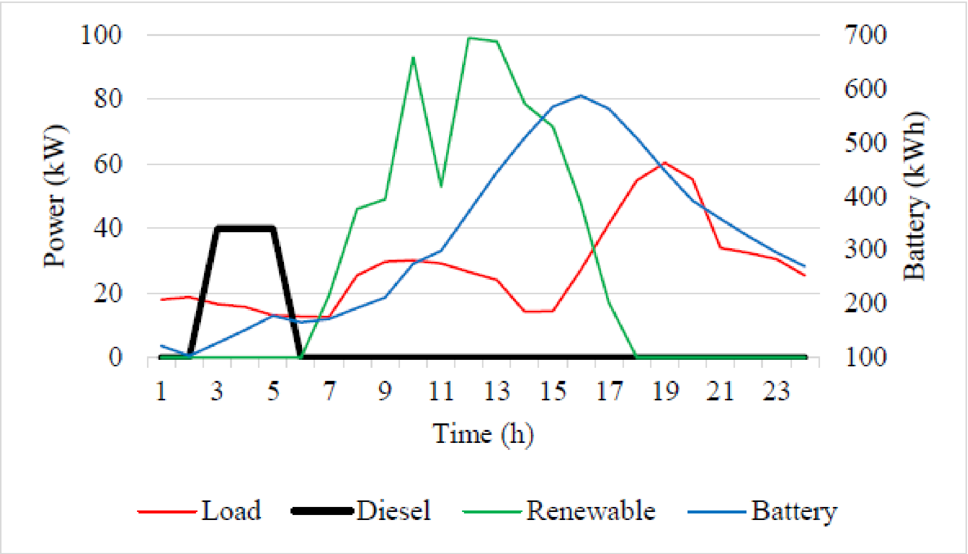


Figure 7-2: Example of cycle-charging dispatching

7.1.3. Rolling Horizon

The mini-grid is operated through a rolling-horizon scheduling of resources depicted in Figure , with hourly time resolution Tr=1 h. Every Th hours, the procedure calculates the optimal system dispatching for the following time horizon To, while the real time operation of the mini-grid is guaranteed at each time step by simple dispatching rules based on a priority list. During the simulation of real time operation, the actual load and PV production approach, can also significantly differ from the corresponding forecasted values. According to such variations, a real time controller corrects the optimal dispatching of the system using a merit order list of resources: first the renewable energy, then the battery, and finally the diesel generator.

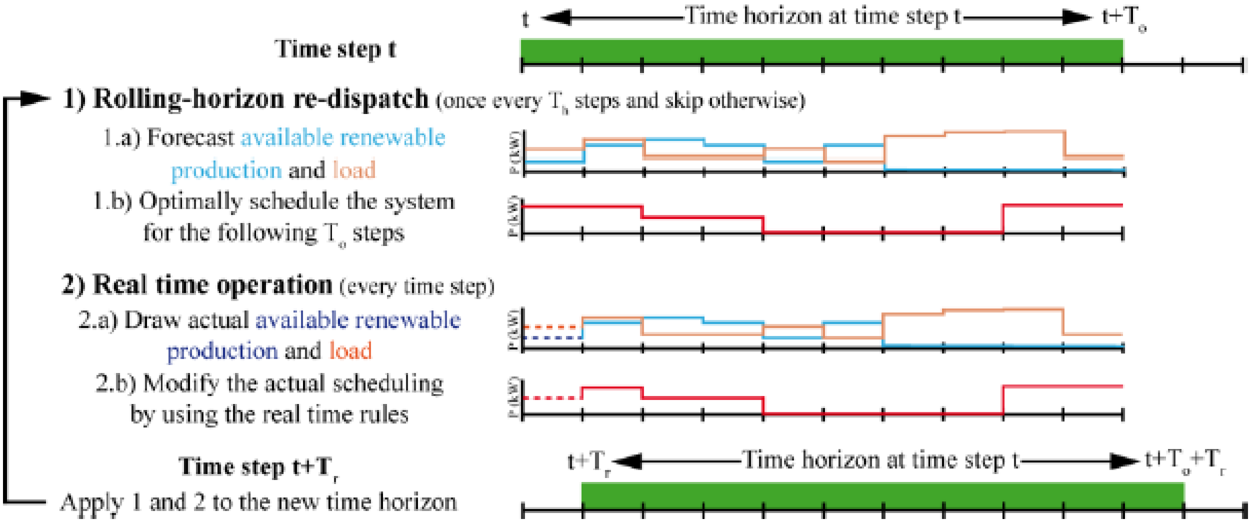


Figure 7-3: Rolling-horizon approach. Source [125]

7.2. Dump loads

In an off-grid power supply system the frequency can be maintained constant by eliminating the unbalance between generations and load consumptions. Acting on the generation side means to use conventional speed governors which use electronics to sense changes in speed in order to control the resource exploitation (e.g. water flow in case of hydropower). Nevertheless, the generation control mechanism is typically not used in rural electrification interventions when the power ratings of off-grid systems are less than 100 kW. Indeed in these cases, the cost of such a governor usually exceed the cost of the generator itself [145] . For this reason, uncontrollable prime movers are preferred. These act on the load side so that the generator output power is held constant despite variations of the users' loads. The different strategies which can be adopted in this direction are: dump load control, priority switched-load control, flywheel, superconducting magnetic energy storage systems, and battery energy-storage systems [146] .

Over the last two decades, especially dump loads in the form of electronic load controllers (ELC) have spread. The ELC functioning is based on the measure of the prime mover speed and on the compensation for variation in the main load by automatically varying the amount of power dissipated in a resistive load, thus keeping the total load just right to attain the correct speed and generate stable frequency. There are several advantages of ELC: the use of simpler and cheaper prime mover with less moving part, less expensive than equivalent flow control governor, high reliability and low maintenance, and they can be fitted at any point in electrical system.

The two most commonly employed techniques used for ELC are [324]:

a) the phase delay action: where the dump load comprises a permanently connected single resistive load. As a result of the detection of a change in the user load, a power electronic switching device adjusts the average voltage applied to the dump load, and hence the power dissipated. This technique introduces harmonics causing overheating of electrical equipment connected to the system.
b) the binary load action: where the dump load is made up from a switched combination of separate resistive loads. In response to a change in the consumer load, a switching selection is made to connect the appropriate combination of load steps. During transitions, full system voltage is applied to the new fraction of the dump load and hence harmonics are not produced at all.

In the Idjwi project, a single 5kW binary ELC dump loads is installed, equipped with PID µp-controlled frequency system. As a result, the plant frequency changes affect the feedback in function of the entity, duration and speed. In numbers, the PID output represents the electrical power to be dissipated by the dump load [147].

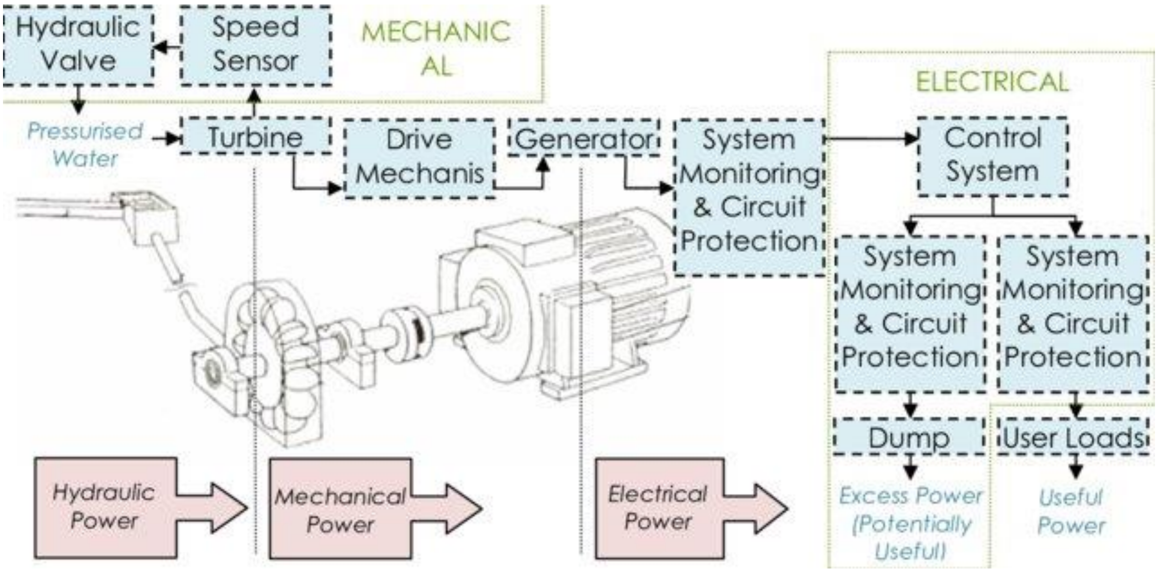


Figure 7-4: Off-grid hydro power control system.
Source: Off-grid hydro power control system.

Source:

7.3. Grid-forming/following

Having reference to the parallel functioning layouts for this first step development of the new modelling approach, the static power sources (as PV panels) and the storage systems (as electrochemical batteries) are connected to the AC grid by means of power electronic systems operating in grid following mode. Therefore, they can be modelled by means of ideal current source which injects power at the grid frequency imposed by the synchronous machine. Still, this model is consistent as for considering that the electro-magnetic dynamics are faster than the mechanical dynamics, and hence the related variables evolve according to a steady-state behaviour.

The new approach and related models have been applied to the case of Idjwi. As already highlighted, a main issue to tackle as regards the development of the hybrid mini-grid is to study the integration of the battery bank with the hydroelectric dump load. Indeed, the batteries can be managed in order to reduce the dissipating power on the dump loads, but this must not compromise the stability of the Banki turbine-synchronous generator block which generate the AC grid at 50 Hz.

Therefore, as a first step in applying the new approach, a model of the MHP plant composed by the synchronous generator, the dump loads, and the user loads have been developed in order to start analysing the issue of battery bank integration. In addition, as already observed when introducing the components modelling.

7.4. Power flow optimization – *Ref. Paper PA-2,3*

Due to renewable source unpredictability, electricity production in a stand alone system can affect the grid quality, thus causing low service standard during operations. Using mechanical and electrochemical batteries as dump load to absorbed voltage and frequency fluctuation can be an effective operation strategy.

In this reference study, an analysis of wind production data generated from one year of actual wind data is used to test the power smoothing performance of a range of battery systems with various storage and power ratings. Different ramp rates thresholds and the effect on battery durability where also assessed. Wind generation ramp rates end up causing voltage and frequency issues in grids or supply limitations in microgrids, which can effectively be limited using energy storage.

7.4.1. Input data from case study

Wind power is a continuously growing renewable energy source, reaching a technological maturity that makes it competitive on the market and viable without subsidies [148]. Integration of wind farm production into power grids poses many challenges due to the intermittent and fast-changing nature of the resource. Wind turbine production is typically characterized by strong ramp rates which may require production curtailment to prevent congestion or high investment in ancillary services [149]. Energy storage systems can help to reduce these negative impacts but the economic impacts are not negligible [150]. Wind energy fluctuations can be particularly critical in microgrids or isolated users. Uriarte et al.

[151] have investigated the effect of renewable sources ramp rates on the stability of microgrids that can be islanded from the main grid. On the other hand, wind power has a great potential to provide access to energy to remote communities that do not have access to the grid. The potential for sub-kilowatt wind turbines has been discussed in [152] and 0.8 million off-grid households are already estimated to have reached energy access through small wind turbines.

The smoothing performance of BES and FES were tested over a wide range of capacities and power ratings as these were considered as the most suited technologies. Since BESS systems are prone to degradation due to cyclic operation, whereas FESs are not, the two technologies are compared by considering both smoothing effectiveness and annualized cost. This comparison is done with a technoeconomic analysis which explores the trade-off between these two indicators by means of a multi-objective approach. The economic analysis considers the capital, replacement and fixed and variable O&M costs, to provide a fair comparison between the two storage technologies.

The wind data used for the study comes from a wind farm in Costa Rica with anemometers situated at a 50 m above the ground. The data series consisted in wind speed data averaged over 10 minutes, coupled with the standard deviation over that time span. The granularity of the data was subsequently increased to a 1-minute interval by generating 10 points randomly extracted from a gaussian distribution having the mean and the standard deviation obtained by the anemometers every 10 minutes. This a simplified, but conservative, approach as it does not take into account the autocorrelation typical of wind speed series. A more detailed analysis would be out of the scope of the study whose main purpose is to investigate the smoothing effect of energy storage on wind generation. In addition, by considering a Gaussian distribution, the "virtual" data points are more fluctuating in comparison to those generated by a distribution which respects the auto-correlation. This wind speed data was used to generate a correspondent set of generated power, by using a piece-wise fit based on the power curve of a commercial wind turbine with a rated power of 200 kW (Hummer H25.0-200KW), which was considered as suitable for the case study. These power values should be considered as ideal, as they does not take into account the inertia of the turbine. Tang et al.[153] have shown that the actual turbine time constant τ is related to its natural time constant τ0 as reported in Eq. 7-1:

$$\tau = \tau_0 \cdot \frac{v_{rated}}{v}$$

Equation 7-1

The rated speed is a characteristic given by the manufacturer. In general terms, τ0 is the time constant of the turbine when reaching its rated rotational speed under its rated torque from a stop condition. To estimate the τ0 of the turbine based on its rated power, a two-term power function to fit the data presented in [153] was used:

$$\tau_0 = a + b \cdot P_{nom}^{c} \quad (3)$$

Equation 7-2

After obtaining the parameters a, b and c from the regression, the τ0 for the turbine was calculated, and then a one-minute dataset of its actual time constant. This dataset was used to adjust the ideal power output as obtained from the power curve by using,

$$P_t = P_{t-\Delta t} + \left(P_t^{id} - P_{t-\Delta t}\right) \cdot \left(1 - e^{-\Delta t/\tau}\right)$$

Equation 7-3

where Δt is equal to the chosen sampling time, 60s. The final output of these processes is reported as histograms for wind speed and actual output power in Figure 7-5 .

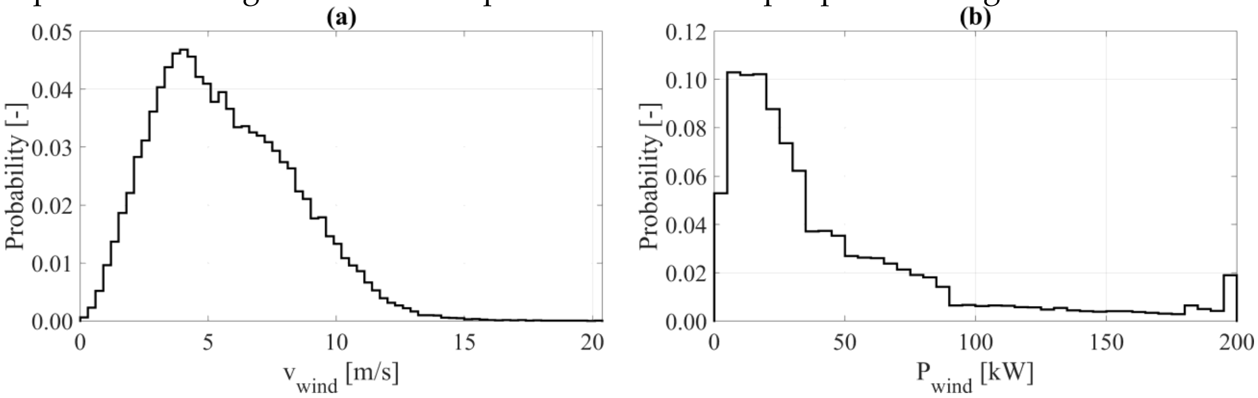


Figure 7-5: (a) Histogram of the wind data series. (b) Histogram of the actual output power obtained from the turbine power curve and accounting for the turbine inertia

7.4.2. Power smoothing algorithm

The calculations have been made by accounting for three different maximum ramp rates, defined as the difference between the powers generated at two consecutive time steps, calculated as a percentage of the turbine power rating. The thresholds are set at 5%, 7.5%, 10%. A variation limit within the 10% of the rated power capacity per minute is reported in the Nordic Grid Code and by the Puerto Rico Electric Power Authority, for example. However, the application of more stringent conditions, as could be needed in isolated system, was simulated as well. Lithium-Ion batteries were considered as a storage with a roundtrip efficiency of ηrt = 0.9, charge and discharge efficiencies assumed to be constant and both equal to ηc = ηd = 0.91/2. State of Charge (SoC) was always bound to be between 0.2 and 0.95 to prevent a quick battery degradation. Several combinations of battery capacities and power output have been considered. As a reference value for sizing the battery, the average hourly energy production was obtained from the power output of the turbine (Ēh) and ten values of Cb were tested, ranging from 0.1 Ēh to 0.5·Ēh . Similarly, for the battery power output, the rated power of the turbine was taken as a reference and ten values of Pb ranging from 0.1·Prated to 0.5·Prated were considered. The model takes into input the actual power output from the turbine and the maximum ramp size; in case the ramp exceeds the set threshold, a battery charging or discharging is necessary according to the sign of the violation. In case of a positive violation (battery charging) one has to consider the energy to be charged, the power of the battery and current SoC. Therefore, the battery is charged by considering the minimum among:

The amount of energy to be charged into the battery to limit the ramp to the prescribed value; The energy that can be charged in a minute using the full power of the battery;
The available storage capacity given by the difference between the current SoC and the maximum one. The same logic is applied in case of a negative violation by considering the discharge capabilities of the battery. The overall procedure is outlined in Figure 7-5:12.

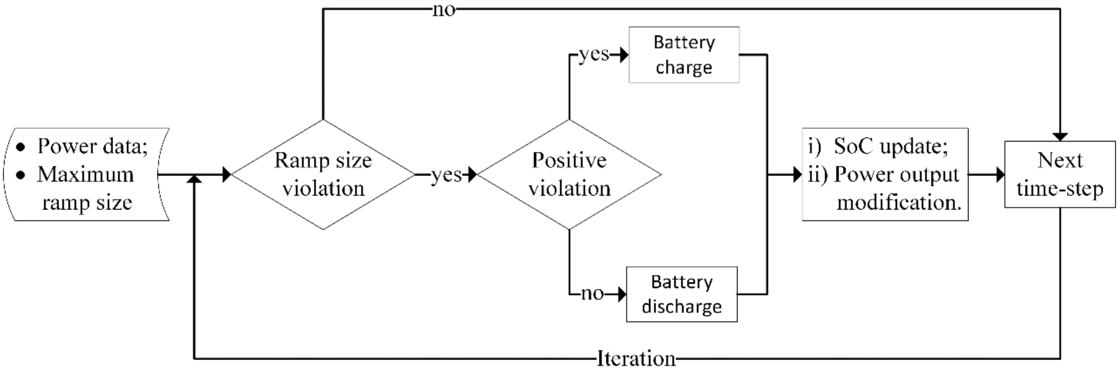


Figure 7-5:12 Schematics of the power smoothing algorithm. Source: authors' elaboration

In case a ramp size violation occurs, after the battery intervention, the new SoC and the modified output power are calculated and their value updated. This repeats for every time step. In case of a positive violation, the SoC has to be updated, depending on one of the three scenarios outlined above, with the following equation,

$$SoC_t = SoC_{t-\Delta t} + min\left[\left(P_t^0 - P_{t-\Delta t} - \rho_{max} \cdot P_{rated}\right) \cdot \Delta t, P_b \cdot \Delta t, \quad (SoC_{max} - SoC_{t-\Delta t}) \cdot \frac{C_b}{{\eta_{rt}}^{1/2}}\right] \cdot \frac{{\eta_{rt}}^{1/2}}{C_b}$$

Equation 7-4

where P0 is the power output the turbine would have without the battery intervention and P the power output after the ramp violation correction, ϱmax is the maximum allowed ramp rate with respect to Prated (ϱmax = 0.05, 0.075, 0.1).
The output power in case of a positive violation is calculated with,

$$P_t = P_t^0 - min\left[\left(P_t^0 - P_{t-\Delta t} - \rho_{max} \cdot P_{rated}\right) \cdot \Delta t, P_b \cdot \Delta t, \quad (SoC_{max} - SoC_{t-\Delta t}) \cdot \frac{C_b}{{\eta_{rt}}^{1/2}}\right] / \Delta t$$

Equation 7-5

Analogously, the same must been done in case of a negative violation for the SoC and the output power,

$$SoC_t = SoC_{t-\Delta t} - min\left[\left(P_{t-\Delta t} - P_t^0 - \rho_{max} \cdot P_{rated}\right) \cdot \Delta t, P_b \cdot \Delta t, \quad (SoC_{t-\Delta t} - SoC_{min}) \cdot C_b {\eta_{rt}}^{1/2}\right] \cdot \frac{1}{C_b {\eta_{rt}}^{1/2}}$$

$$P_t = P_t^0 + min\left[\left(P_{t-\Delta t} - P_t^0 - \rho_{max} \cdot P_{rated}\right) \cdot \Delta t, P_b \cdot \Delta t, \quad (SoC_{t-\Delta t} - SoC_{min}) \cdot C_b {\eta_{rt}}^{1/2}\right] / \Delta t$$

Equation 7-6,7

As a final output of the model, a series of smoothed power production profiles obtained for different combinations of capacity and power ratings of the batteries was obtained. These profiles have been compared with the non-smoothed profile of wind generation, to obtain a ramp abatement ratio, defined as,

$$abatement\ ratio = 1 - \frac{ramp\ violations\ in\ the\ smoothed\ profile}{ramp\ violations\ without\ the\ battery}$$

Equation 7-8

The results have been reported in Figure 7-6 in terms of abatement ratio for different capacity and power of the batteries. In particular, $\gamma b = Cb/\bar{E}h$ (ratio of battery capacity over the average hourly production of the wind turbine) and $\pi b = Pb/Prated$ (ratio of the battery power over the rated power of the turbine) have been used. This allows for a better comparison of the relative values of the energy capacity and power ratings of the wind turbine and the tested battery system, while giving an idea of the energy content associated with the fluctuations of wind power output exceeding the prescribed ramp thresholds. Furthermore, the battery size expressed as (theorical) run-time hours at maximum discharge power are reported. These lines indicate batteries having the same ratio of energy capacity (kWh) over power (kW).

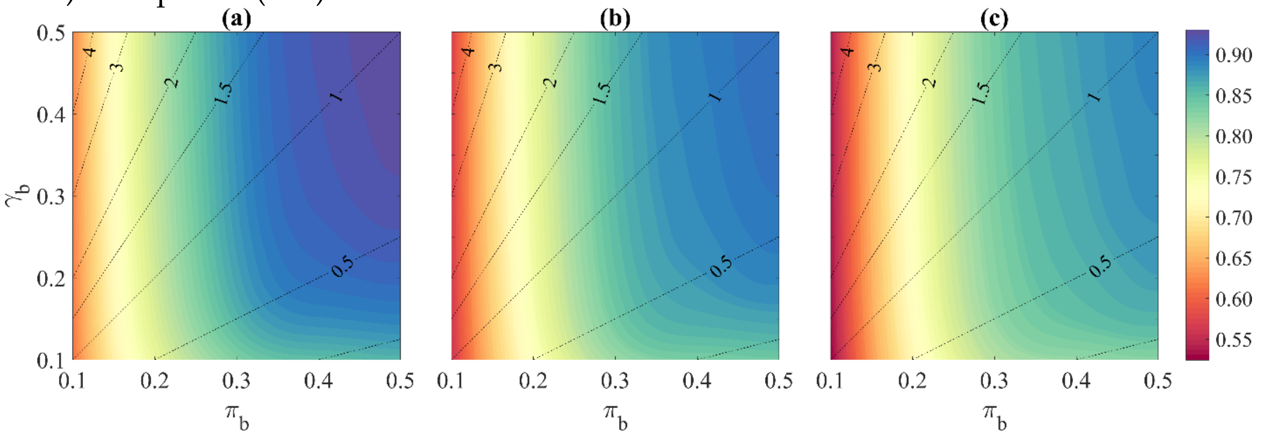


Figure 7-6: Contour lines plot of the abatement ratio provided by the batteries, plotted against their nondimensionalized power ($\pi_b = P_b/P_{rated}$) and capacity ($\gamma_b = C_b/\bar{E}_h$). The dashed lines indicate the run-time hours at maximum discharge power. (a) 5% max ramp ratio (b) 7.5 % (c) 10%.

A high abatement rate of 85% can be obtained with battery power and capacity ranging from $Pb = 0.3 \cdot Prated$ and $Cb = 0.1 \cdot \bar{E}h$, for the 5% case, to $Pb = 0.4 \cdot Prated$ and $Cb = 0.2 \cdot \bar{E}h$ for the 10% case. However, for this system it is not possible to abate all the fluctuations: only with a maximum ramp rate of 5% batteries that have half of the power rating of the wind turbine and about half of its average hourly generation capacity are able to abate more than 90% of the ramp violations. Whereas, if the allowed ramps are larger the associated energy flows are bigger, and in the investigated range no combination of power and capacity can reach the same goal.

7.4.3. Battery degradation

The lifetime of a battery can be expressed as a number of full charge-discharge cycles it can sustain. However, the batteries performing such power-smoothing service actually undergo through an irregular pattern of micro charge-discharge cycles. The Rainflow Counting Algorithm is a technique commonly applied to estimate the battery life [154] by considering a finite number of cycle depth intervals (δm, which is scaled with respect to the allowable Depth of Discharge of the battery, thus comprised between 0 and 1) and counting the number of cycles in each of discharge range. The relative annual battery degradation, Db, can be obtained by summing up the effect of all the M cycle depth intervals, through [155] :

$$D_b = \sum_{m=1}^{M} N_m / \left(A \cdot \delta_m^B \right)$$

Equation 7-9

Eq. 9 requires two empirical parameters, A and B, which are to be determined for each specific battery. However, a number of values for A and B are reported in the literature [156], and the values A=1000 and B=-1/5 have been chosen. Similarly to Figure 7-6, Figure 7-7: reports the results in term of battery lifetime Lb, which is the multiplicative inverse of the relative annual degradation (i.e. Lb = 1/Db) as a function of πb and γb.

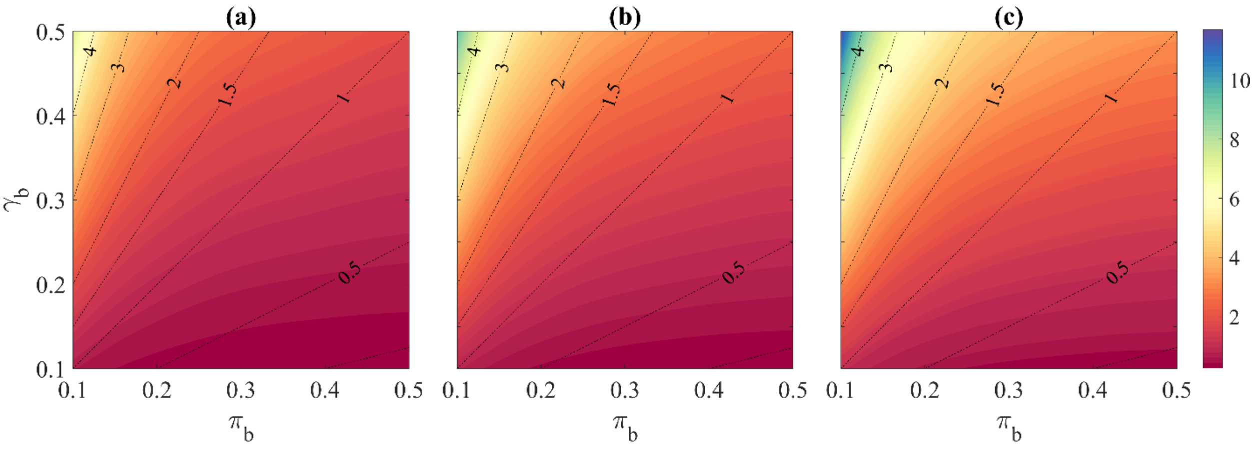


Figure 7-7: Life-time in years provided by the batteries, plotted against their nondimensionalized power and capacity. (a) 5% max ramp ratio (b) 7.5 % (c) 10%.

By comparing last two figures, it can be seen that the iso-abatement curves are "more vertical" meaning that the smoothing capability depends more on the power of the batteries, whereas their durability increases more with their capacity, being the iso-lifetime curves "more horizontal". Thus, the minimum power-capacity pairings capable of guaranteeing an 85% abatement rate lead to a short lifetime, of about one year. In case (c), a 4 year durability can be reached at Cb=0.5·Ēh, which paired with a power Pb = 0.4·Prated enables an 85% ramp abatement ratio. The battery installations lasting longer than 6 years lead to an abatement ratio that can reach 70 to 75% for the three cases.

7.4.4. Conclusions

This study investigated the capability of two different storage technologies in effectively abating wind power production ramp rates. A wide range of storage capacities and powers have been investigated for three values of allowed ramp rates. The expenditures to provide the desired level of abatement were estimated. Abatements up 80% of not allowed ramp rates may be achieved at a relatively low price (around 7.5–8 k€ per year) by using a flywheel. This system was the best technology up to abatements around 90%. After this threshold, batteries outperform flywheels and, for very high abatement effectiveness (between 0.9 and 0.95), they provide the required smoothing for a lower price. For abatement effectiveness higher than 0.8 the storage cost quickly increases, and the economic viability of proposed application should be carefully investigated as the storage costs could easily overpass the economic benefits brought by the wind turbine introduction.

7.5. Demand Side Management

Demand Side Management (DSM) can be defined as the application of a combination of strategies and technologies to modify the shape and amplitude of the load profile of a given power system. The overall goal of DSM is to reduce the cost of energy supply by optimizing the usage of available assets and deferring further investments in generation capacity. Further benefits may include lower energy bills, environmental benefits achieved by efficient energy use and reduction in usage of polluting backup diesel generators, and increased durability of energy storage devices. The main effects that DSM actions can produce on the load curve are visible in Figure 7-8

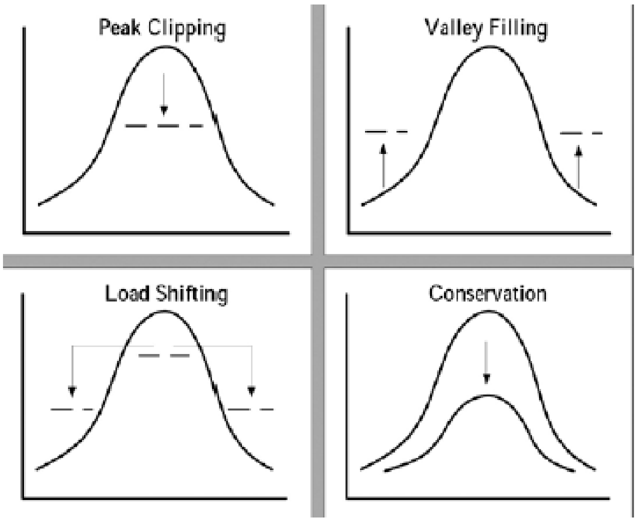


Figure 7-8: Effects of DSM on load profile. Source: Saengprajak, A[157]

Peak clipping aims at directly reducing the maximum load that happens at the corresponding peak time (usually in the evening), effectively "shaving" the maximum power that the generation plant has to provide; valley filling is directed at building an off-peak demand by employing productive or alternative uses of energy (e.g. to power the provision of an additional service); load shifting is a technique to reschedule loads that are time-independent to off-peak hours; conservation is a general reduction of the overall load by intervening directly on the customer side, for instance by enforcing the usage of efficient appliances

In practice, to achieve these effects, DSM actions can be divided into strategies and technologies, as proposed in the seminal work done by Meg Harper for Lawrence Berkeley National Laboratory for isolated micro-grids [158], as reported in the following table:

DSM Strategies	**DSM Technologies**
Efficient appliances and lights	Current limiters
Commercial loadscheduling	GridShare
Restricting residential use	Distributed Intelligent Load Controllers
Price incentives	Conventional meters
Community involvement, consumer education and village committees	Prepaid meters, Advanced metering systems with centralized communication

Table 7-1: Demand Side Management Classification. Source: Harper, M.141.

Demand side management is an important yet overlooked element of a mini-grid project. One of the main issues in the design of mini-grids is the prediction of the load curve of a community and its evolution with time.

Since, it is an input data for the sizing of a plant, defining beforehand DSM strategies and technologies to be adopted will help in making the load characteristics of the plant much more predictable.

DSM can be incorporated in the design of a mini-grid, for example by classifying user loads as critical and non-critical and assigning to them a different reliability threshold for the system to comply with [158]. That is, certain loads are given priority (e.g. evening lights) over others (e.g. fans) which may not be served in case of supply constraint, but both type of loads have by design an assigned reliability rate that limits the possible curtailments that can incur over a year.

Simulation results compared with real scenarios show how this approach can provide an optimized least-cost option for generation and storage that provides the same reliability rate for high priority loads as the actual, oversized system does, compromising on reliability for low priority loads in exchange of significant CAPEX savings[159].

Another study shows how an optimal combination of peak clipping, load shifting and valley filling can result in a reduction of the LCOE by 18% in a reference case study, while also decreasing usage of diesel and increasing the lifetime of batteries [160].

These figures are encouraging, but putting them into practice, especially in an ongoing project, can be extremely challenging since any measure adopted would have a repercussion on the business model of the mini-grid as a whole.

Applying DSM in existing projects would also need holistic actions beyond technical measures and it would affect the satisfaction and the engagement of the community. The cost of such an intervention should be measured in a wider cost-benefit analysis that

considers the tangible costs for planning and coordination, along with the cost of installation of the necessary physical devices.
The possible drawbacks in terms of user dissatisfaction if the DSM programme alters their habits too radically or limits their willingness to use energy in an unacceptable way also needs to be taken into consideration.

Therefore, DSM actions should be embedded in the planning and design phase of a mini-grid, and be part of the business model itself. Especially employing a valley filling strategy requires the presence or the development of some productive use of energy, or the provision of additional services, which can be a source of additional revenue streams for the operator and can have a broader impact on the community.
The specific economic advantage of having a more “business heavy” load profile in comparison with a “residential heavy” one has been quantitatively shown in a study conducted in partnership by the National Renewable Energy Laboratory (NREL) with the U.S. Agency for International Development (USAID), where it demonstrates that the first kind of load can be served with a lower LCOE for various configuration of generation assets compared to the second kind (supposing they have the same overall yearly energy requirement) [161] .

Load-shifting and peak-shaving can be obtained by adopting a differentiated tariff scheme or with hardware devices. Either way the community needs to be involved and tooled to understand, accept and exploit such model, which may be challenging especially for greenfield projects that are usually unfamiliar with energy availability.

The usage of high efficiency appliances and energy conservation can be promoted, but it would require awareness campaigns to discourage users from adopting cheaper technologies such as incandescent lightbulbs. The business model for a mini- grid can include the initial provision of high-efficiency lightbulbs as a part of their connection package, but also the sale of electrical appliances in general. Not only would it constitute an additional revenue stream for the company operating the plant, but it would also stimulate energy take off, especially if incentives or the possibility to pay for appliances’ instalments existed. Advanced metering systems with centralized communication can allow for a more structured control of demand.

7.6. Internet of Things and digitalisation

Internet of Things (IoT) and Machine-to-Machine (M2M) connectivity is the technological root for fully-connected devices within isolated mini-grids. It allows a GSM two-way communication between electronic devices and the service providers’ central servers. In fact, GSM chips and software installed by the producer on an embedded circuit boards permit the communication, monitoring and the execution of some operations, both by automated or manual remote controllers. Devices with embedded M2M modules can receive a proof of payment via the mobile network (often a 2G network) to unlock the service, which would enable electricity flow from the battery to the appliances.

There are several ways how the generation and storage system of mini-grids can be made "smart" with digital technologies. Mini-grids that are mainly powered by intermittent renewable generation technologies (e.g. photovoltaic generators, wind turbines) can for instance profit from weather forecasting algorithms based on numerical prediction models. These can be treated by the energy management system to compute power generation forecasts, enabling the mini-grid controller to automatically optimise the use of battery storage and/or the deployment of diesel generators in hybrid systems [162]. Smart inverters in combination with batteries could further improve the control of the generator and thus provide not only power but also system stability services.

Distribution and control digital technologies enable a better control of the distribution grid and power distribution to the consumers. Real-time management of grid parameters, such as voltage, frequency, active and reactive power flows, as well as the detection of failures can be improved with the help of distributed sensors placed at various points of the system. These include transformers, busbars, switchgears and distribution panels.

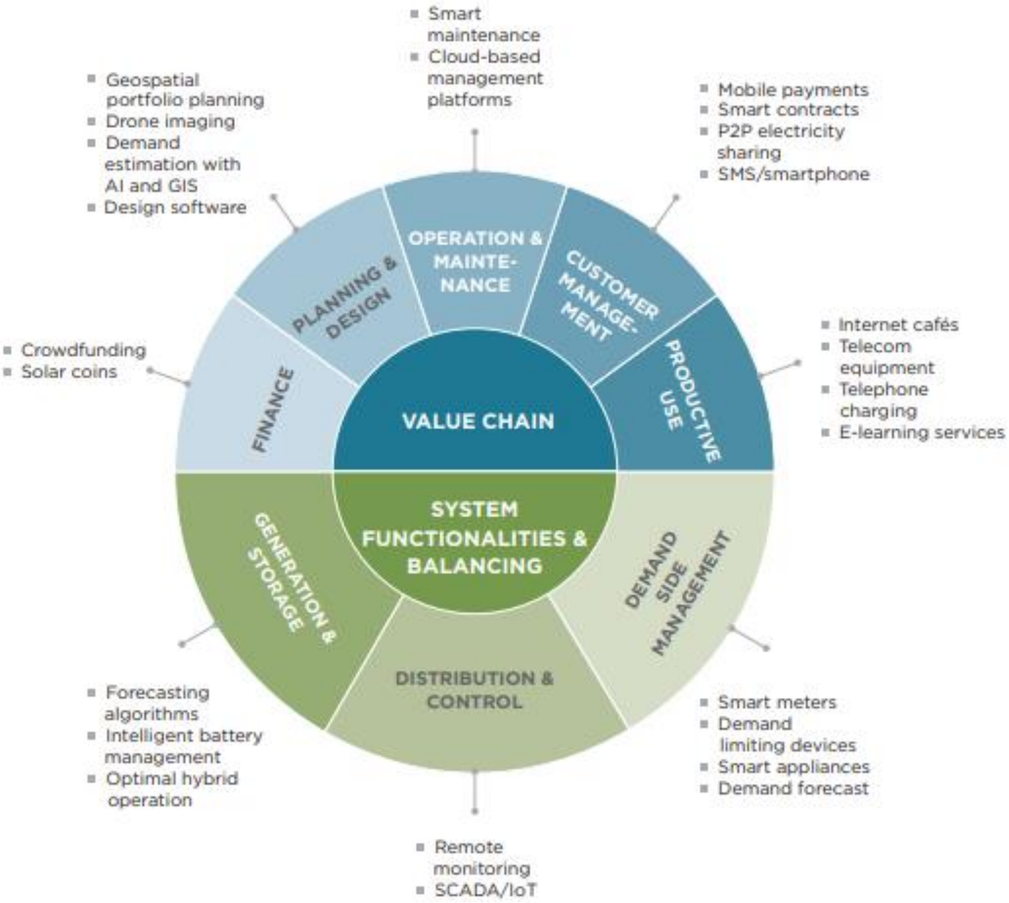


Figure 7-9: Digitalisation in mini grids phases. Source: IRENA

In a wider sense, smart meters and even intelligent appliances also become part of this network of intercommunicating IoT devices.

Next generation system control and data acquisition (SCADA) allow for real-time processing of these data and may be possibly assisted by remote management platforms or cloud-based monitoring systems.

Another important aspect of a mini-grid's system functionality concerns IT-assisted demand side management. Managing the demand of household consumers, small and medium enterprises, or community operated equipment for productive use, like grain mills or water-pumping facilities, can significantly improve the technological and economic performance of mini-grids.

One enabler for smart, IT-assisted demand side management could be flexible tariffs, i.e. electricity prices that continuously change throughout the day according to algorithms assessing the current energy status of the system. The idea is that these price signals would incentivise consumers to shift their power consumption to hours of the day, where enough energy is available.

Such smart management could reduce stress on the system, and increase the life-span of essential and important components of the mini-grid, in particular batteries by improving their charging cycles, and thus reduce costs. Advanced smart meters can limit the power consumption of users as a function of user priority and the available energy of the overall system.

8. Economic Evaluation

A mix of grid extension and off-grid solutions should be properly combined in the country's electrification masterplan to pursue universal access to electricity. Despite the business of individual systems, the viability of which has already been proven in several developing countries, the mini-grid sector still requires to demonstrate solid business models. In this sense, opportunities arise when looking beyond the sole electricity supply: additional services, complementary value chains, innovative partnerships and horizontal integration can bridge the gap between viable and non-viable projects [163].

The electricity then can be used by businesses in the production, storage, handling, and processing of food products. Such "sustainable agriculture production systems" and "climate-smart food systems" can become pragmatic solutions for sustainable development and can also bring significant structural changes, improved livelihoods, and enhanced food security to rural communities in many countries (Figure 8-1).

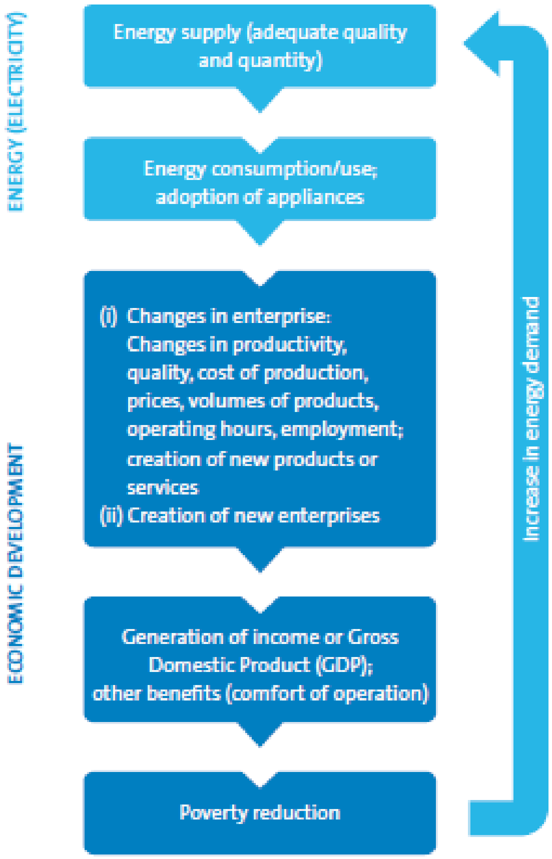


Figure 8-1: Correlation between economic development and energy. Source: FAO.

Despite the higher power capacity requested to run machinery and productive appliances, commercial loads perfectly integrate with photovoltaic-based generation plants since most of the demand can be satisfied through direct solar production during daytime. Irradiation is abundant almost everywhere in Sub-Saharan Africa, and this is also combined with water seasonal demand. In fact, water for irrigation is mainly necessary during the dry season, when solar availability is abundant.

Besides food processing machinery, for many small businesses in rural areas it does not make sense to operate at night, if there is no specific demand for their products/services during evening hours and the market cannot absorb an increased output. However, batteries cannot be completely avoided, since there is still night demand for public lighting as well domestic and commercial activities that rely on: better lighting system to attract more customers.

Although water pumping and food processing can be smartly combined with solar power, there are many other productive activities that can take place in an enabling environment, such as an electrified rural village. Motive power is arguably the most important one, since mechanisation and automation typically allow achieving higher outputs at constant inputs (welding, carpentry, tailoring, etc.)

Quality and reliability of electricity supply is an important factor both for the decision to connect and for the impact on small scale businesses performance. In some countries the reliability is so low that electricity-reliant businesses have no choice but to invest in private diesel generators if they want to maintain business operations at a minimum level of steadiness. The resulting workflow interruptions and the damage of sensitive electrical equipment such as computers caused by voltage fluctuations can curtail profits significantly. Therefore, a battery storage is necessary within a productive mini-grid to stabilize the grid voltage and frequency and to ensure power quality to income-generating appliances.

Another benefit, which can support the long-term sustainability of a mini-grid project and de-risking business model, is that electrification can lead to the creation of new firms or partnership with existing ones. This generates additional income and therefore socio-economic impact in the project's region, as they could be services and/or manufacturing firms created to offer products that were previously imported from other regions or simply not been offered in the area before.

All these effects lead directly or indirectly to higher productivity, as less input is needed to produce the same output. This increased productivity might either lead to higher profits for business owners or higher incomes for workers. Electricity usage, thus, ultimately leads to income generation in the form of higher firm owner's income, employment or wages. At the same time, higher incomes lead to better ability to pay and growing energy demand.
When water, agricultural and farming services are provided locally to a community, further improved local development can be achieved. When the mini-grid operator manages these additional services through an integrated business model, a more coordinated management of the power system and these productive activities is possible to increase the efficiency and profitability of the system, optimally aligning generation and load by using DSM.

In particular, some productive activities like food processing and water pumping/purification have intrinsic storages (e.g. water tank and food storage), whose management can improve the efficiency of the overall system (e.g. by reducing any curtailed RE, conversion losses in converters and storages, as well as fuel consumption). In the case of pumping water, excess of production can be used to pump water into a water storage located in proximity to the village and at an adequate elevation so that water can later flow back with gravity.

Furthermore, the daily working schedule involving electricity-intensive devices in farming activities could be organized in hours with high RE availability, like daytime for photovoltaic systems. Domestic demand usually requires power peaks during the evening, while nocturnal hours have typically the lowest demand.

8.1. Innovative business models – *Ref. Publication PU-1*

This chapter is based on the study driven by RES4AFRICA Foundation called "RE-Thinking Access to Energy Business Models for decentralised energy solutions", which stands as an analysis of the technical, regulatory and financial challenges and opportunities to clearly identify the most viable and scalable business models for mini-grid projects.

The results confirm that a broader perspective including different actors and sectors in an integrated manner is able to pursue *business for impact*.

The more than 20 rural electrification projects in Sub-Saharan Africa analysed in this study give a picture of a growing and innovative sector with heterogeneous experiences.

The study classifies and analyses business models of 21 mini-grid projects in Sub-Saharan Africa, identified among 32 pre-selected cases on the basis of selection criteria which took into consideration:

i. geographic coverage;
ii. location;
iii. technological solution;
iv. services provided;
v. system size;
vi. source of power;
vii. project status.

8.1.1. Data collection

The data collection activity was carried out from December 2018 to March 2019. In the data gathering phase, actual data from operational plants, both from the design and implementation phase (purpose and business model of the project, detailed CAPEX, tariff structure, technical specifications of the mini-grid) and their operational phase (OPEX, actual revenue streams, sale of electricity and other services/products, electricity consumption, number of customers and potential market) have been collected from the developers and complemented also through local stakeholders.

Types of data collected:

- Description of the business model: (i) sales model; (ii) type of services; (iii) ownership; (iv) other.
- Business plan: (i) IRR; (ii) NPV; (iii) payback period; (iv) CAPEX; (v) financial structure (equity, debt, grant); (vi) other.
- Real data: (i) date of commissioning; (ii) current status; (iii) actual investment (real CAPEX); (iv) revenues, over the operational time; (v) tariff, over the operational time (with type of tariff plan); (vi) OPEX, with breakdown costs when available; (vii) repowering, if any (not referring to spare parts but to increase/ modify generation, storage, etc.); (viii) electricity production in operational (kWh produced and and with reference to RE share in the energy mix; (ix) amount of not served energy (kWh); (x) sales volume (amount of product sold depending on the business: electricity, litres of water, Kg of food processed, etc.); (xi) continuity/discontinuity of the service over the operational time; (xii) number of customers (e.g. connections, etc.); (xiii) potential direct market (number of households or population); (xiv) other.
- Other data relevant to the analysis.

8.1.2. Data analysis

An Excel model was created to evaluate the financial sustainability of the plants using as many real performance data available as possible. Where necessary, specific assumptions and projections to estimate financial parameters (NPV, IRR) were included over a 20-year financial plan.

IRR was selected as the reference financial indicator to rank the profitability across projects of different scale and it is not related to the volume of the investment as the NPV.

In calculating IRR and NPV, all projects have been assumed with a CAPEX fully funded by equity, to assess the sustainability and scalability of existing projects, regardless of the usage of grants or loans in the actual financing of the project.

Missing data has been often estimated using a proxy approach from the most similar plant among the case studies, especially ones sharing the same developer and country of intervention.

The modelling has been implemented dynamically, envisaging a growth of electricity consumption and new connections, in consideration of the potential market of each site. From longer operating plants, which had a evident growth in the historical trends, a reference curve for consumer take-off and consumption increase has been derived, and used for newer plants to perform projections.

The possibility of expanding the plants was not considered in doing projections, as the evaluation was limited to the capability of the assets currently on the ground.

An extraordinary maintenance of all the mini-grid components has been assumed to happen at the 10th year of operation and estimated considering current prices and cost reduction trends of the various technologies adopted. However, in case it was known any faulty components, their repayments were assumed at the first year of forecasting.

8.1.3. Results

The most promising models have emerged by using a multi-layer approach which has also taken into account the key features raised in the study: ways to apply a WEF nexus in the project, community categorization in terms of local economy, type of PUE and ability to pay, type of mini-grid operator(s), the required regulatory framework and the correlation between investment size, profitability and impact.

The above mentioned key features can shape the best business model for a given developer, in a given country, with a given investment ticket or capability of fundraising.

On this basis, four business models have been selected with a view to provide viable options:

- Electricity supply & appliances provision: a private operator owns and operate small RE power units providing DC electricity and small appliances to customer clusters.
- Electricity supply & agri-food production: a Special Purpose Vehicle (SPV) owns and operates a WEF nexus integrated business that provide electricity and water to both the local customer base and its own agri-food production and processing activities.
- Electricity supply & water-related services: a public-private-partnership is established, with a hybrid ownership where the public entity usually owns energy distribution network and/or water supply system. The private entity manages electricity and water supply as well as ice production and retail.
- WEF multi-service supply: a private entity operates the electricity supply, along with other energy-related services: retailing of small electrical appliances, microcredit services, and technical assistance. The energy investment is tied and anchored to an agribusiness company which offers rental space equipped or storage and processing services.

The

Table *8-1:* highlights main features and trade-offs between business models. Hybrid ownership and partnerships are often included, whereas the private entity usually maintain a leading role both in the development and operation phases.

Each model brings its peculiar strengths and weaknesses, as well as opportunities and risks. Electricity supply & agri-food production model focuses more on horizontal integration and faces higher capital and regulatory risks as well as higher development impact and revenue expectation.

On the other side, Electricity supply & appliances provision model brings lower risk related to capital investment and leaner ownership. While most of the models address similar customer base, from low-medium to medium income people, each model presents different ownership model and level of WEF integration in the business.

	Electricity supply & appliances provision	**Electricity supply & agri-food production**	**Electricity supply & water-related services**	**WEF multi-service supply**
Ownership	private	private-community or private-private	private-public	private-private
WEF nexus integrated in the business	low	high	medium	high
Type of supported PUE	low-energy intensive	high-energy intensive	high-energy intensive	high-energy intensive
Customer ability to pay	medium	low-medium	low-medium	low-medium
Development impact	low	high	high	high
Capital intensity	low	high	medium	medium
Regulatory complexity	low	high	high	medium
RE sources	solar	solar, biomass or hydropower	solar, biomass or hydropower	solar, biomass or hydropower

Table 8-1: Key features and trade-offs of business models

8.2. Water-Energy-Food economic impact

The main aim and core element of the impact assessment here summed up is to predict the economic effects at an early stage of an investment planning and design, in order to find ways and means to reduce adverse impacts, shape investments to suit the local needs, and present the predictions and options to decision-makers. Impact can therefore be defined as a measure of the changes, and its assessment seeks to establish a causal connection between inputs and changes in terms of magnitude or scale or both.

The evaluation here presented is based on a hydro-powered mini-grid "Ikondo-Matembwe" project developed by CEFA Ngo in rural Tanzania [164], where a local company distributes and sells electricity and water to the surrounding population of around 20.000 residents, as well as to a number of agro-forestry and livestock activities managed by the same company as part of an integrated business model, thus representing both the anchor load and additional revenue streams.

The total investment project cost is USD 3,781,131 split in its components of energy, water and food (including livestock):

- Energy: USD 2,950,472 (78%)
- Water: USD 337,232 (9%)
- Food: USD 493,427 (13%)

In order to evaluate the benefits of the integrated WEF nexus approach, two different scenarios have been considered: (i) sole energy implementation and, (ii) integrated WEF nexus approach.

The sole energy implementation scenario has therefore been compared with an alternative case where all components are implemented together, as in the case of a WEF nexus approach. The rationale for this comparison is that energy is the activating component for the water supplied to the village, bringing about crucial economic benefits to the target population.

In addition, energy is also the activating component of the livestock factor, as farmers need energy to improve their ability to use enhanced cultivation techniques. As per the livestock subcomponent, energy gives the opportunity to increase production through hatchery activities, through the use of electric equipment. This boosts productivity through an enhanced value chain and also improves the animals' environment and welfare.

In terms of project results, the Energy project's Economic Net Present Value (ENPV) turns out to be USD 5.940.652, while the project's highest ENPV is the integrated WEF nexus scenario with more than double ENPV for USD 12.479.239. Simultaneous implementation of the three WEF components of the project thus produces the largest impact in economic terms. These results are linked to the benefits that a sole energy project will produce on local population in comparison with those enhanced by a WEF nexus integrated approach.

The table below represents the benefits of the WEF nexus project compared to those of the sole energy project.

BENEFIT CLUSTERS	**NEXUS Project (USD)**	**ENERGY PROJECT (USD)**
AVOIDED TIME LOSS	3,307,379.52	1,537,276.08
HEALTH IMPROVEMENTS	24,670.84	24,670.84
REDUCED EMISSION	47,363.10	47,363.10
IMPROVED PRODUCTIVITY	2,680,364.20	883,864.04
ACCESS TO EDUCATION	4,958,692.70	4,958,692.70
ACCESS TO WATER	3,724,297.33	
ACCESS TO FOOD	1,902,890.99	
TOTAL	**16,645,658.67**	**7,451,866.76**

Table 8-2: Comparison between nexus and energy benefits. Source: OpenEconomics

Further indicators of project performance are the Internal Rate of Return (IRR) of 16% with a Benefit cost ratio (BCR) of 3,1 for the Energy project, and an IRR of 22,57% project and a BCR of 4,5 for the Energy, water and food integrated project.

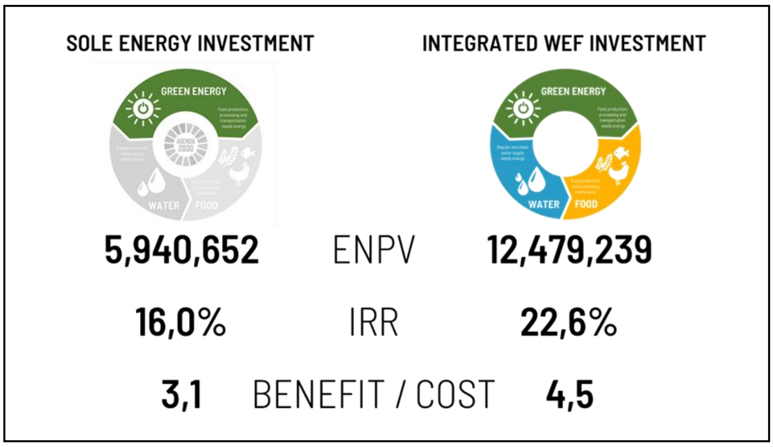


Figure 8-3: - Nexus performance indicators. Source: OpenEconomics [164]

The evaluation suggests that the success of the project depends on:

(i) the interdependence built in the project structure,
(ii) the complementarity of water, energy and food components, and
(iii) the mechanisms of adoption and diffusion that would support the replication and the scaling up of the initial, local based project.

The results suggest the following policy recommendations:

- Animation and participation
- Increase policy synergies among key sectors
- Improving information on the project
- Promote trans-boundary activities
- Create a favourable environment for investment
- Create a gender and children-equality environment

8.3. Mini-grids finance

As any other energy systems, such as grid connected ones, mini-grid systems based on renewable energies require upfront capital investments, which should theoretically be borne by the beneficiary. However, the present situation in most developing countries is that applied electricity tariffs are usually too low to recover mini-grid investment costs due to the customers' low purchasing power in rural areas. As a result, mini-grids are currently not financially viable in this context. Still, given the decrease in the price of renewable-related equipment, mini-grids utilising solar-PV are seen as an increasingly attractive option for electrification.

The total installation costs of mini-grids varies by system size, technology applied as well as choice of energy access tier and soft costs. The median value of the solar-PV mini-grid cost is USD 2.9/W, with little difference for the on- and off-grid projects. The average values are higher for off-grid systems, compared with on-grid systems. Larger systems have a lower cost variance, whereas the cost variation is the largest for off-grid systems under 125 kW (Figure 8-4).

Several factors impact the installation cost of a mini-grid, such as the equipment costs (PV module, inverter, battery if needed, and other hardware), and soft costs as project development, permit, financing and contract fees, interconnection, mark-up, training and capacity building.

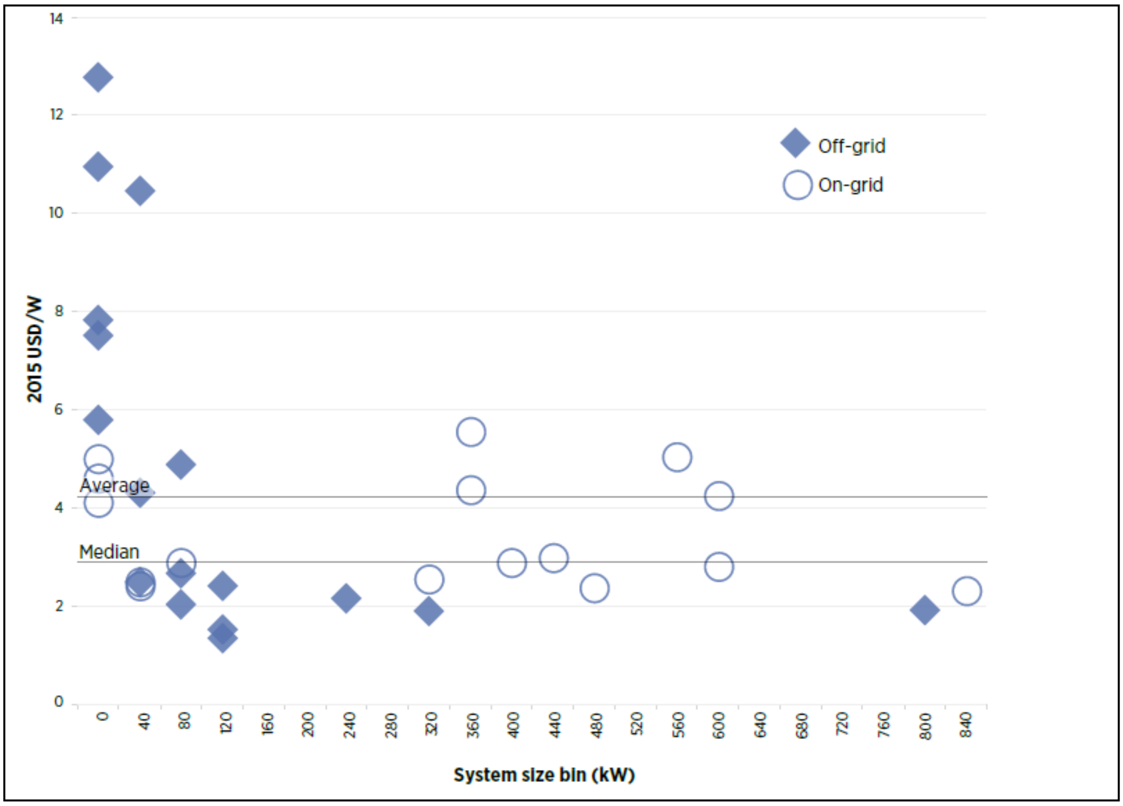


Figure 8-4: PV mini-grid system costs by system size in Africa, 2011-2015. Source: IRENA.

Nowadays, the majority of rural energy projects involve the private sector which usually engages through a concession scheme. In this case, broadly speaking, two types of financing approaches exist[13]:

- **Project Finance**, based on income from individual large asset projects with finance tied to that specific asset and financial incomes from one specific customer. This approach requires regular and predictable revenues from reliable sources (e.g. government or private businesses such as tourist resorts, agro-industries or telecom towers). It corresponds to the Anchor-Business-Community customer model (hence mini-grids usually over 1MW) and is currently not frequent in Sub-Saharan Africa.
- **Corporate Finance**, based on multiple assets shared among different customers, with finance tied to a business that invests in assets which generate financial incomes. This is the model most frequently used one in Sub-Saharan Africa (e.g. mini-grids below 1 MW).

In order to turn a project concept into reality, a sustainable financial structure must be defined, which highly depends on the type of developer, country of intervention and type of business model. With this premise in mind, in theory there are indirect financing forms of support, such as guarantees, and direct ones.

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[13] https://www.usaid.gov/energy/mini-grids/financing/capital

The three main types of direct financing mechanisms for mini-grid developers are grant/subsidy, equity, debt and a mix of these, which can be summarized as follows:

Grant aims to reduce high upfront and capital risks, to allow for higher socio-economic impact or to provide technical assistance, mainly to pilot or scale-up projects. In order to avoid later energy market distortions, which are very often linked to this financial mechanism, such instruments are normally only applied in early stage market phases where market players are fully aware when such support will be reduced or ended. Grants can be results-based or upfront.

- Upfront grants can be used for capital intensive and high risks operations to reduce the capital exposure of the project's initiator.
- Results-based grants provide payments at certain milestones (start of operation, specific amount of electricity produced, number of customers connected).

The main disadvantages of grants/subsidies concern transaction costs and the fact that the more projects rely on grants, the more difficult it is to expand and/or scale them up. Additionally, considering rural customers' low ability to pay, grants/subsidies are crucial even in very successful pilot or scale-up projects. As illustrated by a recent study on two mini-grids in Tanzania conducted by the Next Billion initiative, the tariff reduction led to a significant increase in energy consumption. Interestingly, the loss of revenue due to lower tariffs was almost entirely compensated by the increased revenues from higher consumption. But higher consumptions entail costs for the energy developer (higher OPEX for fuel-based plants or higher CAPEX or revamping for renewable-based plants).

Therefore, the developer needed tariff subsidies to be able to lower tariffs. However, relying on grants is risky due to potential discontinuity caused by unforeseeable changes in support mechanisms by governments or donors. Limiting grant supporting capital expenditures is therefore recommended. As evidenced by the cases presented in this study, most mini-grids in Sub-Saharan Africa currently need grants and subsidies, accordingly for at least 30% of investment costs to reach the financial sustainability.

Sources of **equity** can be impact investors, angel investors, venture capital, investment firms and multilateral or bilateral clean energy funds, which give funds in return for the company's partial ownership. For instance, the EU ElectriFI is an impact investment facility established by 15 European DFIs that invests in RE companies aiming at improving energy access through equity, debt or guarantee. In the case of public financing, equity is usually limited to a minor share to ensure that the ownership remains with the private sector.

Commercial banks are the most common source of **debt**, but the World Bank and other development institutions may use clean energy funds to provide commercial banks with lines of credit for loans to finance mini-grid projects.

9. Sustainability analysis

The International Energy Agency estimates that mini-grids will be the best solution for over a third of the global population currently living without electricity access [165].

Although barriers for widespread deployment of mini-grids in developing countries are reducing, the focus for key stakeholders has been largely technological to date. Business models have also been explored [166], as well as different financing mechanisms and potential for national and international interventions. There remains, however, a lack of understanding of the real social impacts of mini-grids on the community and customers they serve, due in part to the cost of collecting such data. Measuring quantitative use of system factors requires expensive metering, whilst measuring qualitative factors, such as the effect on education or community health, requires resource intensive data collection methods, such as surveys, interviews and focus group discussions. Challenges exist for collecting quantifiable data in a uniform manner that will ensure an accurate and consistent representation of these impacts to be measured across different sites and projects. Regardless, understanding and measuring how communities interact with, and are affected by mini-grids will allow better comparison with alternatives for investment when making decisions on options for sustainable electrification.

Given the potential for mini-grids as a tool within the energy sector for working towards the SDG targets, this thesis will gain insights on quantifying the holistic impact of mini-grids within the context of the SDGs, particularly with regards to the environmental, social and economic returns.

9.1. Environmental & Social Impact Assessment (E&SIA)

As the International Bank for Reconstruction and Development (IBRD) claimed, decentralised energy systems are at the forefront in the fight against poverty and climate change. Electricity services monopolized by large, state-owned or privately-owned utilities fail to meet the needs of most rural and peri-urban populations. This has created opportunities for the private sector to enter the energy field as independent power producers and service providers. Businesses can provide alternative energy supply in remote and rural areas while also providing jobs, lowering energy costs, and reducing greenhouse gas emissions[14] [15].

In developing countries, many low-income and off-grid households rely on traditional biomass, which may lead to school dropout, health hazards from indoor air pollution, deforestation, soil erosion, loss of biodiversity and related negative impacts on ecology and food security. Providing communities with energy would improve the quality of life,

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14 Coote, D. The benefits of decentralised energy. Business Spectator, 2011. Available online: https://www.theaustralian.com.au/business/business-spectator/news-story/the-benefits-of-decentralised-energy/cb371b416e3930f3d8ee7683ea2f3fe1 (accessed on 1 April 2^{019}).

[15] World Bank. *Fighting Poverty through Decentralized Renewable Energy.* In Proceedings of the *Energy SME Conference, Cambodia.* ESMAP. World Bank: Washington, DC, 2010.

including productivity, health and safety, gender equality, and education, as well as reducing greenhouse gas emissions and costs of the extension of centralized power supply lines over vast distances.

Decentralised RE systems offer an intrinsic resilience to extreme events (including natural disasters, acts of terrorism and mechanical breakdowns) that centralised systems oppositely do not. The impact on power supply of a damaged or impaired centralised system is much wider than the one of a decentralised system, as more people are affected. The predicted increase in extreme events due to climate change could have a huge impact on centralised systems in Sub-Saharan Africa in the future. Quantifying the benefits of decentralised RE systems would help mitigating the effects of such events. RE would also help reducing the occurrence of such extreme events, as there is a direct link between fossil fuel derived energy and global warming, which in turn leads to an increase in extreme events.

As an effect on social macro-data, the obvious benefit is that, renewables will not run out, making them the logical long-term option. Fossil fuel resources will become increasingly costly, which, in turn, will drive up the fuel prices at a household level, marginalising the poor. As populations grow, the demand for electrification increases simultaneously. In general, rural communities have lower population densities and a larger proportion of poor households, making it costlier to connect them. Rural grid extension involves investments and therefore risks: heavy subsidisation from governments [167] should be compared with decentralised RE solutions (individual systems or mini-grids) as they can be the best options in some contexts.

The introduction of reliable and affordable electricity provides opportunities to increase production in small rural business by replacing manual tasks with electric tools and equipment. This increases the productivity per worker, which may result in increased sales and revenue. A case study in Kenya from literature [168] found that worker productivity increased by 100-200% depending on the type of work and that income levels can increase by 20-70% depending on the product. However, the supply of renewable electricity alone is not enough to generate this kind of impact, since it should be part of a broader integrated rural development strategy, such as an integrated package of complementary infrastructure, which contributes to strengthen local economy, including better exploitation of the agricultural potential.

Another example where electricity can have positive impacts in a community is the opportunity to develop systems that will reduce storage losses of agricultural products, especially perishable horticultural products, while increasing access to markets over a longer period. Food products that are harvested from a farmer’s field but are lost in the supply systems before they are consumed are considered post-harvest losses. These losses can occur at different stages along the supply chain, and while there are some general patterns, these losses vary by region, crops grown, and markets. Estimates of post-harvest losses are variable, but up to 37% of the mass of all food is lost in Sub-Saharan Africa or 120 - 170 kg/person – year [169].

Electricity supply will be most beneficial for the portion of the perishable food supplies, such as horticultural crops, and have less impact on post-harvest losses for items like grains, where other improvements are needed. Refrigerated storage is especially important in rural areas where mini-grids will be deployed because people often rely on income from food production and spend a significant amount of their income to purchase food. Refrigeration services are also important for other sectors, such as health, where proper storage of medicines and vaccines can contribute to the provision of improved and timelier health care at a lower cost to the community because of reduced travel and lost time.

Small scale energy systems have the potential to generate a range of direct and indirect jobs and contribute to local economic development. Some of these benefits, such as people directly employed with the establishment and operation of the micro-grid, are immediately apparent and easy to measure; however, the number of people directly impacted tends to be small. Indirect economic benefit is created as workers spend a portion of their salaries in the local economy, which subsequently leads to new jobs in the community. The job creation benefits are greater in the community when PUE is boosted by enabling more value-added activities such as processing and manufacturing.

Other studies of rural electrification in Sub-Saharan Africa have shown that the associated economic development benefits are often hard to measure in the first few years. There are changes in the community that can be observed but it can take longer for this to translate into measurable economic development in a community[16].

This suggests that there is a need for good impact analysis that includes baseline data before systems are installed and a commitment in at least some communities to track the impacts and changes over a number of years.

However, the World Bank, which finances and subsidizes many energy access programs, has lately assigned solar mini-grids in “Category B” of Environmental Risk assessment, meaning that negative impacts are expected only at local level and easily mitigated by a sustainable implementation risk reduction strategy.

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[16] Toman, M.; Peters, J. *Rural electrification: How much does Sub-Sharan Africa need the grid?*. 2017. Let’s Talk Development. Available online: https://blogs.worldbank.org/developmenttalk/rural-electrification-how-much-does-sub-saharan-africa-need-grid

9.2. SROI Analysis – *Ref. Projects PR-5,6*

Just a small amount of electricity can change the lives of poor people. The primary benefits from access to electricity include improved education, human health, communication and entertainment, comfort, protection, convenience, and productivity. Until recently, the magnitude of these benefits has not been well documented. The last point of this thesis is to present an extensive methodology for quantifying these benefits from access to electricity.

The traditional method to estimate the financial returns of a mini-grid project is to use a financial model and outline main metrics such IRR and ROI[17]. Both can serve to represent the average annual return of an investment and can be used either as a forward-looking estimate of performance or a backward- looking evaluation of a completed investment. When used together, both metrics can provide valuable insights into an investment's past or potential future performance: while IRR is better suited for evaluating potential long-term investments, ROI may provide a sufficient "back of the envelope" picture for shorter term investments.

From the energy point of view, the indicator Energy Return On Investment (EROI)[18] is widely used to estimate the energy flows linked to an initiative[163][170].
EROI can be defined as the of the amount of usable energy (the exergy) delivered from a particular energy resource to the amount of exergy used to obtain that energy resource IRR, ROI and EROI metrics can be of limited use when evaluating mini-grids for rural electrification since they fail to take into account impacts on social, environmental and economic factors.
Social return on investment (SROI) is a systematic approach that attempts to holistically define whether investing in a mini-grid is beneficial and profitable not only to the developers but also to the community of interest. Though it has its own complexities, SROI for mini-grids can be used to design a business plan, better understand the target group, enhance the customer value proposition and assess to what extent impacts are realized or changes need to be incorporated in the business plan.

The SROI method helps to build on the existing financial model of a mini-grid project by introducing social, environmental and economic indicators and monetizing them to arrive at an enhanced overall return that includes financial with the other aforementioned parameters.

This perspective ideally opens new opportunities and will form the basis for innovative investments that will genuinely contribute to a positive social change. An example of expected outcomes in a mini-grid project applying the SROI approach is given in Table 9-1.

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[17] https://www.investopedia.com/articles/investing/111715/return-investment-roi-vs-internal-rate-return-irr.asp
[18] https://en.wikipedia.org/wiki/Energy_return_on_investment

Aspect	Outcomes
Social	Direct job creation Enhanced gender equality and empowerment Enhanced literacy and earning potential Improved public healthcare, safety and security Time saving (cooking, washing, collecting fuelwood) Improved access to information Strengthened food security
Environmental	Reduced dependence on fossil fuel Reduced waste disposal Reduced air pollution Responsible use of natural resources (land, water)
Economic	Value creation through productive use Access to credit Increased savings Livelihood enhancement Increased consumption of electricity Saving on governmental subsidies Saving on main-grid extension

Table 9-1: Example of expected outcomes in a mini-grid project applying the SROI approach.

Social Returns on Investment (SROI) is a systematic approach to include social, environmental and economic values into the decision-making process for projects. It is perceived that mini-grids for rural electrification influence the social, environmental and economic factors in a rural setting, but it is not yet well understood.

SROI for mini-grids will attempt to holistically define whether investing in a mini-grid is beneficial and profitable not only to the developers but also to the community of interest. Though it has its own complexities, SROI for mini-grids can be used to design a business plan, better understand the target group, enhance the customer value proposition and for assessing to what extent impact is realized or changes that need to be incorporated in the business plan.

The Social Return on Investment (SROI) measures the value added to the society caused by different interventions. Within the scope of an SROI analysis, an impact model establishes causal relationships for a specific project, programme or organisation. The impact identified in this way is measured and, where appropriate, converted into monetary units. It becomes possible to aggregate the individual impacts and correlate them in total to the input. The resulting SROI value represents the relationship between the monetised impacts and the input. Therefore, impacts need to be identified, quantified and then monetised. Unlike a normal cost-benefit analysis the SROI places much more emphasis on impact.

A proper model is needed to correctly design a research and build the impact chains [171].

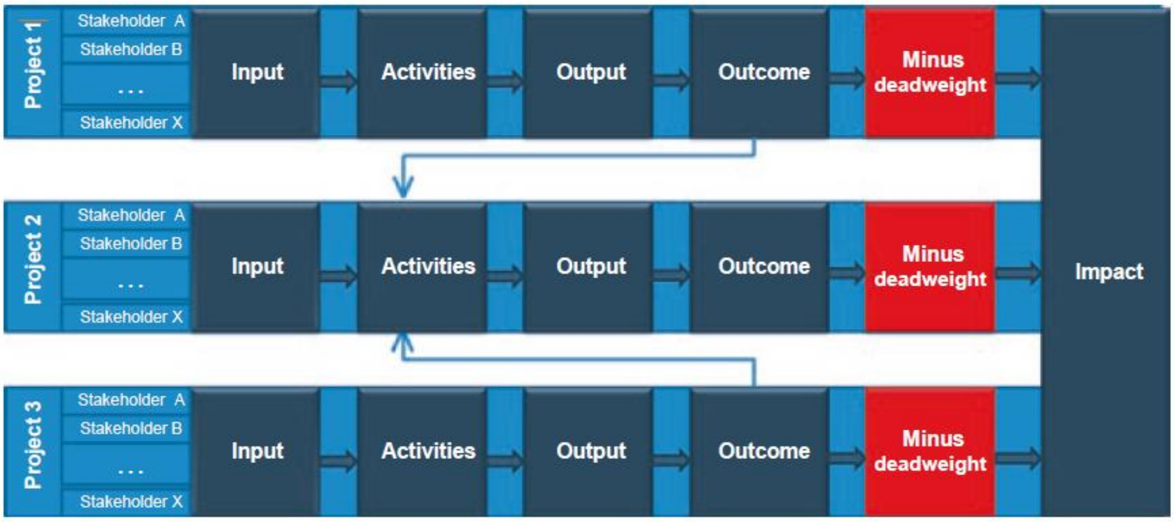

Figure 9-1: Impact model including stakeholder differentiation. Source: Palgrave Studies in Impact Finance

Impact chains, following the Logical Framework Analysis structure, need to be setup for each individual stakeholder, leading to different activities and outputs. These each in turn generate stakeholders' specific outcomes. Behind the overall goal "access to energy", there is more impact from renewable mini-grid projects, such as business stimulation, environmental protection, job placements, enhanced know-how, etc..

Impacts can be looked at and situated at different levels. They can be differentiated, for instance, based on a content level (economic, social, political, environmental, cultural), a structural level (micro, meso and macro) and a temporal level (short-term, mid-term and long term). The model design must be complex enough to be able to verify the strategic objectives of an intervention, but simple enough that it can be performed with acceptable costs and methodological rigour.

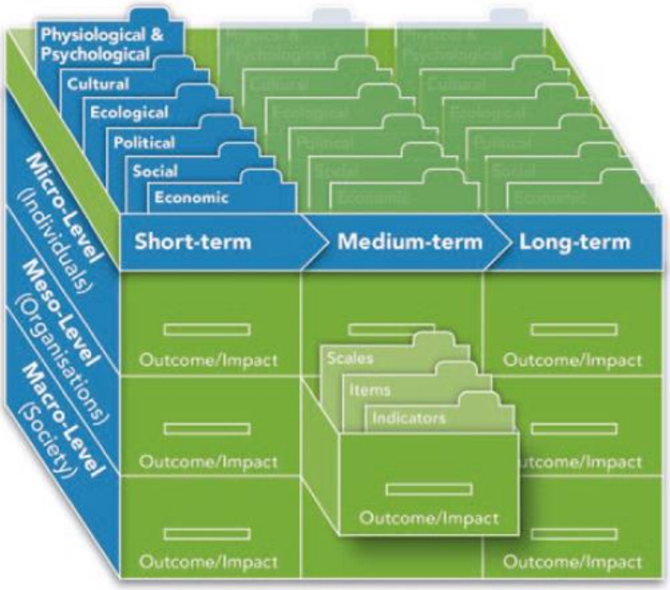

Figure 9-2: Impact box-levels of impact (measurement). Source: Palgrave Studies in Impact Finance

Next section summarizes a study conducted to outline the Monitoring and Evaluation phase of the Kitobo Island solar mini-grid project, intended to complete an SROI analysis of the project in order to demonstrate social impacts benefits gained in accordance with SDGs 3, 4, 7, 8,13, and 16.

The author collaborated with a group of Columbia University undergraduates in conjunction with the mini-grid developer Absolute Energy, the communities of Kitobo and Bukasa, and other independent partners involved in the project since 2017.

Type of analysis: cross sectional.

All the data are collected at the same time, multiple data points can help show the indicators trend. Impact chains are outlined through the Logical Framework approach.

Data collection

The data required to measure some of the indicators have been collected and measured through desktop analysis and field surveys. The data collection mechanism is defined to address the following aspects:

1) Defining the group of interest and sample methodology
2) Indicators that could help measure the outcome if there was no mini-grid intervention
3) Directly attributing the measurements to the mini-grid project
4) Period of data collection

Defining Indicators

The defined outcomes have been used to identify key indicators. These indicators are the input to the SROI model. Indicators needed to be defined to validate if the outcome has occurred and by how much. It is also important to define these indicators such that they are not only measurable but also measure them within the scope of the project. Indicators need to be set against each of the outcome as defined in the previous step.

Valuation of the outcomes

This process of valuation entailed assigning a monetary value to some of these outcomes. The purpose is to reveal the value of the social outcomes and show their relevance in relation to financial outcomes. The methodology of this process for those outcomes that cannot be directly translated into economic terms is to define appropriate proxies for the outcomes. There are of course other complexities to define these proxies as the perceived value of the outcomes can be different for different stakeholders.

9.2.1. Introduction

A few years ago, the island of Kitobo did not have adequate or affordable electricity for its population of 1500 inhabitants. In alignment with Sustainable Development Goal Seven, SDG 7, Kitobo was in need of affordable and clean Energy to improve the livelihood of its people and their environment. The goal of the mini-grid project was to supply energy to the south-western part of Kitobo which contains the majority of the population and infrastructure.

An increase in electricity aligns with SDG 7 because with the system, it was expected that there would be better educational tools, better security, more job opportunities, positive environmental effects and increased hours of operation for businesses and schools.

Stakeholders from the Kitobo project are looking into implementing a similar solar mini-grid on the nearby island of Bukasa, however the current Kitobo system is operating at a financial loss. The current state of operation necessitates both an identification of areas for improvement in technical and economic system efficiency and also an evaluation of the social, economic, and environmental value generated by the system in order to maintain and increase donor support for the Kitobo and Bukasa projects.

Quantification of benefits that are not captured solely by economics helps demonstrate the project’s holistic utility to the community, as well as highlight areas for improvement, ultimately generating increased project efficiency and support. Thus, an impact evaluation is essential to close the gap between the current and desired project states and understanding the positive and negative impacts of the project.

Here, a Social Return on Investment (SROI), which quantifies the impact of a variety of social metrics, is calculated in order to assess the feasibility and benefits of implementing a similar mini-grid on Bukasa as well as suggest areas for improvement to the current project.

9.2.2. Methodology:

In partnership with the aforementioned stakeholders, a SROI analysis has been initiated on the Kitobo mini-grid in order to define its social impact and identify areas for project improvement in moving forward with the Bukasa Island mini-grid project.
However, an additional data collection and analysis procedure for M&E are required for both projects in order to streamline a more thorough process moving forward. For this preliminary SROI of the current Kitobo project, the scope of the investigation is consisting of five key dimensions and relevant metrics of interest for analysis and monetization.

These dimensions are Education, Health, Security, Environment, and Economy. Specific quantitative indicators were selected from each dimension based on their ability to bolster survey responses that had been collected previously.

Dimension	Indicator
A: Education	A1: Enrollment in Third Term A2: Enrollment in Primary School A3: Enrollment in Secondary School A4: Annual Enrollment of Kitobo
B: Health	B1: Vaccination Rates B2: Diversity of Vaccines Offered B3: Refrigeration and Medication Lost B4: Drug Store Hours
C: Security	C1: Rapes & Sexual Assaults on Minors C2: Break-ins C3: Prostitution from the mainland C4: Fire accident
D: Environment	D1: Greenhouse Gases Reduction D2: Environment Treatment Cost D3: Air Quality Index D4: Waste Reduction
E: Economy	E1: Sustainable Economic Growth E2: Informal Employment E3: Material Footprint E4: Hourly Earnings

Table 9-2: SROI selected indicators

Improving the education of the island works to meet SDG 4 is to “ensure inclusive and equitable quality education and promote lifelong learning opportunities for all”. Indicators analysed for education were third term enrolment, final year enrolment, graduation rate, student continuing to secondary education, and primary level exam scores.

Improving the health and well-being of the inhabitants of Kitobo Island is important in order to achieve SDG 3, “ensuring healthy lives and promote well-being for all at all ages”. Specific indicators selected for health analysis include vaccination rates, drug store hours, and patient flow rates at clinics. From surveys and focus groups to actual reports, security has notoriously improved ever since a sustainable power-grid is present on the island of Kitobo. In focus groups, residents reported feeling safer in Kitobo and SDG 16 seeks to “promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels”. Indicators identified for security include rape and sexual assault rates on minors, break in’s, prostitution rates, and fire accidents.

Kitobo’s minigrid works towards accomplishing SDG 13 to “take urgent action to combat climate change and its impacts”. Environmental indicators identified include indoor air pollution reductions, deforestation reductions, and avoided CO2 emissions.

Finally, the energy access should provide more productivity to the local economy. Energy production will diversify the local economy and help to build a more independent and resilient community and will also help with increase quality of the local labour.

9.2.3. Results

For the SROI evaluation, all the benefits identified from different dimensions have been integrated as the SROI is defined as the total social benefit of the project, over the cost or investment of it.

The SROI for solar mini-grids looks at outputs and impacts in social, political, cultural, environmental, and economic contexts to determine a value added to the society because of the solar mini-grid intervention and establish causal relationships for the project.

Unlike other metrics that often rely on only one aspect, SROI is based on several, leading to a well-rounded impression of the positive and negative outcomes of a project. Then, the dimensional indicators outlined in the SROI have been quantified and analysed to determine positive and negative factors of the project, assuming an evaluation period of 5 years.

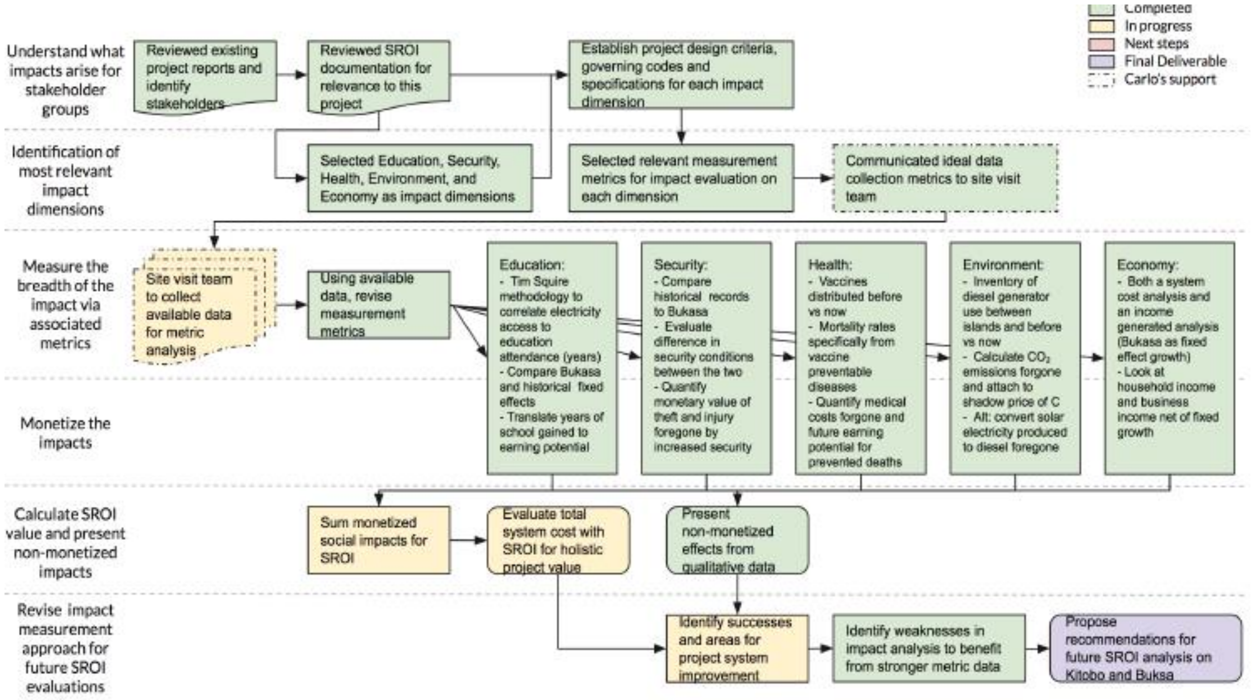

Figure 9-3: Kitobo mini-grid SROI Process Flow Chart

Due to delays in data collection the data analysis is still at an early stage and more information are needed to be able to provide a reliable and sound output.

So far, monetized values of benefits have been estimated at around 52,000 USD, corresponding to an additional 100% of the current project revenues (estimated in 10,000 USD/year in 2017-2018-2019).

Integrated project revenue streams would be more than doubled in this case, showing how relevant extra electricity contributions can be on project financials.

10.Conclusion

Regarding the research questions proposed in Chapter 1, the presented work extensively addressed them getting satisfactory feedbacks.
Following the workflow analysis the first investigated point is the load profiling of target end-users: the energy need assessment is particularly important in the development of rural electrification project, especially in mini-grids, both from (i) business perspective, allowing to reduce the investment risk and from (ii) technical perspective, allowing to develop reliable load profiling and optimize the energy management systems. Reason why the accuracy of inputs used as well as assumptions selected directly affect the technical and financial feasibility studies. Results of the energy need assessment represents such inputs and provide most of the assumptions used in business modelling and mini-grid design.

The effects of uncertainties in load profiles have in fact a huge impact on the sizing, cost and reliability of off-grid systems, where the estimation of average daily load as the starting point for intuitive design approach is not satisfactory, and that alternatives for improving such estimates is not available.
Thus, the proposed energy demand assessment methodology aims to contribute to bridging the gap between the development of modelling tools and the field challenges with a focus on uncertainties of remote communities.

With such outputs, the work moves to the design phase of generation and distribution: available renewable energy technologies explored in this thesis have nowadays reached a certain stage of market maturity and robustness, paving the way to a vast number of possible storage hybridization options and generation multi-source combinations.
Given that, multiple design choices can be made case-by-case, to obtain the best technology mix in terms of cost/benefits and system reliability. In a hybrid mini-grid composed by PV plant, Battery Energy Storage System, and Diesel Generator, the most stressed component of the working condition is the BESS. Different control logics can improve the lifetime of the BESS, thus adapting the Diesel Generator to work in optimal conditions.

Having an improved design and system sizing increase project outreach and avoids extra costs for plant oversizing or unforeseen expansion in case of undersizing, thus maximizing efficiency and profit planning over medium-long term.
Nevertheless, in a short-time horizon for smaller time-steps, operating strategies are fundamental to ensure system reliability and service delivery, mainly to keep voltage and frequency levels within acceptability range and properly deal with unpredictability of renewable sources on daily, even hourly basis.

Demand-side management, control logics and system automation play as well a crucial role in the operation phase, reason why different strategies have been explored and simulated on different generation sources combinations and off-takers behaviours and needs.

The different sizing and planning scenarios analysed in this work indicate that operation strategies in mini-grid systems can have a high potential for both project developers and end-users.

Improvement is mainly achieved by adopting an integrated approach which considers load assessment, sizing, planning, operations and global impact as a whole, dynamic system.

The combination of all methodologies and strategies improve the systems design and operation, helping reduce capital expenditures and operating costs, thus allowing for a lower LCOE.

Another important conclusion of this study is that mini-grids have meaningful socio-economic impacts that have to be taken into account and can be leveraged at fundraising stage. The SROI tool has been presented and adapted to real case studies in order to identify and monetize extra-economic impacts, on a view to enhance financial performance and foster viability of renewable-based mini-grid projects.

There is still a long way to go for this market to get subsidy-free profitability for private sector, but a wide set of positive impacts can drive governments actions toward this direction.

As PV and Bess become more and more commercially viable and technically reliable, operating models will increase accuracy and the integrated management will be the game-changing approach, where engineering models will serve as basis to dedicated softwares for larger energy system planning and control.

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The PhD experience has been an amazing time during which I had the chance to connect with many high-level academics and professionals, passionate scholars and inspiring people.

The research activities allowed me to know Africa and Latin America to get real insights on energy poverty and real people needs, balancing between a student's hunger for knowledge and the drive to have real impact on the ground.

It is easy to imagine how challenging a rural and poor context can be, in terms of carrying out data collection campaigns, reaching stakeholders and local institution in off-grid conditions, difficulties with equipment transport and field activities, but at the end of this journey I can proudly declare my satisfaction with the work done so far and I am not lying by saying that a huge impact has been achieved.

Some clean energy systems are now operational and effective thanks to my research group work at Sapienza University, and more than 10.000 people in Africa are getting access to electricity, which means unlocking many opportunities for economic growth and people's development.

This could not be possible without my research teammates, starting from Professor Andrea Micangeli (as usual) , Valeria Gambino, Paolo Cherubini and Riccardo Del Citto.

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Hopefully this work will benefit people and organizations who are constantly looking towards a better future through renewable energy applications in an environmentally sustainable way, and hopefully this spirit will keep inspiring my life.

The end of a journey is always a new beginning.

Carlo Tacconelli

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