DOTTORATO DI RICERCA IN INGEGNERIA INDUSTRIALE

(PhD School in Industrial Engineering)

XXXIII ciclo *(cycle)*

Analisi di modelli di business e metodologie per ottimizzare la progettazione di sistemi energetici isolati da fonti rinnovabili nei paesi in via di sviluppo

(Business model analysis and methodologies to optimize the system design of renewable energy mini-grids in developing countries)

Settore scientifico disciplinare *(Scientific field)*: ING-IND/09
Sistemi per l'energia e l'ambiente *(Energy systems and power generation)*

Dottorando *(PhD candidate)*
Valeria Gambino

Tutore *(Supervisor)*
Prof. Maurizio De Lucia

Co-Tutore *(2nd Supervisor)*
Prof. Romano Giglioli

Coordinatore *(Head of the PhD School)*
Prof. Gianpaolo Manfrida

Anni *(Years)* 2017-2021

Business model analysis and methodologies to optimize the system design of renewable energy mini-grids in developing countries.

Valeria Gambino, 2021.

Supervisors

Prof. Maurizio De Lucia	University of Florence, Dept. of Industrial Engineering
Prof. Romano Giglioli	University of Pisa, Dept. of Energy, Systems, Territory, and Construction Engineering

Revised by

Prof. Enrico Bocci	Marconi University of Rome Dept. of Subnuclear Nuclear Physics and Radiation
Prof. Linda Barelli	University of Perugia Dept. of Industrial Engineering

Department of Industrial Engineering, University of Florence

Via di S. Marta, 3

50139, Florence, Italy

Abstract

Energy is crucial for eradication of poverty and for combating climate change. Notwithstanding progress in every area of sustainable energy, energy poverty still involves a large proportion of the population living in developing countries, mainly concentrated in Sub-Saharan Africa. To seize the gap of universal access to energy set out by the Sustainable Development Goal 7 a mix of technical solutions is needed. Even if mini-grids are now considered a well-established solution, there is the urgency for involving private capital to reach a wider impact of the international action as well as to open a huge potential market. Thus, the viability of business models and their long-term technical and financial sustainability become fundamental aspects to face the main obstacles retaining private investments, which are usually identified in the financial, technological and institutional areas, accounting for high initial costs and difficulty in access to finance due to the perceived high-risks of investments, low and unpredictable demand patterns, reduced ability to pay and low tariffs, among others.

To address these challenges, there is a need of (i) data-driven study on business models for decentralized RE solutions to identify success factors and viable approaches to pursue the viability and replicability of rural electrification projects as well as of (ii) effective methodologies in both the development and operating phases to optimize systems, de-risk investments and assure long-term sustainability.

Thus, the objective of this research project is supporting the off-grid energy sector to deploy viable and scalable renewable energy systems through methodologies and models for the mini-grid optimization in developing countries.

On the basis of a preliminary work for an in-depth understanding of the context, the core of the research project is focused on (i) a critical assessment of the techno-economic aspects of RE mini-grids and (ii) identification of innovative methodologies and business models for the system optimization and the deployment of RE mini-grids at scale.

The research methodology was structured around (i) field experience in case studies, both in the feasibility studies and executions, and (ii) desk research working on literature overview, stakeholder consultation as well as data collection and analysis of mini-grids in operation. Thus, this research project actually benefits of direct experience in the practitioners' environment and bring it into the academic environment to leverage lesson learnt, food for thought and data by using a scientific approach.

The first phase of the research project was focused on understanding of the rural electrification challenge for the system optimization and the deployment of RE mini-grids at scale in order to identify aspects which actually affect the adoption of the mini-grid solution. The second phase of the research project was focused on the development of specific analysis, methods and methodologies.

Leveraging the business model study carried out in the first phase, an aggregate and

correlation analysis of business model indicators based on 21 RE mini-grids was developed. This work aims to critically analyze in retrospective manner what is the state of the art of the mini-grid sector in SSA so far, starting from older projects commissioned in the mid-eighties up to recent develop of new projects. Such comprehensive techno-economic analysis was integrated with the analysis of political and regulatory frameworks as well as access to financing mechanisms in order to allow for the identification of innovative business models for RE mini-grid projects. The research has highlighted that it is necessary to explore emerging business models, such as water-energy-food integrated projects. If properly designed, they can contribute both to business viability and local development and, in turn, further support the sustainability of the project, in a sort of virtuous cycle.

However, innovative business models require solid assessments. With the aim to de-risk investments and increase the project sustainability, the research focused on the energy need assessment and load profiling. On one hand, a methodology to perform in-depth energy need assessment was developed and validated to provide reliable inputs for the system design and business planning. On the other hand, with the aim to give a proxy of in-depth baselines, a first hypothesis of a framework for characterization of the community's energy needs in greenfield rural electrification project was developed. The tool intends to support the preliminary phase of mini-grid business development and/or small size projects as well as to optimize the rural electrification planning tools to establish more evidence-grounded criteria for extrapolating proxy information.

In conclusion, this doctoral thesis resulted from the adoption of an original cross-cutting approach throughout the multi-dimensional nature of access to energy. It started from the practitioners' point of view to bring the scientific research beyond the state of the art and provide results to sustain the mini-grid deployment at scale in developing countries.

Acknowledgements

This doctoral program has coincided with a very special period of my life, and it contributed to turn it into an incredible and intense experience for me.

I am thankful that DIEF embraced this effort dedicated to rural electrification, giving me the opportunity to bring the field experience into the academic environment.

I would like to express my gratitude firstly to my supervisors, Prof. Maurizio De Lucia and Prof. Romano Giglioli, for their guidance and the trust they put in me throughout these years.

My sincere thanks go to Prof. Umberto Desideri for believing in my project and to Prof. Enrico Bocci and Prof. Linda Barelli for reviewing this thesis.

Nothing would have been possible without Prof. Andrea Micangeli. As my mentor and a constant point of reference, he brought me in the international cooperation and rural electrification sector years ago as well as motivated me to pursue a PhD through its driving force for developing an international research group of students, academics and practitioners.

This research project would not have this shape without my incredible research colleagues: Carlo Tacconelli and Riccardo Del Citto from Sapienza University of Rome, and Paolo Cherubini and Davide Fioriti from the University of Pisa. We dealt with our doctoral program in the same years, and we have shared many experiences and ideas, leveraging our strengths for increasing the results of all.

I would like to thank all the academics, professionals and passionate people I collaborated with for sharing with me their points of view, suggestions and explanations which allowed me to better understand the overall picture and specific details.

Finally, I would like to thank my family. I take this opportunity to sincerely thank my mother and my father for supporting me in every choice and to assist me in managing this special period of my life. I thank Luca, which has been strongly supporting me in taking decisions and pursuing my objectives.

I dedicate this thesis to my young boys Lorenzo and Federico, with my sincere hope to leave a sustainable world for them.

List of Figures

List of Tables

List of Abbreviations

AC	Alternating Current
ATP	Ability To Pay
BESS	Battery Energy Storage System
BCR	Benefit Cost Ratio
BM	Business Model
BNEF	BloombergNEF
CAPEX	CAPital EXPenditure
CBA	Cost-Benefit Analysis
CGE	Computable General Equilibrium
CIRPS	Interuniversity Research Centre on Sustainable Development
CNR	Italian National Research Council
DC	Direct Current
DOD	Depth Of Discharge
DSM	Demand Side Management
ENA	Energy Need Assessment
ESMAP	Energy Sector Management Assistance Program
FS4MGO	Field Studies for Micro Grid Optimization
GDP	Gross Domestic Product
GEP	Global Electrification Platform
GIS	Geographic Information Systems
GSM	Global System for Mobile communication
EARP	Electricity Access Role-Out Program
EAT	Energy Assessment Toolkit
EDA	Energy Daily Allowance
ENPV	Economic Net Present Value
ESIA	Environmental and Social Impact Assessment
ICT	Information and Communications Technology
IEA	International Energy Agency
IBRD	International Bank for Reconstruction and Development
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal Rate of Return
KTH	KTH Royal Institute of Technology
LCOE	Levelized Cost of Electricity
LSMS	Living Standards Measurement Study
MIT	Massachusetts Institute of Technology
MTF	Multi-Tier Framework
MVC	Matembwe Village Company Ltd
NGO	Non-Governmental Organization
NPV	Net Present Value
NREL	National Renewable Energy Laboratory

O&M	Operation & Maintenance
OnSSET	Open Source Spatial Electrification Tool
OPEX	OPerating EXpenditure
PAYG	Pay-As-You-Go
PCA	Principal Component Analysis
PnP SHS	Plug-and-play Solar Home Systems
PPA	Power Purchase Agreement
PPP	Public Purchase Partnership
PUE	Productive Uses of Electricity
PV	Photovoltaic
RE	Renewable Energy
REM	Reference Electrification Model
ROI	Return Of Investment
RWF	RWandan Francs
SAM	Social Accounting Matrix
SDG	Sustainable Development Goal
SEforALL	Sustainable Energy for All
SHS	Solar Home Systems
SOC	State Of Charge
SPV	Special Purpose Vehicle
SSA	Sub-Saharan Africa
SROI	Social Return of Investment
T&D	Transmission and Distribution
USAID	U.S. Agency for International Development
WACC	Weighted Average Cost of Capital
WEF	Water-Energy-Food
WTP	Willingness To Pay

Contents

1

Research statement

1.1. Context

Energy is crucial for eradication of poverty through advancements in health, education, water supply and industrialization, to combating climate change [1]. Notwithstanding progress in every area of sustainable energy, energy poverty still involves a large proportion of the population living in developing countries, mainly concentrated in Sub-Saharan Africa (SSA).

Reaching universal access to electricity by 2030 is a key objective set out by the international community through the Sustainable Development Goal (SDG) 7 [2]. Most recent projections indicate that the global access rate, estimated at 90% in 2018, will reach 93% in 2030, leaving 620 million people deprived of electricity access, 85% of which will be located in SSA [3], and further delay is expected in the light of the ongoing COVID-19 crisis [4].

To mention one of the largest global initiatives showing the international commitment to solve the problem of energy poverty, the United Nations launched in 2011 Sustainable Energy for All (SEforALL), having the core objective to assure universal access to modern and sustainable energy by 2030, improving the rate of renewables in the energy mix and promoting energy efficiency. Also thanks to the high visibility being given to the initiative during the Rio+20 Conference, SEforALL embarked on uncharted territory and rapidly generated momentum, clearly stating, inter alia, that the cooperation among research, private and public sector is the key to achieve these goals [5].

According to SEforALL and other international programs, the approach to the problem of access to energy has gone through a profound change in the last decade and, in particular, an actual turning point in the implementation of policies and regulations in developing countries was noticed in the last seven years, enabling the rural electrification market to private actors. Accordingly, while before cooperation development agencies only supported no-profit actors in rural electrification projects, in the last years they have been allowing private investors to be eligible for funding as well (e.g., the 2016 and 2017 ElectriFI tenders financed from the EU, the RBF calls financed by the English cooperation, the EEP fund financed by the governments of UK, Austria and Finland or the first tender for the profit sector launched in July 2017 by the Italian Agency for Development Cooperation).

To seize the gap of universal access to energy a mix of technical solutions is needed such as a combination of reinforcement and extension of the existing grid infrastructure, and widespread deployment of decentralized solutions such as stand-alone and mini-grid systems [6]. The latter are deemed as the most appropriate technological solution for all the rural communities that are too far from the national grid but are densely populated and with high potential demand [7]. Mini-grids are now considered a well-established solution, thanks to a rapidly increasing diffusion, a more favorable regulatory environment, decreasing costs and increased quality of service [8]. The Energy Sector Management Assistance Program (ESMAP) estimates that some 220 billion dollars will need to be invested in mini-grids to reach universal access by 2030, an effort that would require a strong involvement of private developers and suppliers, in combination with public funding programs [8].

These figures highlight the necessity for involving private capital to reach a wider impact of the international action: in mini-grid projects, the ratio between project budget and beneficiaries is too high to justify grant funding up to 70% on large scale programs of the total budget and no-profit actors cannot afford a reduction of grant funding. On the other hand, private actors are able to invest in such projects to open a huge potential market, even if they assume high financial and development risks. With this in mind, the viability of business models and their long-term technical and financial sustainability become fundamental aspects to face mini-grid projects and a special focus is on effective payment systems.

1.2. Relevance

The main obstacles retaining private investments in mini-grids are usually identified in the financial, technological and institutional areas, accounting for high initial costs and difficulty in access to finance due to the perceived high-risks of investments, low and unpredictable demand patterns, reduced ability to pay and low tariffs and weak policies, among others [9].While these factors are generally present in SSA, they are found declined differently in every specific context, resulting in a lack of a proven business model that can be easily replicated [10]. While private developers are operating and maintaining existing projects and installing new ones, there is not a proportionate stream of data and analyses to capture the current situation and trends. Lack of data and communication is in fact recognized as another key challenge for the mini-grid sector [10], which can be eased by private sector associations that can aggregate information from their members [11].

The "lack of documented experiences, information, knowledge, and open source quality data on renewable mini-grids in sub-Saharan Africa", in the words of Moner-Girona and coworkers, affects as well energy planners and policy-makers [12].

To address these challenges, there is a need of (i) data-driven study on business models for decentralized RE solutions to identify success factors and viable approaches to pursue the viability and replicability of rural electrification projects as well as of (ii) effective methodologies in both the development and operating phases to optimize systems, de-risk investments and assure long-term sustainability.

1.3. Objectives and results

The objective of this research project is supporting the off-grid energy sector to deploy viable and scalable renewable energy (RE) systems through methodologies and models for the mini-grid optimization in developing countries.

On the basis of a preliminary work for an in-depth understanding of the context, the core of the research project is focused on (i) a critical assessment of the techno-economic aspects of RE mini-grids and (ii) identification of innovative methodologies and business models for the system optimization and the deployment of RE mini-grids at scale.

The main **project results** achieved are the following:

R1. Aggregate and correlation analysis of business model indicators based on 21 RE mini-grids by means of a set of 48 indicators identified. It aims to provide a picture, based on the available dataset, of different kind of electrification approaches adopted in SSA, starting from older projects commissioned in the mid-eighties, up to recent ones. Then, in addition to the descriptive aggregate analysis, the research seeks correlations among indicators with the aim to critically analyze in retrospective manner what is the state of the art of the mini-grid sector in SSA so far, and to provide practitioners and developers with evidence to actually support the design, develop and evaluate new projects. R1 is detailed in Section 3.4.
R2. Identification of innovative business models for RE mini-grid projects by means of a critical assessment of techno-economic results given by R1, which was analyzed taking into account their feasibility within the political and regulatory framework as well as their access to financing mechanisms. It aims to provide practitioners and decision makers with viable solutions to boost the mini-grid deployment at scale and promote an enabling environment. R2 is detailed in Chapter 4.
R3. Methodology for the energy need assessment (ENA) to effectively design and deploy mini-grids for rural electrification for high reliable in-depth baselines in greenfield projects, which includes data collection methods, data analysis model, estimation of the willingness to pay (WTP) for electricity and load profiling (current and forecast). It aims to support the viability gap of mini-grid business models identified in R2, but not limited to, by de-risking investments, increasing the project sustainability as well as addressing the need to clearly define, test and validate procedures to be applied at scale in order to provide reliable inputs for the system design. R3 is detailed in Chapter 5.

R4. Framework for characterization of the community's energy needs in greenfield rural electrification project, which includes estimation of the WTP for electricity as well as the shape and amplitude of load profiling (current and forecast) which are correlated to environmental and socio-economic parameters.

On the basis of R1 and R3 for defining the framework of indicators, it aims to provide a proxy of in-depth baselines with reliable inputs for business planning and systems design. Thus, it is a preliminary (or alternative) methodology to that given in R3, to be adopted in two fields of application: (i) the preliminary phase of business development (or small-size projects not requiring in-depth baselines as in R3), and (ii) the optimization of the rural electrification planning tools.

R4 is detailed in Chapter 6.

1.4. Methodology

The first phase of this research was focused on an in-depth understanding of the rural electrification challenge, by leveraging previous experiences and researches as well as conducting literature overview, stakeholder consultation and gathering a data base of mini-grid projects. In particular, I have brought my background of 5 years professional experience in the international cooperation, working with both profit and non-for-profit mini-grid developers.

The main mini-grid projects I was involved in and which have supported this research projects thanks to lesson learnt, food for thought and data, where clearly specified as in the Tanzanian case (see section 3.3), are the following:

- ***2014: Increasing access to modern energy services in Ikondo Ward, Njombe (Tanzania).*** Rural electrification of 7 villages through a hydro-power generation of 430 kW. *Developer:* CEFA NGO, co-funded by European Commission.
- ***2015-16: Sustainable energy services for Kitobo island (Uganda).*** 228 kWp solar photovoltaic (PV) with storage, diesel backup and LV distribution smart grid connection about 600 customers. *Developer:* Absolute Energy, in partnership with AVSI Foundation and CIRPS, co-funded by EEP.
- ***2016-17: Ndurumo sustainable energy partnership (Kenya).*** 320kW hydroelectric power plant and MV distribution smart grid connection about 7,000 customers. *Developer:* Absolute Energy, in partnership with AVSI Foundation and CIRPS, co-funded by EEP and Shell Foundation.
- ***2016-17: Solar hybrid mini-grid in the village of Rutenderi (Rwanda).*** 50 kWp solar PV with storage, diesel backup and LV distribution smart grid. *Developer:* Absolute Energy, co-funded by EnDev.

Furthermore, the methodology for ENA, which was validated during this research project, comes from an extensive testing phase I have been dealing with since 2012. The first methodology's formulation was born from the CIRPS experience in the mini-grid sector and it was applied and improved time and time again along ***7 data collection campaigns carried out in 36 villages in Honduras, Uganda and Kenya*** in the period before this research project (2012-2017). Each data collection campaign (and related energy need assessment, including load profiling and WTP) revealed margin for improvement and suggests strengths and weaknesses of the methodology, which were addressed time after time to increase the results' reliability. The methodology for ENA was validated and applied again during this research project, in further 4 data collection campaigns in 24 villages in Rwanda, Mozambique and Democratic Republic of Congo as detailed in Chapters 5 and 6.

The key output of this first phase was the identification of aspects which actually affect the mini-grid deployment at scale. Thus, starting from the practitioners' point of view, this academic research selected those aspects that could go beyond the state of the art by leveraging our background and technical expertise.

The second phase of this research was focused on the development of analysis, methods and methodologies related to such aspects and that represent the **research project's results**, as summed up in section 1.3. Specific methodologies applied in each activity, associated to the project research's results, are extensively described in sections 3.4.3 (R.1), 4.3 (R.2), 5.3 (R.3) and 6.4 (R.4). The overall process is shown in the Figure 1.

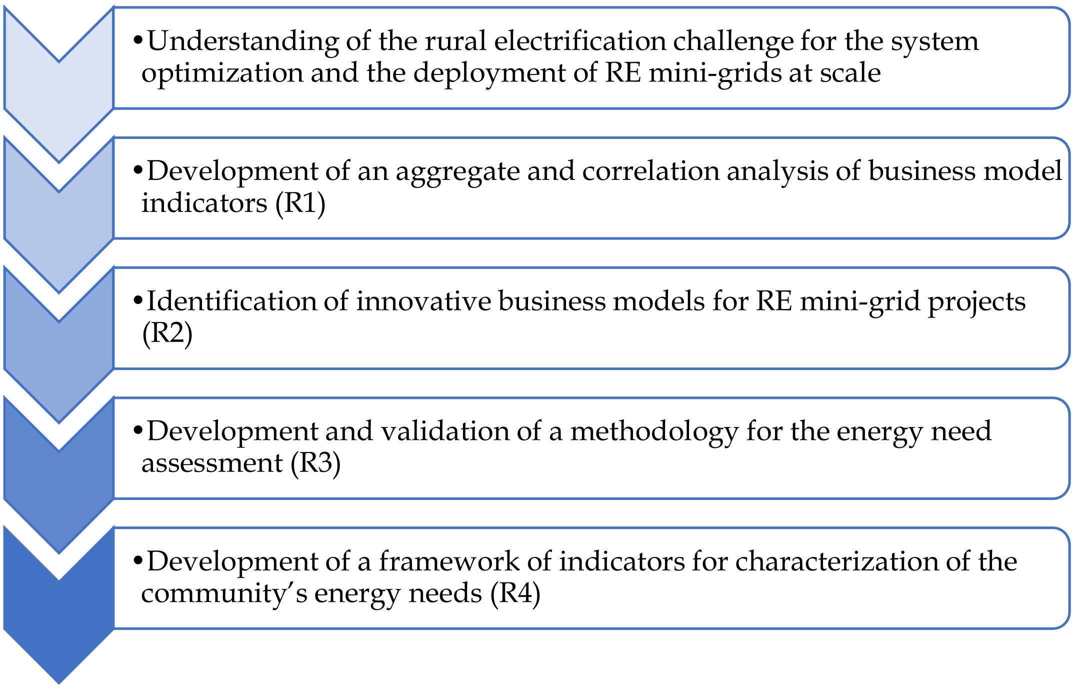


Figure 1 - Flowchart of the project research

This research was carried out within the framework of the Field Studies for Micro Grid Optimization (FS4MGO) in collaboration with RES4Africa Foundation, with specific reference to the desk analysis to understand the context and the business model analysis.

FS4MGO is an academic research group composed of international universities with the purpose of enhancing the global access to energy, in line with the UN Sustainable Development Goals, and fostering a sustainable economic growth in developing countries.

Active FS4MGO members are University of Rome, University of Pisa, Massachusetts Institute of Technology, Columbia University of New York (USA), State University of New York (USA), University of Oxford (UK), 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.

1.5. Reference publications

This thesis is based on the following co-authored reference publications, which were finalized during the research project's period:

1. *Gambino V., Cherubini P., Tacconelli C., Micangeli A., Giglioli R.* ***Methodology for the Energy Need Assessment to Effectively Design and Deploy Mini-Grids for Rural Electrification.*** *Energies 2019, Vol. 12, Page 574, vol. 12, no. 3, p. 574, 2019. https://doi.org/10.3390/en12030574*

2. *Gambino V., Cherubini P., Micangeli A., Giglioli R.* ***Case Study Analysis of 21 RE Mini-grids in Sub-Saharan Africa: Aggregate and Correlation Analysis of Business Model Indicators.*** *Renewable and Sustainable Energy Transition 2021, in course of publication.*

3. *Gambino V., Cherubini P., Micangeli A., Giglioli R.* ***A Framework for Characterization of the Community's Energy Needs in Greenfield Rural Electrification Projects.*** *Renewable and Sustainable Energy Transition 2021, in course of publication.*

4. *Gambino V., Cherubini P., Micangeli A., Trotter P., Sisul M., Garcia A., et al.* ***RE-thinking Access to Energy Business Models. Ways to Walk the Water-Energy-Food Nexus Talk in Sub-Saharan Africa.*** *RES4Africa, Gangemi Editore International, 2019. ISBN 978-88-492-3804-4.*

5. *OpenEconomics (Gambino V. among the working group members).* ***Applying the Water-Energy-Food Nexus Approach to Catalyse Transformational Change in Africa.*** *RES4Africa, OpenEconomics, 2019.*

Specifically, reference publications for each section are reported hereafter:

- **Chapter 2.** Understanding the rural electrification challenge
  RE-thinking Access to Energy Business Models. Ways to Walk the Water-Energy-Food Nexus Talk in Sub-Saharan Africa. Reference sections: 1.1-1.2-1.3-5.1-5.2-5.3-7.1

- **Chapter 3.** Analysis of mini-grid business models
  3.1. Rationale behind a focus on mini-grid business models
  RE-thinking Access to Energy Business Models. Ways to Walk the Water-Energy-Food Nexus Talk in Sub-Saharan Africa. Reference sections: 2.0

  3.2. Integrated strategies to foster mini-grid deployment
  RE-thinking Access to Energy Business Models. Ways to Walk the Water-Energy-Food Nexus Talk in Sub-Saharan Africa. Reference sections: 3.1-3.2-3.3

3.3. WEF nexus integrated business model: a successful case study from Tanzania operating since 1987
Applying the Water-Energy-Food Nexus Approach to Catalyse Transformational Change in Africa. Reference sections: 3.1-4.1-4.4-6.1-6.4-6.5-8

3.4. Case study analysis of 21 RE mini-grids: aggregate and correlation analysis of business model indicators.
Case Study Analysis of 21 RE Mini-Grids In Sub-Saharan Africa: Aggregate and Correlation Analysis of Business Model Indicators.

3.4.4 Business model classifications
RE-thinking Access to Energy Business Models. Ways to Walk the Water-Energy-Food Nexus Talk in Sub-Saharan Africa. Reference sections: 2.1

- **Chapter 4.** Action roadmap to sustain the deployment of mini-grids
  RE-thinking Access to Energy Business Models. Ways to Walk the Water-Energy-Food Nexus Talk in Sub-Saharan Africa. Reference section: 9
- **Chapter 5.** Methodology for the energy need assessment
  Methodology for the Energy Need Assessment to Effectively Design and Deploy Mini-Grids for Rural Electrification.
- **Chapter 6.** Characterization of the community's energy needs
  A Framework for Characterization of the Community's Energy Needs in Greenfield Rural Electrification Projects.
- **Chapter 7.** Conclusions
  Methodology for the Energy Need Assessment to Effectively Design and Deploy Mini-Grids for Rural Electrification.

  Case Study Analysis of 21 RE Mini-Grids In Sub-Saharan Africa: Aggregate and Correlation Analysis of Business Model Indicators.

  A Framework for Characterization of the Community's Energy Needs in Greenfield Rural Electrification Projects.

  RE-Thinking Access to Energy Business Models. Ways to Walk the Water-Energy-Food Nexus Talk in Sub-Saharan Africa.

  Applying the Water-Energy-Food Nexus Approach to Catalyse Transformational Change in Africa.

2

Understanding the rural electrification challenge

2.1. Off-grid market size

2.2.1. Access to electricity: current status and forecast

It is estimated that 1.2 billion people gained access to electricity between 1990-2016 [13], and that the global share of population with access to electricity increased from 71.4% to 87.4% [14]. The progress has been substantial and has accelerated in the last years: whereas 62 million people gained access each year from 2000 to 2012, this amount has raised to 100 million people per year since 2012 [13]. In 2018, the number of people without access to electricity worldwide fell below 1 billion for the first time in modern history [15].

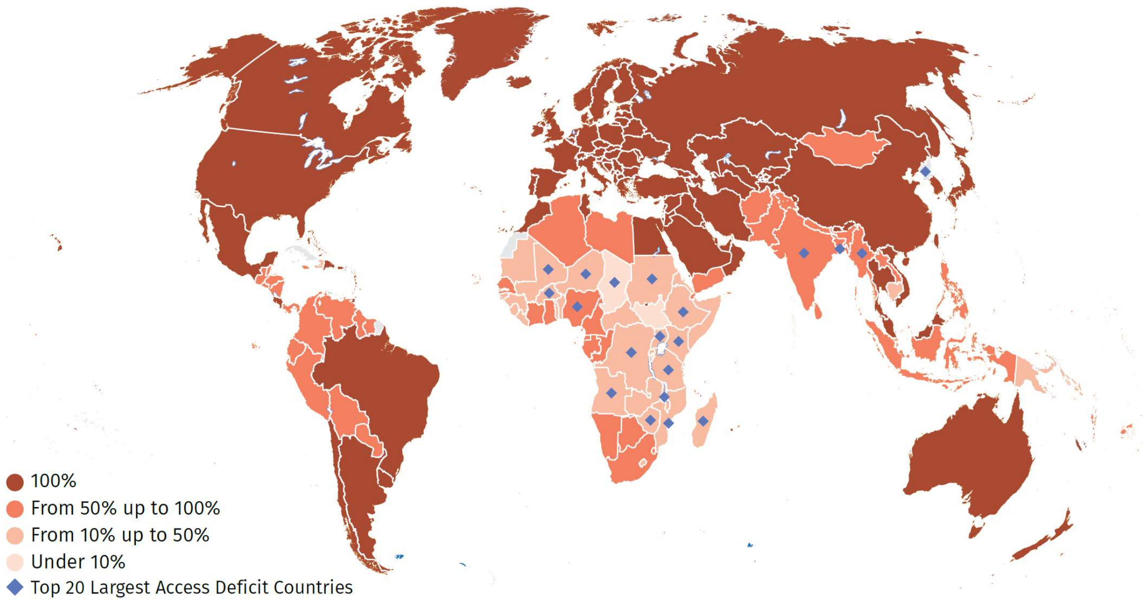


Figure 2 – Share of population with access to electricity in 2016 (%). Source: World Bank [16].

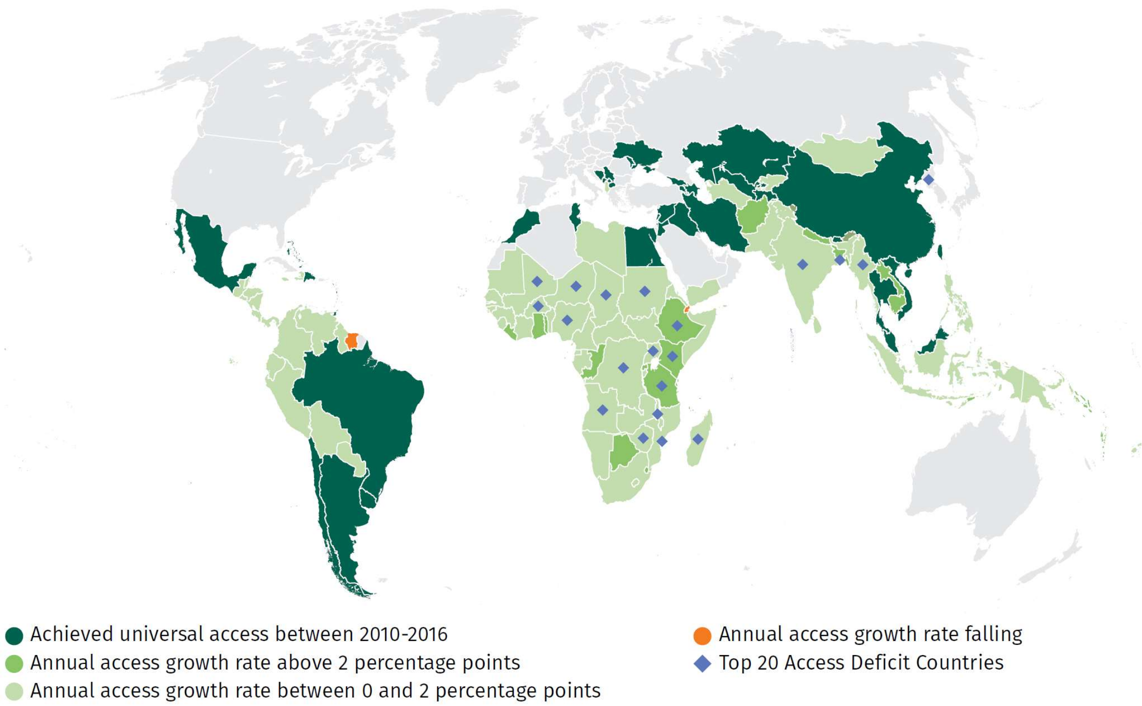


Figure 3 – Annual increase in electricity access rate in 2010-2016 in access deficit countries. Source: World Bank [16].

Despite all these encouraging achievements, the world is still off-track to comply with the targets of SDG 7 (ensure access to affordable, reliable, sustainable and modern energy for all by 2030). Taking as reference the most recent issue of the World Energy Outlook [17], International Energy Agency (IEA) draws two scenarios to assess the future of access to electricity:

1. the New Policies Scenario, which considers the policies and implementing measures adopted as of mid-2018 along with relevant policy proposals announced;
2. the Sustainable Development Scenario, which considers the steps to be undertaken to comply with the objectives set out with the SDGs, particularly SDG 7.

In the first scenario, which considers an average annual electricity access investment of USD 30 billion, there would still be 650 million people without access in 2030 and 720 million in 2040, due to population growth outpacing the rate of access: an outcome that would clearly be very far from the universal access goal. For the second scenario, the IEA estimates that about USD 55 billion need to be invested every year between 2018 and 2030. Thus, compared to the New Policies Scenario, the Sustainable Development Scenario implies an additional investment of 82% in SSA alone.

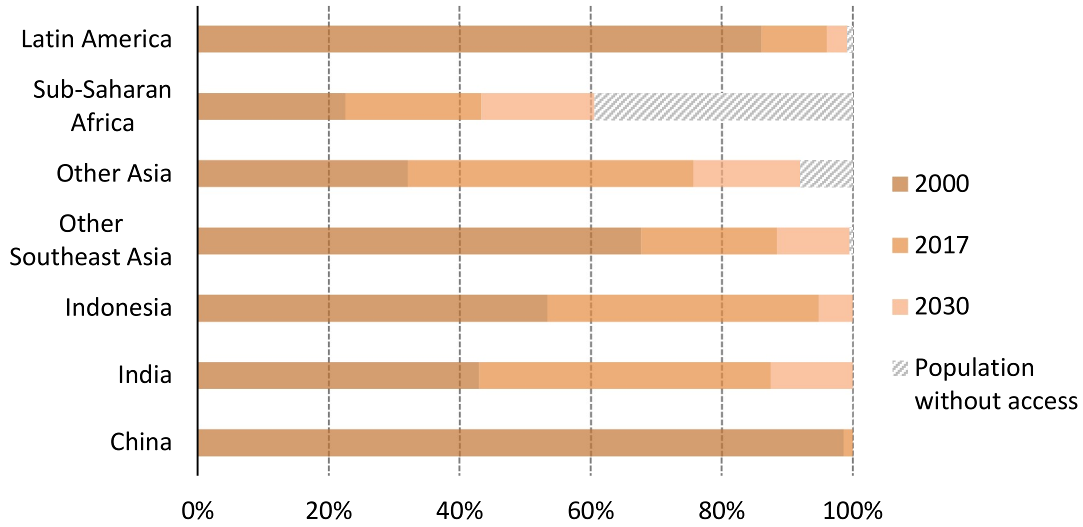


Figure 4 - Progress since 2000 and outlook to 2030 for electricity access in the New Policies Scenario. Source: IEA[17].

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 [18]. SSA 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 [17]. As a result, SSA's share in the global access deficit has more than doubled between 1990 and 2016 [16]. Furthermore, the IEA highlights how progress in the region has been uneven: 60% of new accesses since 2011 have been concentrated in Kenya, Ethiopia, Tanzania and Nigeria only.

Therefore, by looking at the IEA's forecasts (Figure 4), it is evident that with the current and announced policies, SSA will be the region mostly affected by lack of electricity access. In fact, out of the 650 million people still lacking access to electricity worldwide in 2030, most of them will live in rural settlements in SSA, which will have reached only a 61% electrification rate.

2.2.2. Demographic and electrification trends

As anticipated in the previous section, the forecast of electricity access in SSA largely depends, among other factors, on the population growth. Therefore, to get an insight of the future electrification needs and potential markets, demographic and migratory trends should be considered. 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 [19]. 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 [20]. 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 [20] (Figure 5). This shift will pose new challenges to urban electricity infrastructures: for instance, the IEA cites the case of South Africa, which saw its electrification rate decline since 2014, mostly because the electricity supply has not been upgraded in urban areas in response to population growth [16].

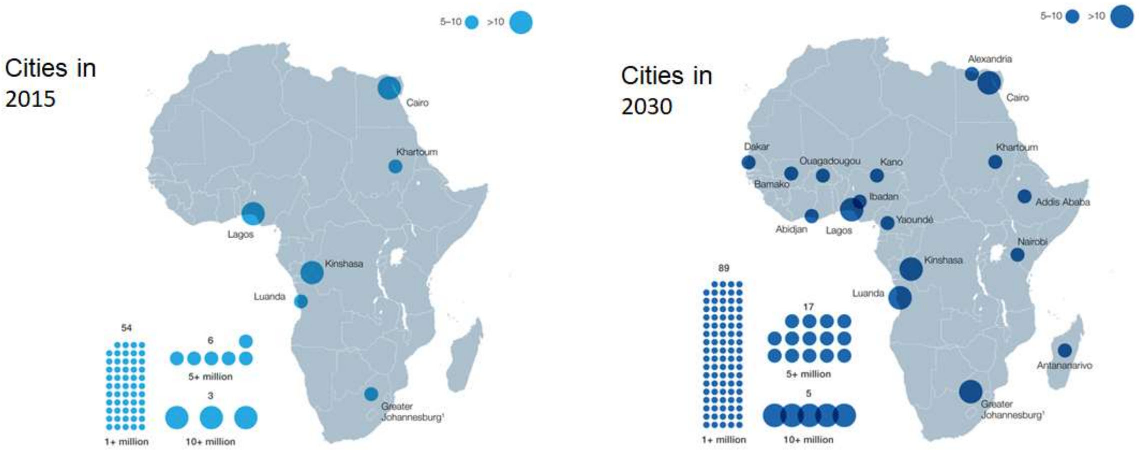


Figure 5 – African cities by population in 2015 and 2030. Source: McKinsey&Company [20].

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 [16], in SSA 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 [13].

The IEA estimate that with the current and announced policies, 80% of people with no access to electricity in 2030 will live in rural areas [13], confirming that achieving SDG 7 will depend on finding sustainable business models for the deployment of decentralised solutions and supply electricity to the more remote segments of the population.

A picture of the current status and needs is presented in Figure 6, which highlights the 20 African countries with the highest number of people lacking access. The millions of people without access to electricity in each country are shown with the corresponding percentage of urban and rural population lacking access.

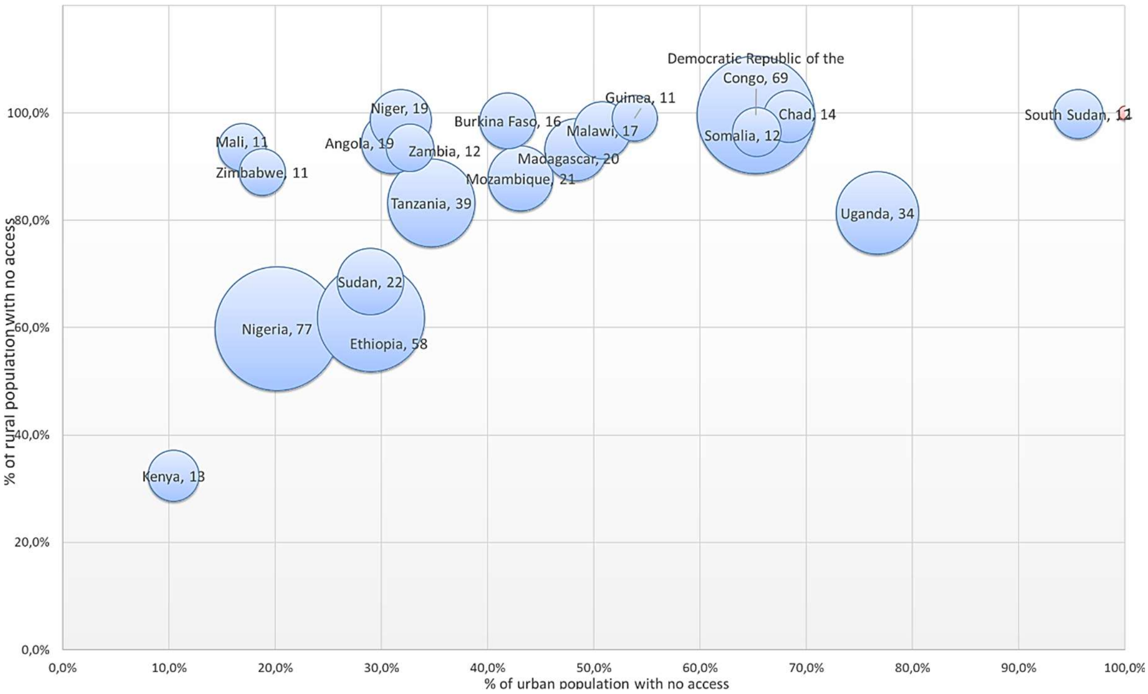


Figure 6 - Millions of people without access to electricity, with respect to urban and rural population lack of access. Blue bubbles represent the twenty countries with the highest amount of population without access. Source: IEA[17].

Although data on people living in urban and rural areas without access to electricity provide an initial estimation of the volume of intervention needed in each country, they do not provide a clear indication of the market size for decentralised RE solutions. In fact, there are many other factors influencing the optimality (in general intended as the least-cost solutions) of the three main ways to achieve access (grid extension, mini-grids, individual systems). They are analysed in section 2.2.

2.2. RE solutions for universal access to electricity

It is estimated that about 60 million people in SSA have to be provided access to electricity every year in order to achieve universal access by 2030 [13]. This will require a combination of investments in national networks, both in terms of added generation capacity and transmission and distribution (T&D) extension, and deployment of off-grid solutions either mini-grids or stand-alone systems. The best solutions for electrification are generally evaluated in terms of the least-cost solution that provides the prescribed tier of supply, which can be pursued systematically in developing national plans, as discussed in section 2.2.4.

Thus, considering the three options, grid extension and stand-alone individual solutions have traditionally received greater attention, while mini-grid systems have been left behind, even if they can offer a collective solution at a relatively lower cost and they tend to facilitate basic needs as well as productive use of electricity (PUE) thereby promoting local economic development. This is probably because the electricity supply business developed by means of mini-grid has to face a number of challenges including risky business environment due to unknown consumer characteristics and unfamiliar business activities, weak institutional arrangements arising from non-supportive regulatory and policy frameworks, limited access to low cost finance and inadequacies in local skills and capacities. However, mini-grid is currently considered as a key solution for rural electrification.

For SSA, the IEA provided outlooks for investments in the three main energy access pathways, considering both the New Policies Scenario, based on current and announced policies, and Energy for All Scenario, a path of compliance with SDG 7, as reported in Figure 7.

In the first scenario, the cumulative investment is estimated to be USD 84 billion over the 2017-30 period. 40% of cumulative investment is for decentralised systems (including mini-grid and off-grid solutions, such as individual systems, as classified by IEA in the figure) while mini-grids alone will account for around 15% (USD 12.6 bn). Even if less than a half of the investments will be addressed to decentralised solutions, they will provide energy to two thirds of the people living in rural areas. However, it is important to stress how this scenario will result in 600 million people with no access to electricity in 2030, with 80% of them living in rural areas.

In the second scenario, more than a four-fold cumulative investment will be needed compared to the first scenario in order to achieve universal access to energy. More than half of those who gain access will do so through decentralised systems. Mini-grids will attract half of the additional investment (USD 143 bn), which will cover 44% of the additional 600 million people to be connected.

Thus, projections show that the mini-grid contribution is particularly relevant to reach universal access to electricity by 2030: it results to be the least-cost solution for 30% of total connections in the Energy for All Scenario.

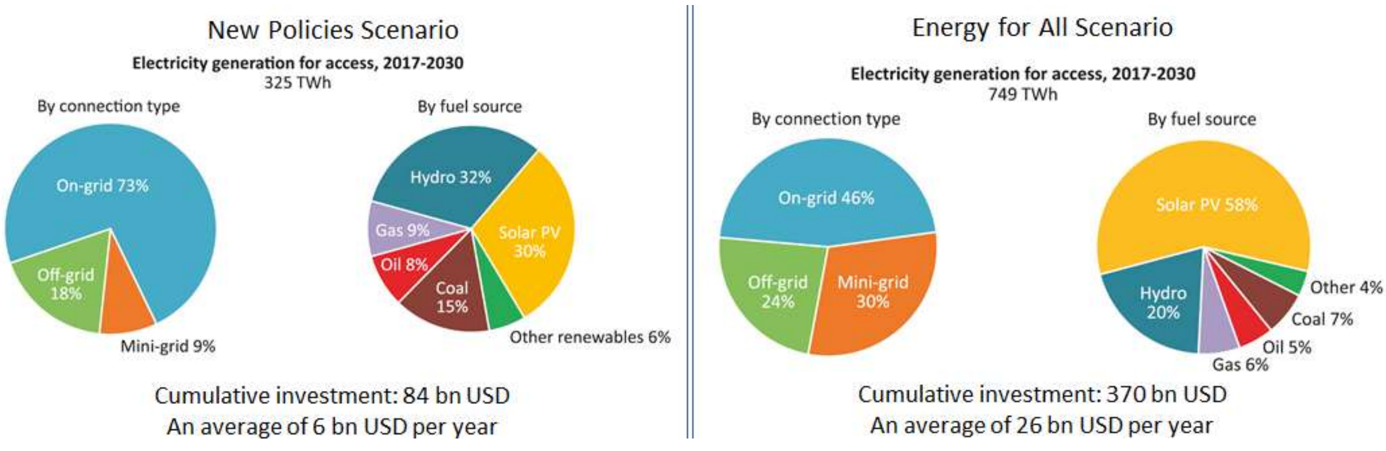


Figure 7 – Type of new connections, generation technologies and overall investment needed in SSA for 2017-2030 in the New Policies Scenario and the Energy for All Scenario. Source: IEA [13].

Furthermore, if we look at the status of investments for 13 countries in SSA in 2015-16 (Figure 8), we can see how the financing for electricity investments has been unevenly distributed among countries, too small in volume to meet SDG 7 and still reliant on grid connected fossil fuel plants. Investments in the off-grid sector are rising quickly but are mostly driven by solar stand-alone system companies in East Africa and Nigeria, thus confirming the urgency to fill the viability gap for mini-grids.

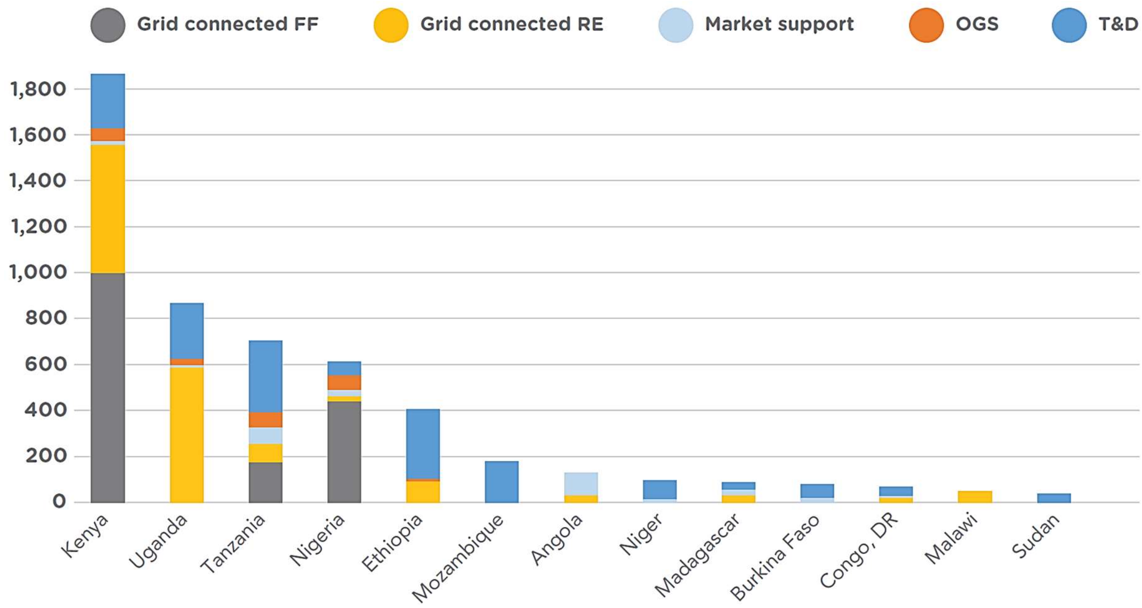


Figure 8- Electricity sectors financed in SSA in 2015-16 (USD million). Source: SEforALL [21]. Legend: FF: Fossil Fuels, RE: Renewable Energy, OGS: Off-Grid Solutions, T&D: Transmission and Distribution

2.2.1. Grid extension

Extending the national grid is the often the most obvious and desirable solution to increase access. According to BloombergNEF (BNEF), connecting new customers via grid extension costs between USD 266 and 2,100 per household [22]; 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 (Figure 9). 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 [23].

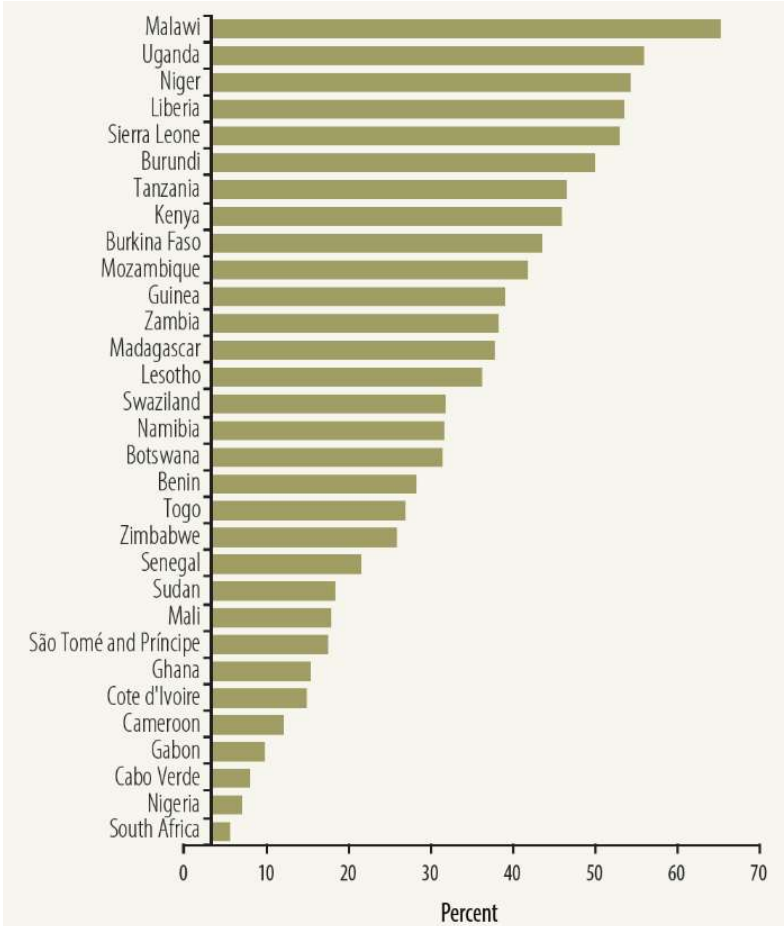


Figure 9– Percentages of people living under the grid but not taking up. Source: World Bank [24].

2.2.2. 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 [7]. Historically, rural mini-grids were powered by diesel generators and relied entirely on fossil fuels. More than 2000 mini-grids are currently installed in Africa, but only 40% of them are solar projects [25]. Overall, IRENA estimates that between 50 and 250 GW of off-grid diesel capacity worldwide could be hybridized with renewables [26]. The retrofitting of existing mini-grids represents a market opportunity as it could bring environmental benefits and significant operating expense (OPEX) savings, and reducing the risks tied to oil price fluctuations. Furthermore, the deployment of mini-grids has benefitted from steadily decreasing costs of renewable generation and energy storage, and this trend is expected to continue. IRENA estimates that the unsubsidized costs for renewable mini-grids, that in 2015 ranged from 0.47 to 0.92 USD/kWh, will fall in 2035 to the 0.19-0.35 USD/kWh range [27]. The need for hybridization is not restricted to mini-grids for local communities: BNEF estimates that, globally, mobile network operations and cellular tower operators spend USD 3.8 billion for diesel fuel annually, and that they could get a 54% cheaper service by using hybridized off-grid towers [28]. This example highlights the potential of hybrid mini-grids in combining productive uses of energy with last-mile access to energy. GIZ, the German development agency, proposed an Anchor-Business-Community model [29], by which, among the potential off-grid communities in a given area, a developer should identify a potential anchor customer to ensure a high volume of sales backed up by enough purchasing power, and then target businesses and rural households. Aggregating the demand of households and commercial customers, in addition to providing enough demand to ensure the financial viability of a project, can also help on the technical side by balancing loads that peak at different times. That would be the case, for example, of the integration of domestic rural electrification with the connection of small agribusinesses, which can greatly improve their yield through irrigation, their productivity through mechanization and their products' added value through processing [30].

Since mini-grids can provide the same service quality of a reliable grid, this opportunity can be extended to all existing or intended productive use of energy, such as drying, cooling, processing, washing, water purification and so on.

2.2.3. 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 [13], falls under the category of "individual system". However, this term generally refers to PV devices with a variety of power ratings, which start from Pico Solar systems (below 11 Wp) [31], comprising single light systems such as solar lanterns that provide a level of supply below Tier 1 (with reference to the Multi-Tier Framework discussed in section 2.3.1), or simple multiple-light systems, providing also mobile charging [32]. Plug-and-play solar home systems (PnP SHS) are packaged kits with PV panels for 11 Wp or more, which are equipped with 3-4 lights and other basic appliances, such as a fan, a radio, a TV, and so on [32]. Solar home systems (SHS) can reach up to 100 Wp of PV panels and even more, making them capable of operating DC appliances for productive use, such as refrigerators, solar water pumps or other processing tools in agriculture or other crafts [33].

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 (PV 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 [31]. SSA 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 [31].

2.2.4. Combining delivery modes

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 are one of the main factors to be investigated: assessing needs for domestic users and existing or potential business and anchor loads, 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 Tool (OnSSET) 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 [34]. 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 [35].

With a similar purpose of geospatial electrification planning, the Universal Energy Access Lab, a project by Massachusetts Institute of Technology (MIT) and Instituto de Investigación Tecnológica 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 [36]. 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 (named isolated in Figure 10).

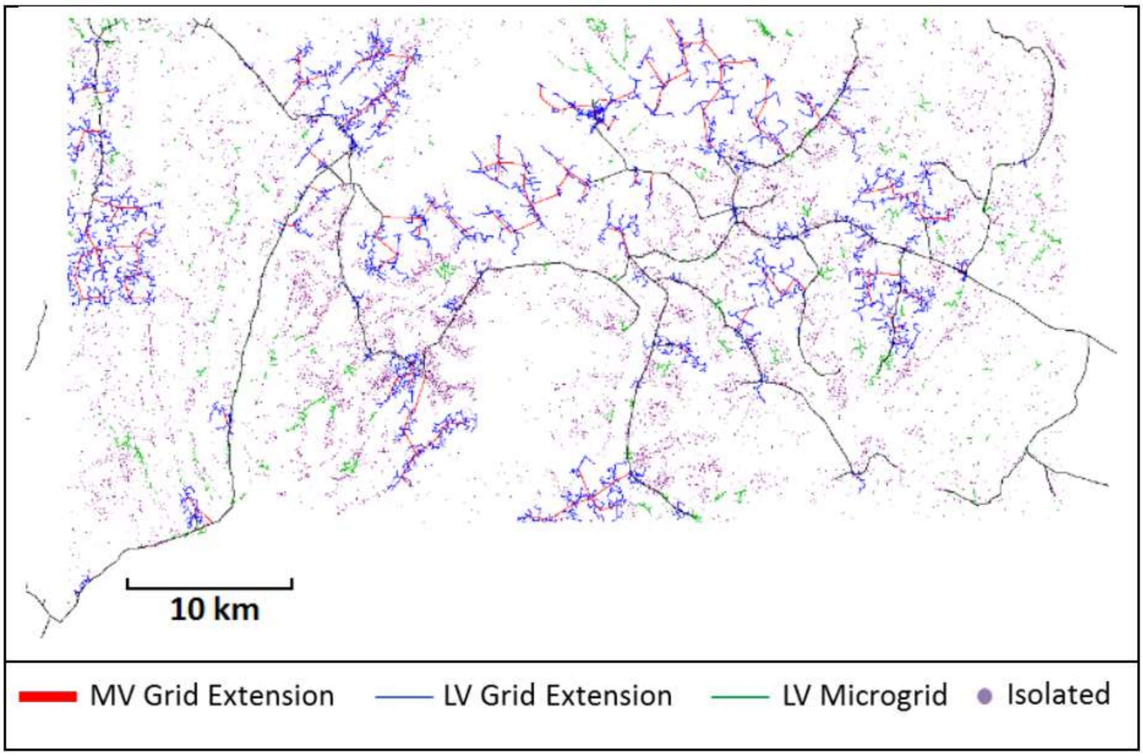


Figure 10 – Example of REM outputs for a reference case study electrification solution. The MV existing power grid is represented with black lines. Source: Amatya, R et al. [36].

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, ESMAP and KTH Division of Energy Systems Analysis [37], available as a web-based open source application for developing universal access scenarios in Zambia, Nigeria and Tanzania.

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 11 shows how increasing the target level of access drastically changes the feasibility of grid extension and mini-grids in comparison with individual systems (named stand-alone - S.A. - in the figure).

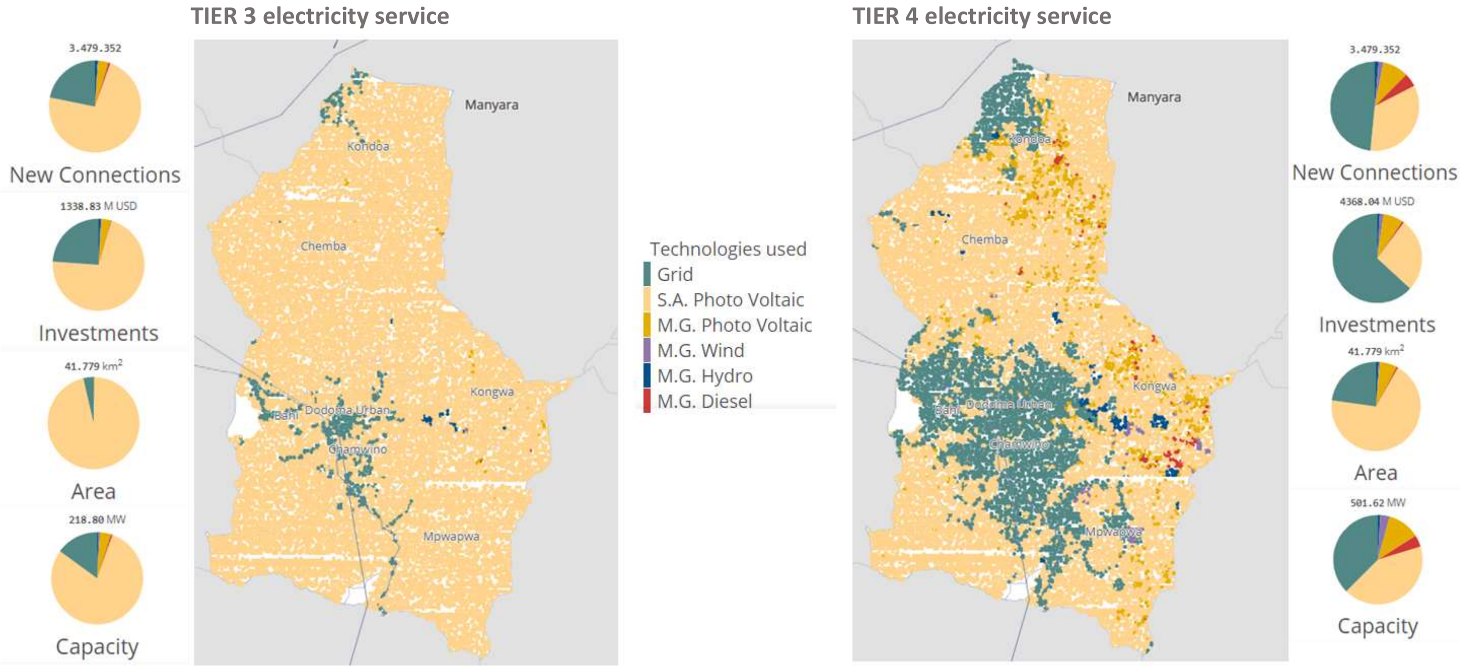


Figure 11 – Comparative results of universal access pathways with Tier 3 and Tier 4 service for the Dodoma Region of Tanzania, with a diesel price of 0.82 USD/l. Source: World Bank, KTH [37].

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 SSA hardly have structured and digitized information on their low-voltage distribution lines [38].

2.3. Energy for socio-economic development

The potential impact of electrification in SSA is substantial and multi-faceted. The United Nations has defined 17 SDGs and 169 associated specific targets to be achieved worldwide by 2030. Recent research has shown that the overwhelming majority of these targets (143 out of 169) have synergies with SDG 7 [39] (ensure access to affordable, reliable, sustainable and modern energy for all). As such synergies make it clear in terms of development (see section 2.4), electrification impacts three main domains, namely (i) economic development, (ii) social wellbeing and quality of life, and (iii) environmental aspects, including natural resource use and the water-energy-food (WEF) nexus. However, as the following discussion of these three topics indicates, a positive and sustainable impact of electrification is not an automatic given but requires an adequate and encompassing developmental approach going forward.

Before approaching the topic, it is important to have a clear picture of the different options in terms of levels of access to electricity provided (tiers), how they can be classified and thus easily identify indicators in the rural electrification projects that actually allow to achieve expected targets and impacts.

2.3.1. Electricity access tiers

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 [40]. However, in the last years, the idea of energy access as such binary parameter has been challenged to find a more comprehensive metric that uses a technology-neutral multi-tier framework [41] 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 [42] 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 12 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 13 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
1. Peak Capacity	Power capacity ratings[27] (in W or daily Wh)		Min 3 W	Min 50 W	Min 200 W	Min 800 W	Min 2 kW
			Min 12 Wh	Min 200 Wh	Min 1.0 kWh	Min 3.4 kWh	Min 8.2 kWh
	OR Services		Lighting of 1,000 lmhr/ day	Electrical lighting, air circulation, television, and phone charging are possible			
2. Availability (Duration)	Hours per day		Min 4 hrs	Min 4 hrs	Min 8 hrs	Min 16 hrs	Min 23 hrs
	Hours per evening		Min 1 hr	Min 2 hrs	Min 3 hrs	Min 4 hrs	Min 4 hrs
3. Reliability						Max 14 disruptions per week	Max 3 disruptions per week of total duration <2 hrs
4. Quality						Voltage problems do not affect the use of desired appliances	
5. Affordability					Cost of a standard consumption package of 365 kWh/year <5% of household income		
6. Legality						Bill is paid to the utility, prepaid card seller, or authorized representative	
7. Health & Safety						Absence of past accidents and perception of high risk in the future	

Figure 12 – Multi-tier Matrix for Measuring Access to Household Electricity Supply. Source: World Bank [41].

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 13 – Load levels, indicative electric appliances, and associated Capacity tiers. Source: World Bank [43].

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 42.9% level of access for Ethiopia in 2016 [44]. The MTF survey [43] 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 14 and Figure 15: 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.

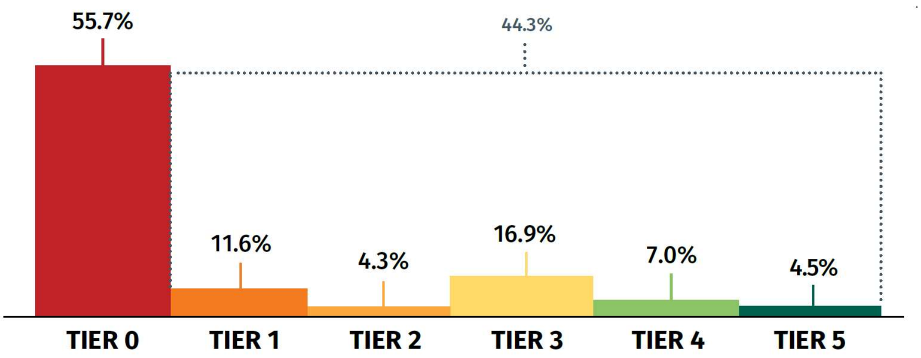


Figure 14 – Aggregate data for tiers of access/lack of access in Ethiopia. Source: World Bank [43].

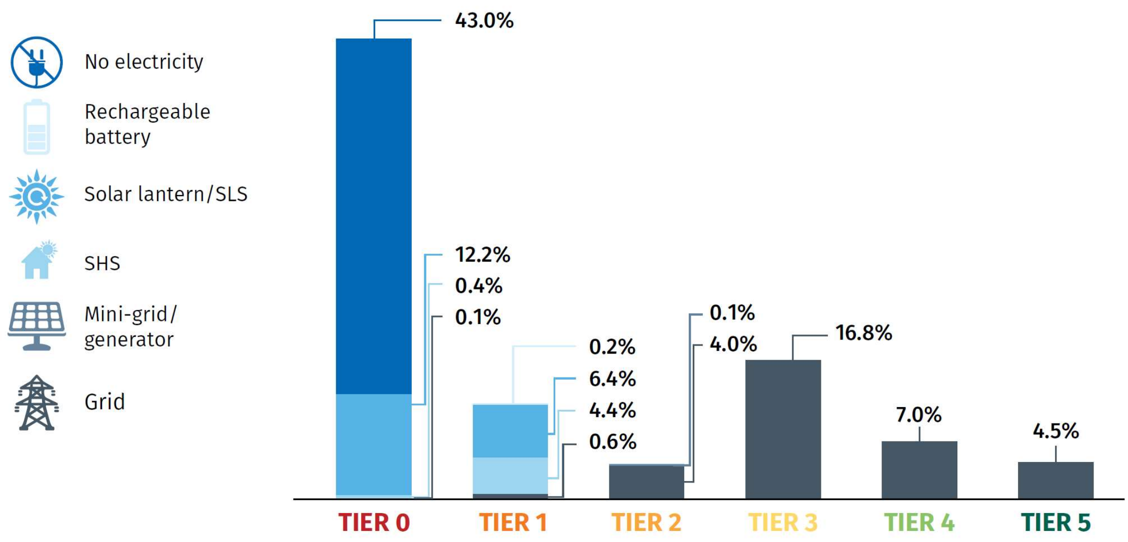


Figure 15 – Disaggregate data divided per energy source. Source: World Bank [43].

MTF surveys provide data also on energy spending and use, WTP 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 tiers of supply for new users. The output of the MTF implementation in Ethiopia suggests, for example, that 96% of unconnected households have the WTP 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 WTP 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.

2.3.2. Impact on socio-economic development

A recent review of the academic literature has found that a majority of researchers observe positive economic impacts of electrification in developing countries [45]. 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 PUE. Electric appliances for productive use can be grouped into requiring either light, medium or heavy amounts of electricity (see Table 1 for some examples). 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.

Appliance type	Electric appliance	Productive use and types of businesses
Light appliances	Lights	Longer opening times / improved appeal for shop owners
	Sockets	Mobile phone and laptop charging business
(< 0.1 kW)	Mobile phones	Rental of phones for calls on fee basis
	TV sets	Small community cinema / football broadcasts
	Sewing machines	Textile manufacturing
	Hair clippers / salon driers	Hair dresser / barbershop
Medium / continuous appliances	Power tools	Metalworking and carpentry
	Washing machines	Cleaning business
(0.1 – 1kW)	Water pumps	Water supply business
	Sprinklers, drips	Irrigation for farmers
	Commercial dryers	Drop drying, fish drying
	Electric stoves (mostly resistive heating coils)	Restaurants
Heavy / continuous appliances	Continuous refrigeration, freezing and ice making	Dairy farmers, fisheries, butchers, food and medicine transport and storage, bars
	Electric brick makers	Construction
(> 1 kW)	Electric mills	Value add for grains and cereals
	Oil seed processing machinery	Producers of vegetable oils (groundnut, sunflower, etc.)
	Air conditioning	Improved shopping experience in large retail shops

Table 1- Examples of electrical appliances and their productive use (power requirement are indicative only and depend on the individual application).

It should be noted, however, that the positive impacts observed in the academic literature are more salient in developing countries outside of rather than within SSA. In fact, of the 8 studies on Sub-Saharan African countries reviewed by Bos et al.[45], only 3 find clear positive effects of electrification on economic development, while the other 5 find no significant effects. For instance, a study examining Rwanda's Electricity Access Role-Out Program (EARP), an ambitious plan to expand the grid to rural areas, finds no notable increase of household income after more than 3 years of electrification and that both the amount of consumed electricity and the uptake of new appliances remained at low levels. Similar results on limited appliance uptake are reported for productive use in micro-enterprises [46].

In summary, it is clear that electrification is a necessary but not sufficient condition for sustained economic development in remote areas of SSA. Access to finance, quality education, effective industrial policies, and a generally favourable environment need to have been in place for some years in order to achieve tangible results.

Impact on wellbeing and quality of life

There is a widespread agreement among scholars and policy makers that electrification increases the wellbeing and quality of life of those electrified [45][47][48][49]. The following specific impacts have been documented:

- **Positive effects for education**
  The most evident and documented benefit provided by electric lighting to education is the possibility for children to study at home during dark hours, in a safe way and with increased quality compared to traditional lighting sources. Teachers are more favourable to work in rural schools if these are served by electricity, and therefore access to electricity also promotes student attendance [50]. Furthermore, electricity enables the usage of computers and internet connection as educational tools, and also the establishment of after-school programs [51].

- **Positive health-related effects**
  Reliance on inefficient fuels combined with inefficient technologies such as traditional cookstoves or kerosene lanterns exposes poor people to health-related problems. Electric lighting significantly reduces indoor air pollution, and specifically the risk of kerosene poisoning, which commonly affects children in rural households [52]. Moreover, media (television, radio and internet), access to which is enabled by electricity, are a major source of knowledge about sanitary and welfare issues, contributing to improve the health status through enhanced health knowledge [50].

- **Positive effects for social interactions and leisure-time**
  There are several household activities that involve energy: cooking, cleaning, maintenance, ironing and caretaking, consumption of information and entertainment, communication as well as income-generating activities [53]. In addition to the direct benefit given by the usage of electrical appliances, electric lights help carrying out such activities with more efficiency, flexibility in their scheduling, and saving time [54]. Mini-grids also enable the usage of appliances, such as pumps, grinders, mills and blenders, that alleviate labour-intensive tasks especially in agricultural and food processing activities [54]. The overall result is an improvement in quality of life and increase of available free time, which can be spent for leisure activities and improved social interaction. Entertainment opportunities are increased and varied, through access to TV, radio and internet.

- **Empowerment of women**
  Women's empowerment is defined by Winther et al. [53] as "a process towards gender equality, understood as women's and men' s equal rights, access to and control over resources and power to influence matters that concern or affect them". In this sense, there are many evidences showing a direct and universal impact of electricity on factors like education, access to information through television, and time use that are 'empowerment enablers' [53]. In some cases, the reduction of drudgery translates to a permanent reduction of the domestic workload, opening to employment opportunities for women outside the household; awareness about family planning gained through television leads to a controlled reduction of fertility [54]. The increased women autonomy and agency can ultimately determine a shift in gender norms and reduction of inequalities.

2.3.3. Productive use of electricity (PUE)

Researchers have been propagating three complementary strategies to ensure that electrification has a broader developmental impact in SSA, namely (i) a comprehensive rural development strategy, (ii) the promotion of off-grid electrification solutions, and (iii) the promotion of productive use of energy.

With a focus on the latter, and considering there are several attempts to come up with a clear definition of the term 'productive use', the meaning adopted in this research is aligned to the Productive Use of Energy (PRODUSE) Manual [55] that defines productive uses of electricity as "agricultural, commercial and industrial activities involving electricity services as a direct input to the production of goods or provision of services."

Thus, policies that actively foster the productive use of energy linked to the promotion of renewables need to be implemented [56] to pursue both small scale PUE and a broader sustainable low-carbon industrial development. At a small scale, this includes to enable the proper usage of commercially available AC and DC appliances by providing financing mechanisms or setting up appliance rental systems as well as increasing off-takers awareness. This approach would enable customers with limited savings to benefit from these appliances by being able to add economic value to the goods and services they provide and use the extra income to payback the appliances / rental fees. Furthermore, developers of mini-grid systems would benefit of a higher energy demand, which mainly arises from the business activities and possible anchor loads, and indirect impacts on socio-economic development (see section 2.4). At large scale, this contributes to the mitigation of climate change [56] and support mini-grid project to reach the financial sustainability by counting on reliable anchor loads.

Lastly, it is relevant to underline that the concept of productive use of energy differs from the one of WEF nexus, even if they can be overlapped or integrated in some cases, as described in section 2.3.4.

2.3.4. Water-energy-food (WEF) nexus

In addition to the energy challenges, access to clean water is a significant problem in many areas of rural SSA. 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 [57]. About 60% of the population in rural SSA areas rely on rainfed, small-scale farming activities as the primary income source [58]. 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 [59]. Yet policy-making and planning approaches are often sectorially driven [60] which can result in conflicting, counterproductive strategies [61]. By contrast, an integrated approach goes beyond the sole provision of household electricity and incorporates clean water supply, irrigation, and agro and fish-processing activities (see section 3.2.1), 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 [62] featuring joint efforts from developers, communities, financiers, and researchers as well as policy-makers to set the formal framework for frictionless project implementation.

2.4. Sustainability of mini-grid projects with PUE and WEF nexus

2.4.1. Sustainable Development Goals

In 2015, the United Nations promulgated 17 SDGs to be reached by 2030. The SDGs offer a framework to help Africa's RE industry grow sustainably while addressing the continent's energy challenge. As outlined in the United Nations 2030 Agenda for Sustainable Development, the SDGs are a set of integrated priorities, which means that many of the goals interact and influence each other. These interlinkages are important to understand so that progress for one SDG does not occur at the expense of others' (Figure 16).

Figure 16 - Sustainable Development Goals. Source: United Nations [63].

Sustainable energy interacts with several SDGs through the SDG 7, which aims to "Ensure access to affordable, reliable, sustainable and modern energy for all", specifically focuses on ensure universal access to affordable, reliable and modern energy services (7.1), increasing substantially the share of renewable energy in the global energy mix (7.2), and doubling the global rate of improvement in energy efficiency (7.3).

First, SDG 7 ties in with SDG 1, "Poverty Reduction", as energy is necessary for poverty alleviation. Replacing fossil fuels with clean energy leads to savings on fuel expenditure such as for fuel wood, charcoal, kerosene and diesel [64] and thus, with a view to maximize the socioeconomic and environmental impact, energy supply should enable income-generating opportunities. Moreover, powering productive uses of energy – such as in agriculture, industry and commercial activities – can lead to increased income through greater productivity, new income-generating opportunities, and improved access to markets [55].

The SDG 7's targets related to clean and universal energy access are also directly linked with SDG 2 "Food production and security", SDG 3 "The functioning of essential healthcare services", SDG 4 "Quality Education", SDG 6 "Clean water and sanitation", SDG 8 "Economic growth and employment" as well as SDG 11 "Climate Action".

Studies analyzing the interactions of SDG 7 with other SDGs have generally indicated positive influences, but there are potential negative or neutral impacts that should be noted. For example, the International Council for Science report [65] shows that there are many positive interactions between portions of SDG 7 and SDGs 1, 2, 3, 6, 8 and 13, but it also highlights some potential negative interactions associated with targets 7.2 and 7.3. Awareness of the possible positive and negative interactions is important to ensure that collectively the greatest benefits are generated and negative impacts are minimized when developing and deploying mini-grids. In order to track and understand these changes, impact assessment systems, that include good baseline data, should be designed and implemented so that lessons will be learned and passed on as the rate of deployment of mini-grids expands. In particular, being aware of these interactions and utilising them as deployment models for integrated WEF nexus is important to maximize the benefits across SDGs.

This study focusses on the lack of access that seriously hinders economic growth and sustainable development within the region, and it explores how decentralised renewables, together with the reliability of energy supply, could offer a solution to achieve electrification's economic benefits [66]. In this perspective, the SDGs offer a compelling growth strategy for business leaders across Africa. Achieving the goals are anticipated to open at least USD 1.1 trillion by 2030 for the private sector in Africa [67]. Rapid economic growth and changing demographics are driving an unprecedented need for greater access to affordable, reliable and modern energy services across the continent. Although there are positive trends in the pace of electrification in Africa, progress is uneven [68]. This presents a great opportunity for both developers and financiers in the energy sector to use the SDGs to set strategies and implement programmes in order to maximise positive impact and minimise the negative while creating business value.

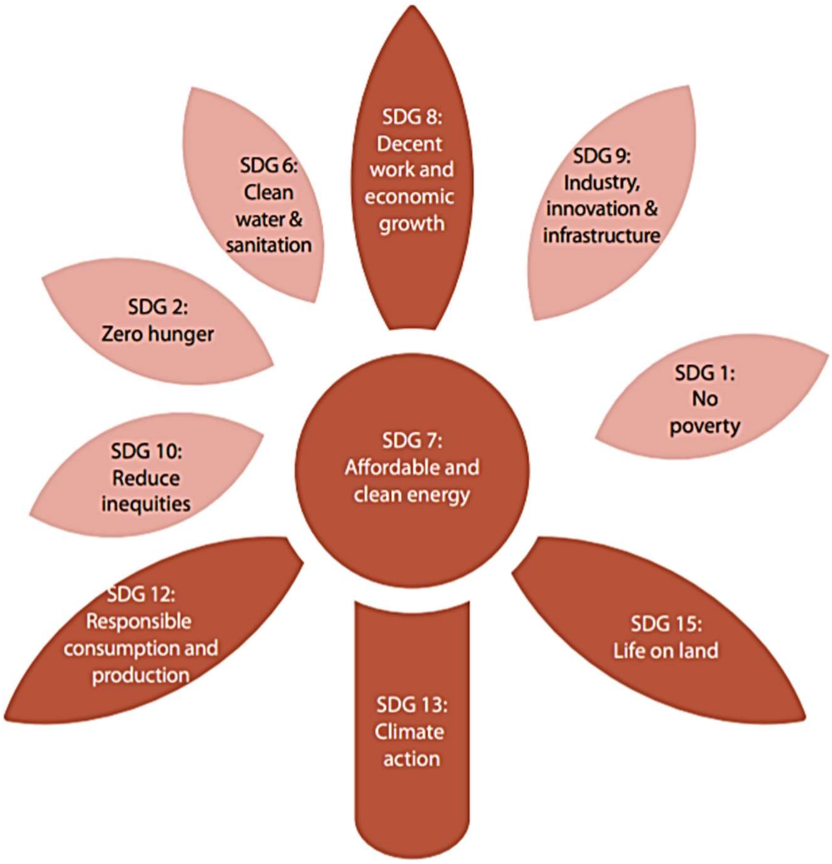


Figure 17 – Interlinkages SDG 7 and other SDGs. Source: RES4Africa Foundation [69].

In recent years, businesses have been increasing their focus on sustainability as a whole, looking not only at the economic but also at the social and environmental sustainability. Thus, even if profitability still remains a key driver for RE investment in SSA, business actors are aware that funding renewables in developing countries could create a wider opportunity to increase revenues if coupled with promotion of access to modern energy as per the SDGs. This approach leads not only to direct economic and social benefits for local development, but clean energy access also raises human security and builds resilience in states and communities in order to help limit the risks of large-scale migration across the African continent [17].

From another perspective, the RE sector through the 'shared value' approach has the potential to create positive environmental and social growth, in addition to economic one. Shared value is a modern strategy in which companies find business opportunities in solving social issues. While the most traditional corporate philanthropy focuses efforts on "giving back", which often results in expenses for the company, shared value focuses on maximizing the competitive value of finding solutions to social and environmental problems [70]. It is vital for businesses to understand the economic benefit of creating shared value in projects in SSA by turning sustainability into a business strategy. It is not enough to promote renewables: projects should be sustainable too.

In conclusion, a focus on electrification alone is not enough to sustain socio-economic development in SSA. The integration of food, water and energy security through a holistic approach could assist in reducing costs as well as negative environmental and social impacts, while enhancing investment benefits.

2.4.2. Environmental impact

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 [71]. 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 [72][71].

Recent advancements in decentralised RE systems allow for renewable energy to outcompete the traditional decentralised solutions based on fossil fuel and to be a feasible alternative to the centralised energy system model, also reducing greenhouse gas emissions [66]. An estimated 2.5 billion people are reliant on fossil and biomass fuels. Black carbon, which is produced by incomplete combustion of these fuels, is the second largest man-made substance driving global warming after CO_2, and is linked to a high degree of atmospheric heating [73].

Climate change has the potential to seriously affect human lives, livelihoods and health, and this is particularly true in the case of poor and vulnerable people. Direct effects include injury or death related to floods or heat waves, the magnitude and occurrence of which become more severe and frequent as the climate changes. Indirect effects include changes in the distribution or impacts of some infectious diseases related to altered agricultural productivity: for example, higher temperatures, humidity and an increase in the melting of permafrost is thought to have led to the release of dormant pathogens in the Arctic. Animal carcasses carrying these pathogens become exposed after thawing of the ice [74], and in some cases, this has led to mortality of livestock and humans.

Decentralised renewable resources, such as small-scale solar and wind generation units, are more environmentally sustainable as they use locally available and RE sources and generally employ less water, thus resulting in a reduced environmental impact compared to the extraction, transformation and distribution of fossil fuels [75]. In addition to the reduction of greenhouse gas pollution and the resultant climate change, there are a range of additional benefits of producing and distributing RE in a decentralised manner.

In SSA, many low-income and off-grid households rely on traditional biomass [76], 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, 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.

2.4.3. Social impact

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 SSA 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.

Climate change is placing more pressure on water, food and energy sources: this means that applying the WEF nexus approach is more vital than ever. The rising energy needs of the growing world population are in tension with the urgency of the challenge to decarbonise and reduce the water intensity of our energy systems. Resilient economies require a coherent and effective planning of water, energy and food that balances consumption, production and trade requirements against the country's natural resource endowments. That planning also needs to mitigate and manage the risks of climate-related variability and disasters.

The priority in a response to these linked trends is to build resilience into national development strategies. It is not possible to predict in detail what the consequences of population pressures, changes in consumption patterns and climate change will be. A resilience-driven approach acknowledges this factor, recognising that there are multiple complementary reasons for building flexibility into our design and management of food, water and energy systems, including the infrastructure and institutions linked to them. They need to build in the capacity to absorb climate- and population-driven shocks of many kinds in order to reduce their impact on people and on the natural systems on which we depend, and to mitigate their likelihood, depth and frequency.

In addition to its impact on climate change, burning fossil fuels for energy has a higher accident risk than other forms of energy production. According to the Intergovernmental Panel on Climate Change (IPCC) [77], the safest form of fossil fuel (natural gas) is four times more dangerous than the least safe form of RE (biomass in a combined heat and power plant). These figures relate to deaths and serious injury from accidents, and do not include the health impacts of everyday emissions from fossil fuels. In addition to being safer and reducing health risks, decentralised RE provides the foundation for 'energy independence', as countries can supply their own energy instead of relying on foreign energy sources that monopolise energy supply.

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 [78] should be compared with decentralised RE solutions (individual systems or mini-grids) as they can be the best options in some contexts (see section 2.2).

Over a total of 21 cases analysed in this research (see section 3.4), mini-grids with a prevalent diesel generation component are financially unsustainable, with a uniform national tariff plan not able to cover even the fuel expenditure. Furthermore, they often feature poor technical design choices, with an underperforming or faulty renewable component generation while diesel generators result oversized and work at idling speed at a low efficiency rate, thus increasing operational costs. On the other hand, case studies applying the WEF nexus approach are through to be the most environmentally sustainable.

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 [79] 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 SSA or 120 - 170 kg/person/year [80]. 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 [81].

Other studies of rural electrification in SSA 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 [82]. 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.

These benefits could be multiplied by the use of the WEF nexus model.

With reference to the analysis conducted in this research (see section 3.4), almost all case studies providing "electricity supply & other energy-related products/ services" and "electricity supply & other WEF nexus-related services" are included in the top-11 ranked models (see correlation [16-23] in section 3.4.7 for justification of the only one exception). This suggests that business models applying integrated services could represent an added value for the developer since they sustain local development and ultimately may lead to an improvement in the quality of life for the customers. Additionally, it is interesting that all cases applying the WEF nexus approach showed encouraging financial results. 3 out of 4 cases applying the WEF nexus approach are implemented through a "build, short operate, transfer" business model, which identifies projects developed in this classification by non-profit actors. All of them ran water-related services as not for profit public services - such as water supply - at a social tariff just to cover maintenance costs. This highlights that developers focused on the socio-economic benefits of the beneficiaries have exploited innovative solutions to integrate food- and water-related services into their energy supply business models, demonstrating their actual feasibility.

2.4.4. Financing models for the mini-grid's economic sustainability

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 Sub-Saharan African 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 in Africa 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 [83] (Figure 18).

IRENA also highlights regional differences, with PV mini-grids in North Africa and East Africa having a lower cost per watt compared to systems in West Africa. 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.

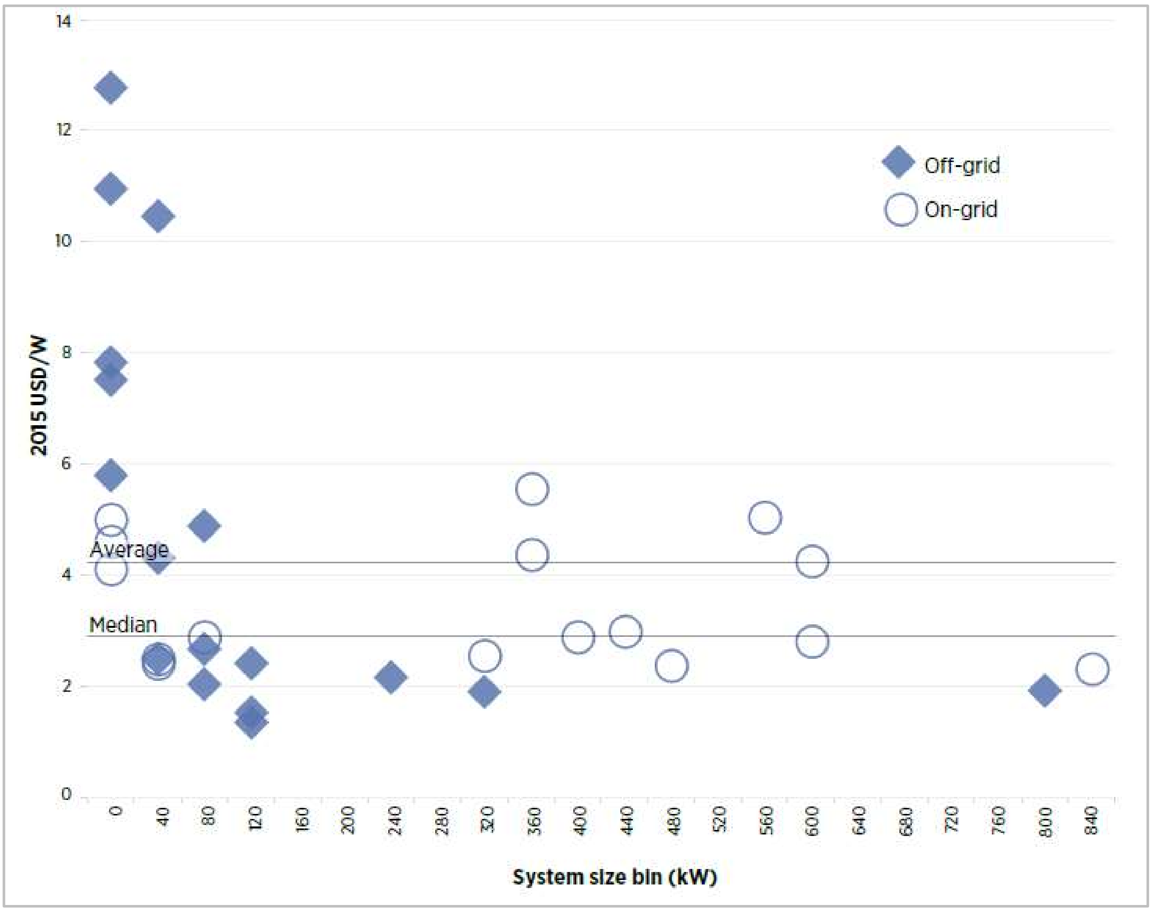


Figure 18 - PV mini-grid system costs by system size in Africa, 2011-2015. Source: IRENA [83].

According to results of the analysis of techno-economic indicators (see section 3.4), mini-grid business models (excluding plants <10kWp and those applying a cost-reflective tariff) still require financing support mechanisms since investments in such initiatives with a fully equity structure are not viable.

However, viable solutions can be explored by applying innovative business-for-impact model for green mini-grid projects based on PUE and WEF nexus approach as well as on win-win partnership between energy-players and agri-players as well as between public and private actors.

Such kind of integrated project can be potentially eligible for innovative financing mechanisms, such as blended finance or impact funds (which are already activated by development banks, donors, etc.) that are required to reach the business viability or to further increase the financial performance and investment attractivity. As EG claims in an article published by ARE [84], "going beyond the sole energy delivery is able to attract blended finance in off-grid RE projects". Considering the urgency to accelerate the mini-grid industry's growth, reach commercial viability and facilitate access to finance, one of the key aspects to take into account is the multi-dimension of the off-grid RE projects in developing countries: multi-actors, multi-customer types, multi-technical solutions and multi-sources of financing. Thus, with a view to properly deploy effective risk reduction strategies, a comprehensive approach should be applied, paying particular attention to, among others, mitigation measures of financial risks and market risks which are crucial and should be faced in an integrated manner.

Considering that market is a major risk for rural electrification projects as well as a success barometer (being related to the amount of electricity that is sold as well as related positive impacts), the market risks highlight the relevance of blended finance and impact investments as de-risking financial mechanisms. According to the OECD, blended finance is the mobilisation and scaling up of commercial finance for development priorities and projects. Social impact investment, on the other hand, is the provision of finance in order to address social needs with the explicit expectation of a measurable social, as well as financial return. They can come together e.g. in impact funds with an explicit focus on mobilising private finance to be invested in impact relevant projects, with the aim of generating both financial and developmental returns. In particular, blended finance could make a difference by deploying development resources to improve the risk-return profile of individual investments to demonstrate project viability and build markets that ultimately are able to attract further commercial capital for development.

Aligned with this approach that intuits the multi-dimension of the off-grid RE sector, 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. Off-grid RE business models identified by this study are emblematic projects able to attract funds from blended finance and impact funds thanks to the WEF nexus approach and the positive spill-overs of the PUE. In order to deploy such innovative business models with multi-utility structures, hybrid ownerships or public-private-partnerships, such financial mechanisms can support the project's long-term sustainability, de-risk investments and increase project's impact.

3

Analysis of mini-grid business models

3.1. Rationale behind a focus on mini-grid business models

As mentioned in the previous chapter, a mix of grid extension and off-grid solutions, such as SHS and mini-grids, should be properly combined in the country's electrification masterplan to pursue universal access to electricity. Furthermore, considering the current investment gap, achieving SDG 7 will largely depend on the capacity of each country to attract private investments in the off-grid sector and, particularly, in the mini-grid sector, which is estimated to attract a significant part of worldwide investments in increasing access to electricity (see section 2.2). Despite the individual systems' business, which is proven to be viable and running in several developing countries, the mini-grid sector still requires an analysis and investigation of innovative business models that go beyond the sole electricity supply, looking at additional services, complementary value chains, innovative partnership and horizontal integration. Thus, this research has exclusively analysed mini-grid business models for access to electricity with a focus on PUE. It excluded captive projects with a unique industrial off-taker since their financial feasibility is already demonstrated and they represent a notable potential market in developing countries, and still relatively untapped. **The research is fully focused on sub-Saharan African countries.**

3.2. Integrated strategies to foster mini-grid deployment in Africa

To accelerate the green transition and energy access partnership between EU and African countries, there is an urgency to explore innovative approaches for a sustainable development by leveraging the huge RE potential to support the development growth and economic transformation in Africa through a low-carbon and climate resilient solutions. The main challenges lay in demonstrating innovative and sustainable solutions for RE power generation with storage as well as energy efficiency for off-grid RE projects. At the same time, and compared to other technologies/solutions in the African context, they should be able to support climate change adaptation strategies and pursue the energy security and affordability as well as the development of its industrial base to create much-needed jobs. Considering energy access as a driven for human development, a mix of grid extension and off-grid solutions (to be integrated with the grid sooner or later) should be properly combined in the country's electrification masterplan to pursue universal access to energy (electricity/cooking). Despite the business of individual systems, which viability has been already proven in several developing countries, the mini-grid sector still requires to show solid business models and efficient technical solutions which are able to provide affordable energy supply and achieve economic, environmental, social and health benefits. In this sense, opportunities come when looking beyond the sole electricity supply: additional services, complementary value chains approached through the circular economy perspective, innovative partnerships and horizontal integration of WEF sectors, leveraging the productive use of energy, can bridge the gap between viable and non-viable projects. An approach that integrates clean water supply, irrigation, and agri-processing activities, can capture different types of value: needs-based irrigation increases food producers' resilience against droughts and breaks the cycle of seasonal income. 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 the economic sustainability of off-grid projects by supporting the energy consumption.

So far, mini-grid business models (excluding plants <10kWp and those applying a cost-reflective tariff) still require financing support mechanisms (hopefully appropriate financing solutions) and capacity building at local (technical and vocational trainings) and national level (high-level workshops and trainings) since investments in such initiatives with a fully equity structure are not viable. Access to finance for mini-grids is slowly achieving maturity but the transition from a grant-based structure to more commercial sources of funding needs to be supported by tailored policies and development finance. Additionally, governments struggle to support them because of public energy companies' poor balance sheets and political priorities, which are usually linked, whereas innovative business models and an enabling environment can attract European and African private capitals.

Rural electrification alone will not be able to support local development and create its own energy demand. However, if rural electrification is integrated with investments along the food value chain and other productive uses of energy, it can bring substantial development results and thus attract the attention of governments, international development agencies and investors, who pay attention to impact objectives and indicators. In recent years, the majority of funding programmes led by international cooperation agencies, development banks, foundations and public institutions have recognized energy and its productive uses as key drivers for local development. In this perspective, the more a developer is able to prove the effectiveness of its strategy to ensure both the business sustainability and achieve a notable impact on the ground, the more it increases its competitiveness in accessing finance. Building energy projects and services around productive uses of energy, and leveraging on positive spill-overs of the WEF nexus approach, can support developers in attracting blended finance. On the other side, in order to stimulate access to electricity and PUE, governments and donors should establish credit schemes and concessional loans, as well as test innovative finance instruments such as results-based financing and targeted subsidies.

In conclusion, governments, private sector actors, international financing institutions and development agencies are called to collaborate to: (i) ensure clear and effective policies and regulations, (ii) provide access to the right finance, and (iii) prove business models. The in-depth analysis of these three dimensions reveals that the current vision is partial, or at least too sectorial. Accelerating rural electrification also depends on the capacity to support local socio-economic development, and it requires energy and non-energy players to go beyond their comfort zone, working and investing together.

3.2.1. Opportunities from PUE and WEF nexus

Access to modern energy is a necessary requirement for sustainable development and can be an enabler for poverty alleviation since it does not represent an end-good itself: it acts as an input factor to a large set of activities that can improve welfare, increase productivity and generate income. In developing countries energy is mainly required to produce, transport, distribute and prepare food, as well as to pump, transport and treat water. Cities, industry and other commercial and residential users claim increasingly more water, energy and land resources and, at the same time, face problems of environmental degradation and, in some cases, resource scarcity.

For SSA's poorest households, food can account for 50% to 80% of total expenditure, compared with 7% to 15% in the average household in developed countries [85]. Where affordable energy can be provided, increases in productivity can be seen along with reduced food losses from better preservation and hence livelihoods improvement is enabled. Affordable energy access can also improve food processing and storage as well as increase value addition.

Many small, remote rural communities remain without access to modern energy services due to poor road infrastructure and the national grid not yet having reached the area. Even where electricity distribution lines have been constructed, energy supply may be very unreliable due to frequent outages and unstable power quality. In such locations, diesel-generators are often employed to produce electricity, but since the cost of the delivered fuel is relatively high, food production has become increasingly vulnerable to energy price fluctuations.

Reducing the dependence of the agri-food system on fossil fuels by utilizing renewable energy is feasible for on-farm activities such as irrigation, milking, cooling, vegetable grading, aquaculture production, food processing, packaging, distributing finished food products, and cooking. Reduction of post-harvest losses by investing in dryers, cooling equipment, storage facilities etc., can have a large impact on the agriculture value chain. Access to electricity is needed to heat the air for drying, power the fans, run the refrigeration plants etc., and electricity is not always available on islands or in remote regions that distribution lines cannot reach.

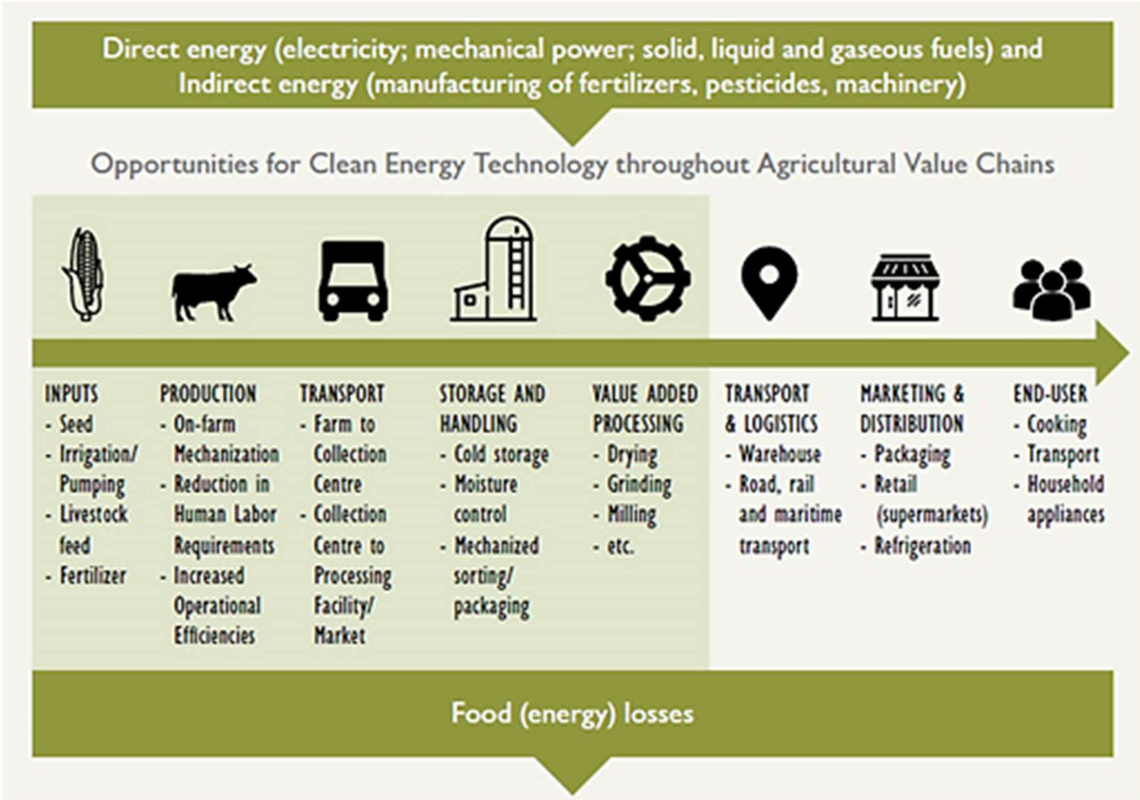


Figure 19 – Opportunities for clean energy technology throughout agricultural value chains. Source: FAO [85].

In such contexts, dedicated RE generation for the described productive uses presents an additional opportunity to provide much needed basic energy services to the local population. The land area required for RE mini-grid projects is usually relatively small, with the exception of biomass energy crops. Wind farms typically use a smaller portion of the total dedicated land area; small hydro run-of-the-river projects usually need only a small area of land for the turbine power house, canal and penstock, whereas small scale PV arrays can use building rooftops or roof shelters or PV ground systems just require around 1,500 square meters for 100 kWp or could be installed floating solar-PV solutions combining energy generation with agriculture to make land more productive.

RE based mini-grids can be a cheaper alternative in locations where the resources are widely available, although high up-front investment costs and low expected consumption can be major barriers: new electricity users in rural areas are the most unattractive market segment, due to low demand densities and a relatively higher fraction of low-income households compared to connected areas. A detailed market assessment has to be carried out to properly address the energy needs related to any productive opportunities.

Peri-urban and rural areas are mostly dedicated to primary economic activities such as farming, which historically did not need electricity. In order to enhance the economic performance of a mini-grid investment, one should understand how crucial energy access is for agricultural value chains. For all agri-food chains, the value of the products tends to increase as more processing occurs and more inputs (electricity, water, packaging materials) are consumed. Taking milk as an example, the energy used for producing, pasteurizing, and bottling fresh milk is around one-tenth of the total energy used cheese making [85].

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 20).

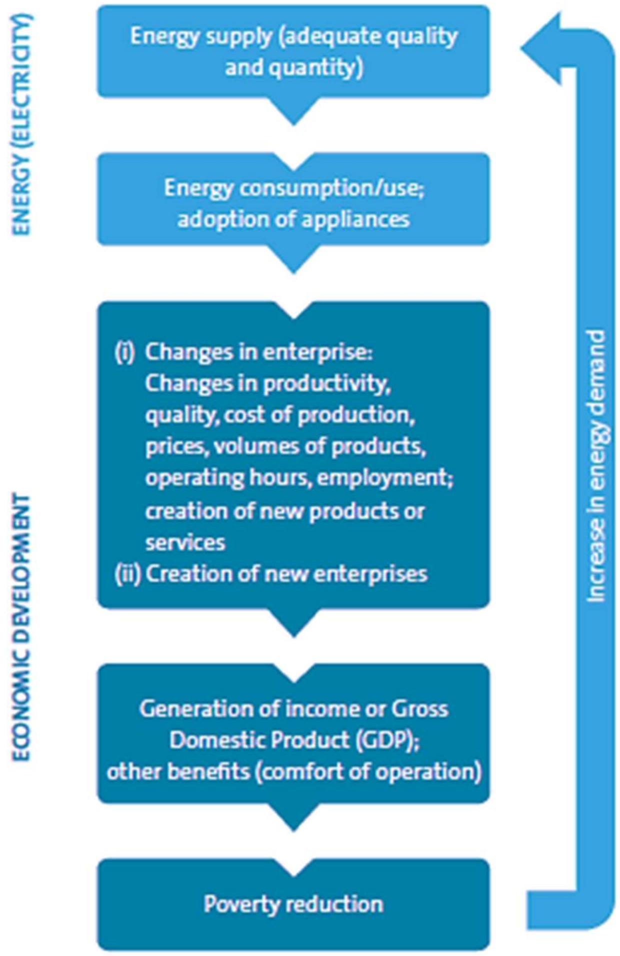


Figure 20 - Correlation between economic development and energy. Source: FAO [85].

Despite the higher power capacity requested to run machinery and productive appliances, commercial loads perfectly integrate with PV-based generation plants since most of the demand can be satisfied through direct solar production during daytime. Irradiation is abundant almost everywhere in SSA, 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.

Consequently, there is no need to size systems with large batteries, since water can be pumped up during sun hours and stored in tanks until irrigation is necessarily deemed, usually in early morning or late evening. Since plastic water tanks are cheaper than electrochemical batteries, they would be the preferred storage option. Drip irrigation systems are usually combined with solar mini-grid for water and energy efficiency (less water lost in the soil and therefore less energy required to move water).

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 [86].

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.

It is remarkable to report that the oldest mini-grid analysed in this research, which was commissioned in 1986 in Tanzania, is the one that best applies an integrated business model based on the WEF nexus, in which the electricity supply is coupled with forestry, livestock and animal feed production as well as with water supply for domestic and productive uses. It has been successfully operating for 33 years (see section 3.3).

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.

Besides productive uses, other activities can play a crucial role in the RE dissemination process. For example, public lighting can prevent crimes and enhance the perceived security level within a community, leading to a shared vision about the importance of the energy service. Public institutions also benefit from affordable and clean energy mainly in health and education sectors, contributing to improve livelihood. Having said that, productive uses and social institutions are both relevant to ensure a growing development of energy projects and finally to help customers becoming actively engaged with the role of energy for development.

3.2.2. Customer management and payment systems

Global System for Mobile communication (GSM) coverage in SSA boomed in the last years, experiencing a very rapid growth that shortly outpaced the development rate of other infrastructural services, such as access to electricity and to improved water and sanitation. It is estimated that in 2017, 2G coverage reached over 90% of the population in the area, whereas broadband network access is still lacking for around 400 million people [87]. Data from 2014 suggests how 59% of the off-grid population in SSA is covered by mobile networks but lacks access to electricity [88]. It is important to note the interconnection between energy and connectivity access, since power is involved in all the steps of the connectivity value chains, from powering telecom towers to recharging the phones of the end-users. Therefore, the spread of connectivity is hampered by lack of power, whereas, when present, it can greatly facilitate energy access initiatives, for instance by enabling mobile money payments. In fact, SSA is the leading region in the world in terms of mobile money customers, even if it's very uneven across its region: in 2017 the total number of mobile money accounts was distributed for 56.4% in East Africa, for 30.9% in Western Africa, 9.7% in Middle Africa and 3% in Southern Africa [89].

This scenario has to be clear to developers of decentralised RE systems as it can have multiple repercussions on the business model they adopt. Lack of internet coverage can be seen as an opportunity in the provision of connectivity services (e.g. with temporary 4G vouchers) since it can constitute another revenue stream integrated in the off-grid business model. On the other hand, connectivity unlocks the possibility of PAYG or second-generation prepaid systems that can be operated entirely via mobile and it doesn't need magnetic or scratch cards. In conclusion, mobile money payments are an opportunity but should be carefully employed by considering the effective penetration in a given area. Also, their adoption might rise issues about affordability, considering that the that the operator can apply to a transaction can constitute a significant additional component of the incurred cost [90]. Even if a prepaid electricity system comes at a higher investment cost, the operator has the benefit of eliminating the risk of non-payment and the cost associated with meter reading whereas it helps the users to monitor his expenditures better, and typically avoids or reduces the need of an initial deposit [91].

Having access to internet also has an impact on the technical solutions that can be adopted in a RE system; real time communication between the various components of the system can enable the adoption of advanced dispatching strategy and advanced demand side management (DSM) techniques involved (see section 3.2.3). The mini-grid sector as a whole is currently taken aback also by the lack of data collection and management done on the operating system, and when present it is often fragmented and unreliable. A remote monitoring system of a mini-grid should be considered a must for new and existing projects, so that operators can check the status of the various assets and continuously monitor customer data. Data on actual energy consumptions, adoption of appliances, issues with payments, customer satisfaction and so on should be readily available and cross-referenced with baseline data obtained in the preliminary development stages to fine-tune the parameters of the business model adopted.

With reference to the results of the analysis conducted in this study (see section 3.4), the most common payment systems are PAYG systems and monthly payments, accounting for 53% and 47% of total cases analysed respectively. Among those applying PAYG systems, only 27% use mobile payments, and among those applying monthly payments there are 2 cases with special customer-based solutions which allow tailored payment deadlines and periods. Furthermore, the customer management of the mini-grids analysed can be described in brief through the following key aspects: operational structure, supporting equipment and tools as well as technical and management constraints.

On one side, the operational structure foresees local maintenance staff for all the case studies, even if technical expertise of local personnel differs case-by-case and they are usually supported in case of extraordinary maintenance. On the other hand, remote management, which consists of software and hardware to monitor and manage data electricity generation, supply and payments, is applied by 48% of the total cases, which includes all the private initiatives and all the cases that apply the most promising business model, build-own-operate (class A), as discussed in section 3.4. Despite the expectations, there is no a clear correlation between remote management and payment systems, but it must be underlined that their application mainly depends on the developer or technical advisor's choice and less on the project ownership. In fact, PAYG systems are used in all the mini-grids in West Africa having Trama TecnoAmbiental as technical advisor but all of them have a local O&M, except for one, and a public or hybrid ownership model. Similarly, the non-profit organization ACRA installed PAYG systems in a very remote mini-grid, which is fully owned, maintained and managed by a local company, properly shadowed during the start-up phase.

Among PAYG systems, installing a mobile pre-paid payment system, despite having a higher investment cost due to the use of smart meters instead of (cheaper) traditional meters, has three main advantages from the management point of view: (i) to eliminate costs associated with meter reading and billing, (ii) to avoid missed payments and efforts to deal with users' arrears (iii) to improve customer assistance and control, reducing risks of electricity theft. Furthermore, smart meters allow to create a well-structured data management, which plays a crucial role for access to finance, optimization of the mini-grid design and scaling-up strategy (see section 3.2.4).

Whereas first-generation prepaid systems require a local vendor to top-up the credit of the magnetic card that is used to activate the meter, using mobile payment allows to disintermediate completely the purchase of "credit", while also giving access to very granular user data made available by the service provider. Evidence from this study shows how the user base that regularly purchases electricity is a subset of all the connected users, meaning that not all of them purchase electricity every month depending, for instance, on the seasonality of their income. This requires a customer risk-reduction allowing them to sustain an expenditure for electricity consistent with their ability to pay and, on the other side, it opens up possibility of employing tailored customer care strategies to keep the user base engaged and active. For instance, among the case studies analysed, those developed by DCGO in South Africa allow users to schedule payments according to their income cycle (e.g. users with salary pay at the end of the month, while those receiving governmental grants pay at mid-month). The company also found a way to adapt mobile PAYG systems to a local market which is not familiar with mobile solutions, by establishing vendor agreements with existing trading stores that awarded a commission on an electronic wallet at each sale of DCGO service to users.

3.2.3. Demand side management (DSM)

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 21 below.

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 [92].

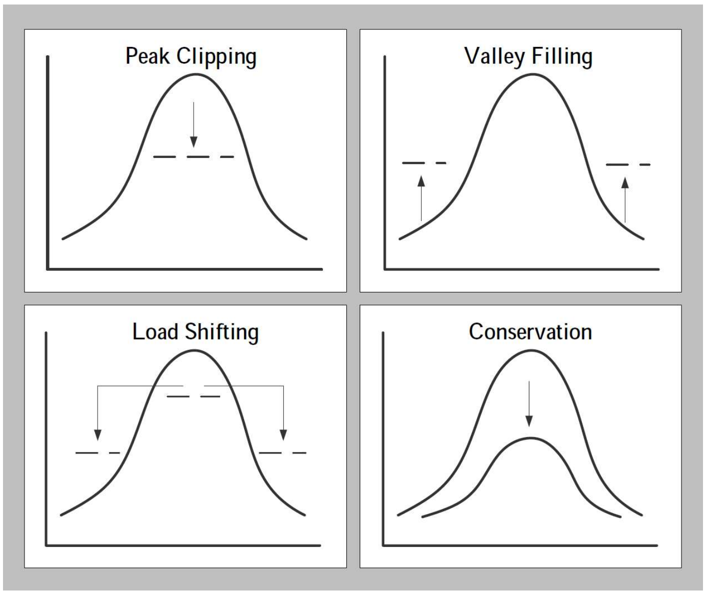


Figure 21 – Effects of DSM on load profile. Source: Saengprajak, A. [92].

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 [93], as reported in the following table:

DSM Strategies	DSM Technologies
Efficient appliances and lights	Current limiters
Commercial load scheduling	Grid Share
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 2 - DSM classification. Source: Harper, M. [93].

DSM 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.

Academic research shows how 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 [94]. 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 capital expenditure (CAPEX) savings.

Another study shows how an optimal combination of peak clipping, load shifting and valley filling can result in a reduction of the levelized cost of electricity (LCOE) by 18% in a reference case study, while also decreasing usage of diesel and increasing the lifetime of batteries [95].

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 (CBA) 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) [81].

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. This is a strategy that can be borrowed from the sector of individual solar systems, and is being adopted, among the companies featured in the case studies, by DCGO, and is in the future plans of Redavia.

Advanced metering systems with centralized communication can allow for a more structured control of demand. Among the selected case studies, 7 feature meters based on the energy daily allowance (EDA) concept, which limits the available power rating for a user, and has a daily energy limit that works as a "virtual individual storage" that gets recharged in case of low consumption or depleted otherwise [96]. Moreover, it encourages energy consumption by signaling to the user when there is an excess of PV production, which favours the EDA, or discourages energy consumption when batteries have a low state of charge (SOC), which penalizes the EDA (e.g. energy is recorded at a double rate).

3.2.4. Complementary activities to sustain successful projects

In the development process of a mini-grid, several factors and data contribute to design a technical solution that is considered financially viable. The electricity demand pattern is necessarily affected by several factors including socio-economic and environmental factors by which the pattern forms diverse complex variations. Keeping in mind that every target community differs from one another in terms of needs and context conditions [97], complementary activities represent a means for engaging local communities, promoting community inclusion and pursuing the project sustainability. In fact, access to energy by using off-grid systems results in favourable solutions when coupled with targeted support to local potential capacities and opportunities through capacity building [98] and other type of supporting initiatives.

They mainly consist of activities not strictly necessary to activate the electricity supply services. However, even if the project could technically achieve its objective to install the infrastructures and activate the electricity sale service, it is barely able by itself to mitigate relevant implementation and investment risks as well as to achieve other project objectives related to socio-economic aspects.

In order to provide an overview of complementary activities in rural electrification projects, with reference to the analysis' results conducted on 21 case studies during this research, the most common ones are: businesses incubation, awareness campaigns, technical trainings, other capacity building activities, microcredit support as well as knowledge and data management, which differs from others being an activity directly targeting the developer's benefits instead of local beneficiaries, indirectly affected by related effects.

17 case studies analysed include complementary activities, representing 81% of the total. The remaining 19% is only composed of cases which apply a business model classified as B.7 in section 2.1.2 (build-own-outsource, with only electricity supply). The activities carried out are the following: 5 projects carried out business incubation programmes, 13 awareness campaigns, 14 technical trainings, 11 other capacity building activities, 1 data management and 0 microcredit support and knowledge management programmes, which would, instead, strongly support existing and potential local entrepreneurs (Figure 22).

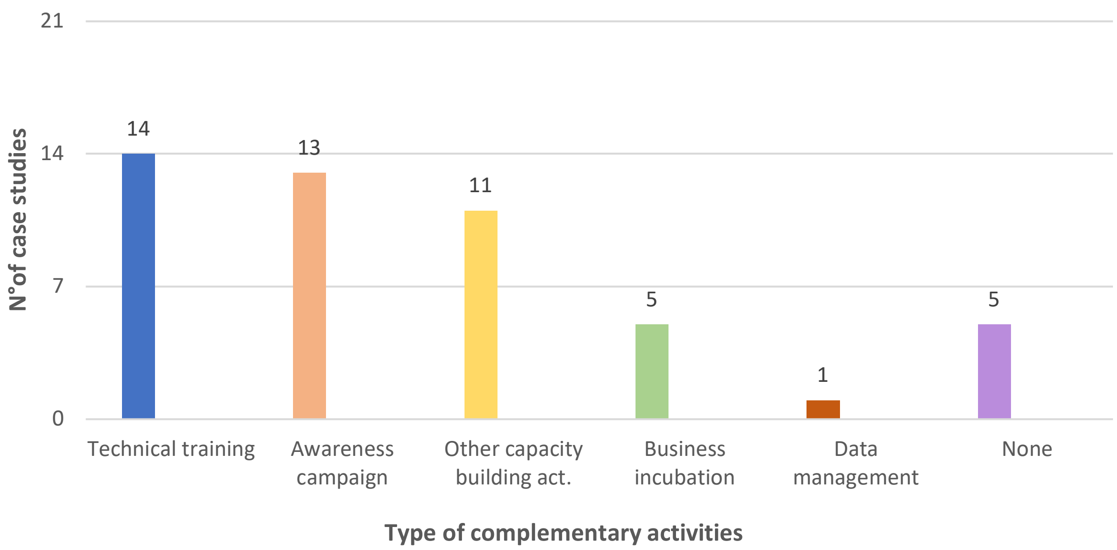


Figure 22 - Complementary activities in mini-grid projects.

Once the terms of the discussion have been clarified, the crucial question is: *what kind of outcomes are expected in a mini-grid project by implementing complementary activities?* The purchasing power of the potential market is expected to increase thanks to the promotion of income-generating activities focusing on energy consuming businesses as well as business and employment opportunities. Such approach empowers the targeted communities while boosting demand for electricity, resulting in a mutual positive effect for off takers and utilities. This is particularly relevant for local economies based on agricultural activities, where there is typically an unexploited potential in food processing businesses. A set of impact indicators are usually developed at the beginning of the project to monitor the effect of such activities and provide economic evidence of the added value from a business perspective. An upgrade of the standard M&E activities is represented by the Social Return of Investment (SROI) analysis.

The research carried out on the 21 case studies reveals evidence of economic and financial effects of complementary activities. Looking at the ranking based on IRR, the top-12 have implemented complementary activities. Among the rest, the last 5 have also implemented complementary activities, but their low financial performance is strongly hampered by the national electricity tariff plan adopted, despite of contrary technical advisory, and they operate in steady loss (see sections 3.4.6, 3.4.7).

In order to implement an effective complementary activities programme, the key aspects to take into account are the following:

(i) identification of expected outcomes and impacts during the project design as well as indicators to be monitored;

(ii) accurate selection of actors involved and related responsibility that can be summed up in a project operation chart;

(iii) accurate activities' scheduling since timing strongly affects their effectiveness as they have to be coordinated with construction of the infrastructures and activation of the services and it could hamper the start-up phase by reducing customer engagement and economic expectations of the business plan;

(iv) distinction between activities to be carried out during the implementation phase and those to be carried out during the start-up phase, since evidence from the analysis strongly advise follow-up activities to reinforce both the market and operation & maintenance (O&M) management of mini-grid, particularly in the first year of operation;

(v) challenges and external conditions that may affect the expected outcomes a risk analysis on the correlation between complementary activities and response of potential market to such supporting programmes is recommended.

Complementary activities come with a cost, but the developer should consider them a positive investment and clearly identify what kind of benefits they could entail. From one side, by investing in the final off-taker the project aims to grow the energy demand in the mid-term, so as to increase energy sale and foster the mid-long term commercial sustainability of the business. On the other side, it is an additional financial risk as it increases CAPEX (usually of about 5-15%).

However, complementary activities may represent a project's strength for access to financing sources, which pay particular attention to SDGs achievement and impact indicators at mid-long term, since the value propositions could include effective marketing campaigns and customer care services, which considerably affect the start-up phase of the business. In fact, in recent years, the majority of funding programmes promoted by international cooperation agencies, development banks, foundations and public institutions have recognized energy and its productive uses as key drivers for local development and have required and promoted the integration of complementary activities to support access to energy. In this perspective, the more a developer is able to prove the effectiveness of its strategy to both ensure the business sustainability and achieve a notable impact on the ground, the more it increases its competitiveness in accessing finance. Therefore, in order to justify the capital extra-costs due to complementary activities, on one side the project's financial plan should show their added value in terms of economic effects such as increased revenues or reduced operational costs and, on the other side, impact indicators should reflect benefits ascribed to such activities. As mentioned before, the SROI analysis aims at supporting this approach.

With a view of sustaining access to finance and encouraging the involvement of other sectors such as microfinance entities and ICT companies, the research reveals that the crucial role of a well-structured knowledge and data management is underestimated. This is a weakness of most of the projects whereas it should represent a must in the rural electrification sector, where different levels of uncertainty are the key barrier for access to finance and to ensure projects' sustainability and viability.

3.3. WEF nexus integrated business model: a successful case study from Tanzania operating since 1987

The WEF Nexus' holistic approach can provide access to essential resources for an appropriate human sustainable development. Access to clean water, modern and un-polluting energy services, nutrient and sufficient food is at the very core of the fight against global poverty and the efficient implementation of the SDGs. This integrated approach generates added value thanks to the multi-sectoral shock induced by an activity specifically designed to transform the traditional environment and operating mode. It aims to enhance and secure the three most important natural resources, energy, water and food, and manage them in an integrated way. Most importantly, it is crucial to ensure the accessibility and affordability of basic resources to all sections of the population. In order to advocate actions to drive Africa's sustainable transition, it is fundamental to evaluate what kind of positive effects can be achieved through a WEF approach.

In doing this, it is crucial to build up an impact assessment of the benefits and challenges that might arise from this specific designed activity, in order to further and promote sustainable institutional programmes and policies. With specific reference to a case study presented in this section, the main aim and core element of the impact assessment is to predict the economic effects at an early stage of an WEF nexus integrated business model: impact assessment of a successful case study from Tanzania 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 CEFA's hydro-powered mini-grid "Ikondo-Matembwe" project in rural Tanzania, 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.

3.3.1. Project background

Project Location

The project, as assumed by CEFA, covers an area of 8 villages, sited in five rural wards of Tanzania (Matembwe, Ikondo, Lupembe, Ukalawa and Kidegembye) in the Njombe Rural District. A ward is a local administrative area, typically used for electoral purposes. Wards are usually named after neighbourhoods, thoroughfares, parishes, landmarks, geographical features and in some cases historical figures connected to the area. The Njombe Rural District is a former district of the Iringa Region of Tanzania and is located -9.081716, 35.247725°. The total population of the area is 20,928 inhabitants, with an overall number of households of 4,435.

Within the Njombe Rural District people rely on farming, with agriculture being the largest sector of the local economy. A share of 67% of the households has a farming activity and agriculture is crucial for their food provision and living. Agriculture is also the main reason for income, especially through the cultivation of local harvests such as beans, tea or maize. Another important means of livelihood for the local population is livestock. Beef is the largest meat product followed by lamb/mutton in mainland, while chicken and pork are mainly produced in rural areas thanks to the lower prices of the meat.

As the population is dependent on agriculture and livestock, and still uses traditional techniques on non-irrigated lands, the income generated from these activities is particularly low; approximately 68% of Tanzania's 44,9 million citizens live below the poverty line of USD 1.25 a day and 32% of the population is malnourished [99]. Furthermore, Tanzania faces high environmental challenges because of unsustainable harvesting of its natural resources, unchecked cultivation, climate change and water- source encroachment.

The project examined tackles the agriculture issue by using a range of technologies based on improved seeds, machinery, and other modern inputs, thereby displaying a significant impact on production by increasing yields and labour productivity. Poor nutrition remains a persistent problem with a 16% of children population that are underweight and 34% experience stunted growth as a result of malnutrition [100]. Malnutrition is also due to maternal de-nourishment, poor infant feeding practices, hygiene practices and poor healthcare services.

Another criticality within the target area is access to water. Water supply and sanitation are poorly accessible to the population. Although the National Government has embarked on a major sector reform process since 2002, access to potable and drinking water is still difficult for local population as water points are poorly managed and far from main aggregation centres. A decentralisation in the water supply has been carried out since the local government authorities and is carried out by 20 urban utilities and about 100 district utilities as well as by Community Owned Water Supply Organisations in rural areas.

Project Structure

CEFA's project presented hereafter covers two community-scale hydro-powered energy access projects. The Ikondo-Matembwe electric infrastructure is based on two interconnected hydro power plants that have a total generation capacity of 550 kW of electric supply and is able, through a local grid that currently counts 1,102 connections, to provide access to energy to the entire target population, approximately 890 households, 186 businesses and 26 public services. The older plant installed in the village of Matembwe features a 120 kW turbine, whereas the newer one installed in the village of Ikondo features two turbines for a total capacity of 430 kW. The two plants are interconnected and distribute electricity through around 65 km of medium voltage lines, serving through a dedicated distribution network the whole target households and businesses. In addition, the Ikondo-Matembwe mini-grid is owned and managed by the Matembwe Village Company Ltd (MVC).

MVC is a rural-based multi-utility operating in the sectors of energy and water provision, agro-forestry, animal-feed and livestock production. Focusing on the energy sector, MVC provides reliable and affordable clean energy to three groups of local users: households, private enterprises and public service providers. In November 2016 the Ikondo-Matembwe mini-grid was connected to the national grid, making MVC the second biggest client in terms of consumption with its animal-feed factory and the hatchery.

Electricity is the crucial element within the presented WEF nexus model of the project as it is the enabler par excellence. Thanks to electricity it has been possible to supply around seven aqueducts providing water. Water is depurated and pumped thanks to electricity. Plus, the installation of water access spots gives the possibility to supply with fresh water the entire targeted population.

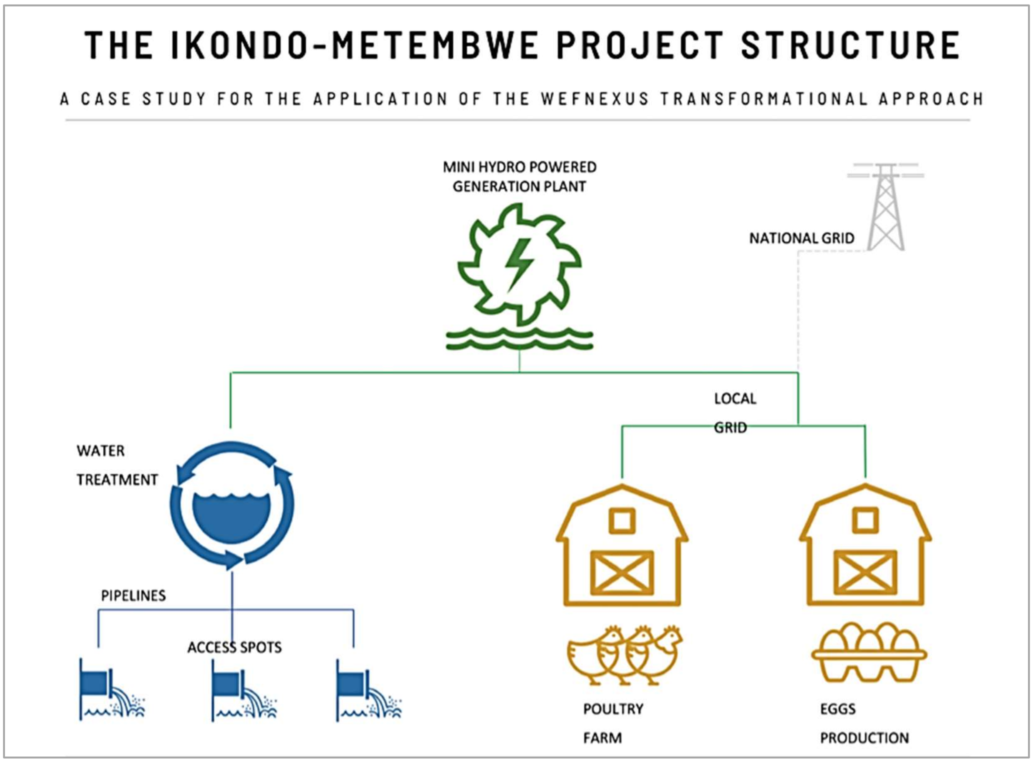


Figure 23 - The Ikondo-Matembwe project structure. Source: OpenEconomics [50].

In the Ikondo-Matembwe project area, the electricity activated by the hydro plant enables the increasing in the production of an animal feed factory and a poultry hatchery. This business and the related activities are fostered by the abundant and reliable energy supply that provides electricity, at a lower price and for a longer period of time of the former energy-generating solution, permitting an increase in agricultural and processing activities, such as poultry feeding and seed production.

3.3.2. Methodology for the project impact assessment in brief

The aim of this assessment was to evaluate the effects that the innovative WEF nexus project can have on a specific area. In doing this, a microeconomic impact assessment was developed to evaluate economic, social and environmental costs and benefits, in order to further and promote sustainable institutional programmes and policies.

The assessment was carried out by OpenEconomics, which adopted a methodology to evaluate the benefits of the integrated WEF nexus approach consisting in developing two different scenarios:

1. sole energy implementation and,
2. 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.

Additionally, the impact assessment of the project applying an integrated WEF nexus approach has been carried out in two dimensions:

1. microeconomic impact assessment and,
2. macroeconomic impact assessment.

Within the assessment process led by OpenEconomics, **our research group** (specifically University of Florence, Sapienza University of Rome and University of Pisa) **was responsible to carry out the following tasks:**

- provide investment cost, as detailed in section 3.3.3;
- provide operating and economic costs, as detailed in section 3.3.4;
- provide the scalability setup, as detailed in section 3.3.6.

3.3.3. Investment costs

Our research group dealt with data collection and processing to provide OpenEconomics with the investment cost. The Ikondo-Matembwe project came at a cost of USD 3,781,131 split in its components of energy, water and food/livestock according to the following tables:

CAPEX related to the ENERGY component	USD	%
Project management and development - Human Resources (local)	110,880	3.8
Project management and development - Human Resources (expat)	165,984	5.6
Project management and development - Local transports	212,016	7.2
Project management and development - Other	28,616	1.0
Project management and development M&E activities	8,960	0.3
Supporting activities for local communities	66,696	2.3
Legal and authorization costs	11,200	0.4
Land purchase	8,400	0.3
Generation plant and distr. Line- Human Resources (local)	142,464	4.8
Generation plant and distr. Line- Human Resources (expat)	107,520	3.6
Generation plant - Asset costs	1,246,168	42.2
Distribution line - Asset costs	544,320	18.4
Last- mile connections - Asset costs	246,848	8.4
Local Office costs	50,400	1.7
TOTAL	**2,950,472**	**100.0**

Table 3 - Capex related to the energy component.

CAPEX related to the WATER component	USD	%
Supporting Activities for Local Communities	11,200	3.3
Legal and authorization costs	5,600	1.7
Pumping plant and distr. line - Human Resources (Local)	77,952	23.1
Pumping plant and distr. line - Human Resources (Expat)	40,320	12.0
Pumping & distribution pipe - Asset costs	202,160	59.9
TOTAL	**337,232**	**100.0**

Table 4 - Capex related to the water component.

CAPEX related to the FOOD component	**USD**	**%**
Supporting activities for local communities	33,600	6.8
Legal and authorization costs	9,520	1.9
Land purchase	50,512	10.2
Plant - Human Resources (Local)	78,624	15.9
Civil works and buildings - Asset costs	177,072	35.9
Plant machinery and equipment - Asset costs	144,099	29.2
TOTAL	**493,427**	**100.0**

Table 5 - Capex related to the food component.

3.3.4. Operating and Economic Costs

Our research group dealt with data collection and processing to provide OpenEconomics with the operating and economic costs. The costs considered in the economic CBA were disaggregated following the investment costs for energy, water and food/livestock components.

For the energy-related project, households pay an electricity tariff of 0.06 USD/kWh, public services pay a tariff of 0.043 USD/kWh and private business pay a tariff of 0.11 USD/kWh. Considering all the beneficiaries of clean energy due to the project, the total cost would be USD 742,406 in net present value (NPV) for the entire project life. For the water-related activity, households would pay 0.0010 USD/litre after project implementation. Considering a consumption of 95.70 litres per day, the total cost would amount to USD 1,872,198 in NPV for the project lifespan. Regarding food /livestock activity, households would pay for livestock (poultry) and fodder. Considering a unit amount of USD 0.68 per animal and USD 21.35 per 50 kg of fodder, the total amount is USD 871,038 in NPV for the entire project lifespan.

The O&M costs refer to administration, audit and insurance, as well as ordinary and extraordinary maintenance of infrastructures. For the energy part, these costs are calculated at USD 396,253 for the entire project life; for water at 57,179 USD in NPV and for food/livestock at USD 395,029 in NPV.

3.3.5. Microeconomic impact assessment

The microeconomic analysis is a powerful tool for empirical analysis and evaluation of certain benefits deriving from the specific project, according to the WEF nexus model.

As shown in Figure 24, an investment project is characterized by a set of productive activities that, through capital formation, is involved to certain economic-financial objectives at times deferred over time. Every time a productive input of a company is used, consequences are generated on the production or consumption of units that are different from the decision-making unit that gave rise to the production itself, thus generating external economies (or diseconomies). These have the peculiarity of the repercussions on other companies, on consumers and also on the prices paid and received, with the possibility of generating both benefits and external costs, impacting on the environment, infrastructure and the economic system in general. In this context, a thorough analysis of the effects of the investment project becomes crucial, evoking an approach to the evaluation of the investments considering two distinct and successive moments.

The first of these consists of the identification and measurement of the effects, or rather of the physical and institutional changes that the project generates within the environment in which it is inserted. This identification will be proposed to the policy maker as a set of distinct consequences of the project.

The second moment of evaluation consists in attributing an economic value, first of all to each of the consequences generated by the project and together through appropriate homogenization and aggregation procedures.

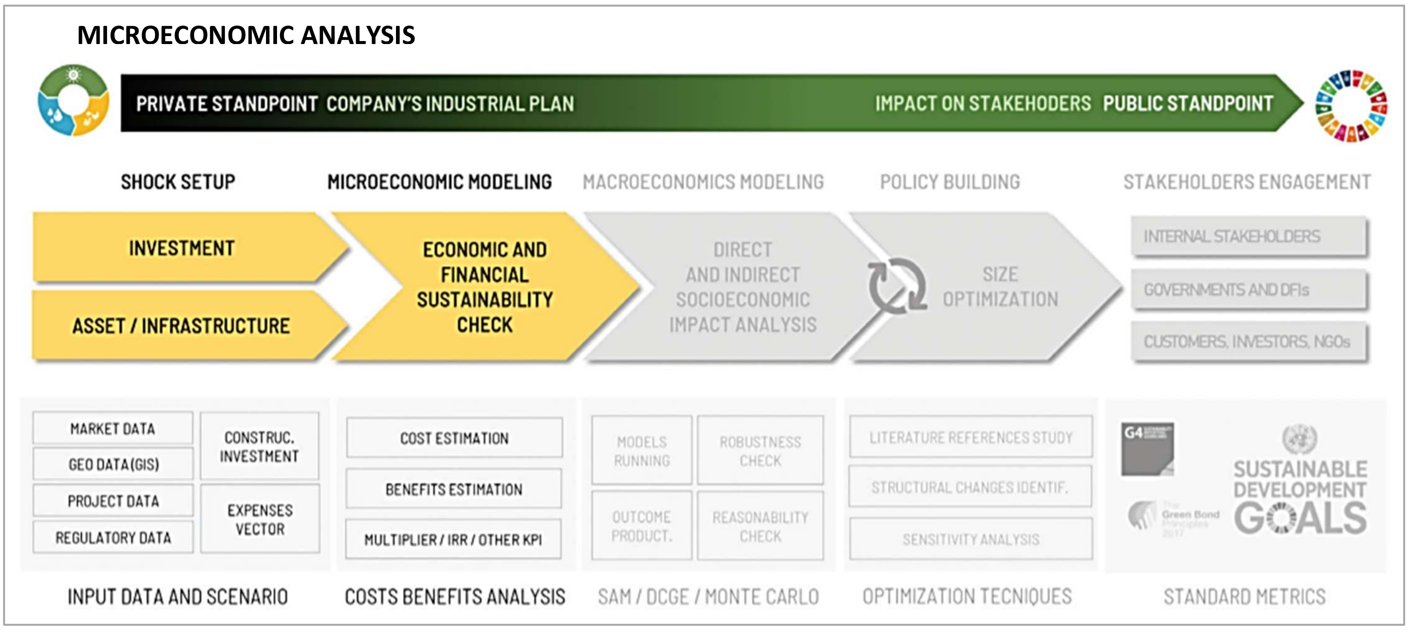


Figure 24 - Microeconomic modelling. Source: OpenEconomics [50]

To carry out the Economic Cost-Benefit Analysis (CBA), two different scenarios have been considered for the three project's components:

(i) simultaneous implementation;
(ii) implementation at different times.

In the second scenario, the energy part alone is the main component with the major investment costs. This implies two distinct alternatives for water and livestock, consisting, respectively in the combination of (i) energy and water and (ii) energy and livestock. This scenario has been compared with an alternative case where all components are implemented together. The rational 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 improved 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 environment and the wellness conditions of the animals. In terms of project results, the Energy project alone Economic Net Present Value (ENPV) turns out to be USD 5,940,652, while the Energy and Water project combination and the Energy and Food project yield respectively an ENPV of USD 10,651,791, and of USD 7,768,100. Therefore, the project with the highest Economic NPV is the integrated WEF Nexus Project, consisting of Energy, Water and Food, with an ENPV for USD 12,479,239. Simultaneous implementation of the three projects thus produces the largest impact in economic terms.

PROJECT	ECONOMIC NPV (USD)
ENERGY	11,200
ENERGY AND FOOD	5,600
ENERGY AND WATER	77,952
ENERGY, WATER AND FOOD	40,320

Table 6 - Project results in terms of Economic NPV.

Although there appears to be only a small difference in terms of ENPV and economic benefits between the Energy and Water project and the complete Ikondo-Matembwe project, it must be considered that without Energy, the other two projects would not be adopted, as the investment costs would be much higher than those as assumed in the project. This is because energy is crucial for all activities and in the absence of the energy project component, it would have to be produced at much higher costs. This conclusion can be seen also through the lenses of a project expansion; the Energy project opens the possibility to further develop the Water and Food components.

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% and a BCR of 4,5 for the Energy, Water and Food integrated project.

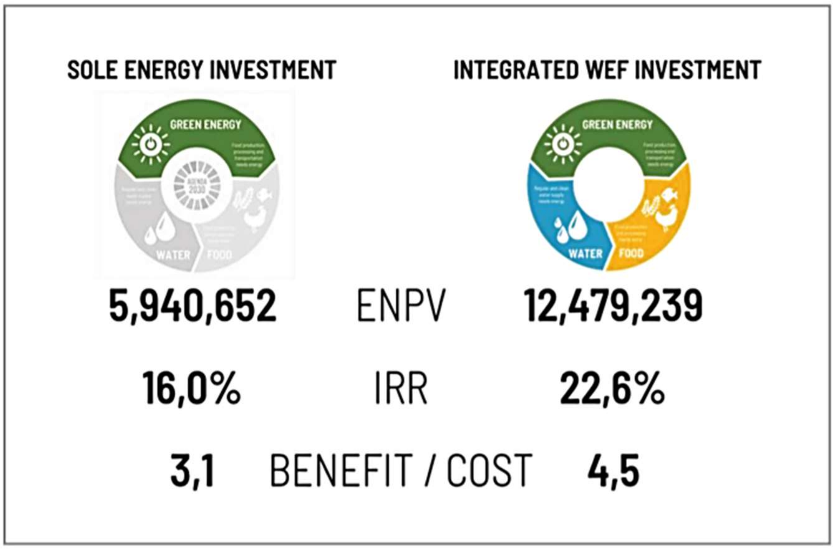


Figure 25 - Energy and integrated investment IRR and cost-benefit ratio. Source: OpenEconomics [50].

The BCR indicator is indicative of the peculiarity of the integrated project compared to the sole energy investment. The 1,4 points differential among the two projects has a clear explanation: energy is the enabler of the integrated project, if energy is not activated, the other two components would not be enabled. This is significant as in this case with a little investment quantified for the energy sector, it is possible to collect high benefits from the energy, water and food components.

In addition, whilst the WEF nexus approach brings about mostly positive externalities, it is true that negative externalities might arise as well. If a positive externality is a benefit enjoyed by a third party, a negative externality implies a cost for the mentioned as result of an economic transaction. A traditional case of negative externality is the case of pollution, imposes costs on society and individual reducing, therefore the possible project benefits. The identification and quantification of these negative externalities, and especially their conversion into monetary terms, is important when evaluating the economic benefits and costs of a project although they are very difficult to compute. As per the WEF nexus itself, negative externalities do not arise and the very few ones are not major negative externalities but only marginal ones. For instance, a kind of negative externality might be related to the reduction of diesel sales, brought by the switch undertaken by the project to produce energy from this conventional source into a RE based technology. Another externality that might be linked to such kind of projects is related to the land expropriation and land right issue and it is a crucial advocacy aspect. However, it is not related to this specific project as it is assumed that those land that will be deployed to develop it are uncultivated, public lands with no economic value that will not affect neither farming nor farmers as agriculture is well known to be the main economic activity in rural areas.

From the assessment results it is possible to state that investing at the same time in all the three components would give better performances in terms of economic results for the local stakeholders, compared to the implementation of the Energy project alone. The evaluation model developed addresses the positive impacts and benefits deriving from the Ikondo-Matembwe project that enables to achieve concrete improvements in the wellbeing of the local population. The starting point of the study is the provision of sustainable energy and improved access to it through the generation from renewable sources with the energy ass the enabling factor empowering the other components of the WEF integrated approach, permitting a dynamic mechanism.

In conclusion, the results of the ECBA validate its desirability from the society point of view and its economic and financial feasibility. Total ENPV, which is estimated at USD 12,479,239, covers the entire financial gap of the financial analysis and delivers important positive results for all project stakeholders. Moreover, the economic benefits of the project and the potential impact on the well-being of the population and area considered suggests that the project may be productively replicated at regional and national level. The transformative nature of a project lies in its potential to change the production technology at regional basis. The mix of technology, project dimension, business model and area considered may help to lay the basis of a structural change into the economy, that together with governmental financial support can enable the conditions for sustainable development. Because of these reasons, the WEF integrated Ikondo-Matembwe project can therefore be financed by the public counterpart, and thus lays the foundations for a further feasibility analysis based on a scale-up of the technology in remote and disconnected areas of the country.

Such analysis of the project's scale-up and its transformative effects nature (see sections 3.3.6 and 3.3.7) is performed through the macroeconomic model, that will allow to focus on the territorial impacts in terms economic, social and environmental values, as well as on the SDGs, backing its foundation for a comprehensive consideration of the collective well-being of the country and hence in line with the most appropriate economic policy.

3.3.6. Scalability setup

c

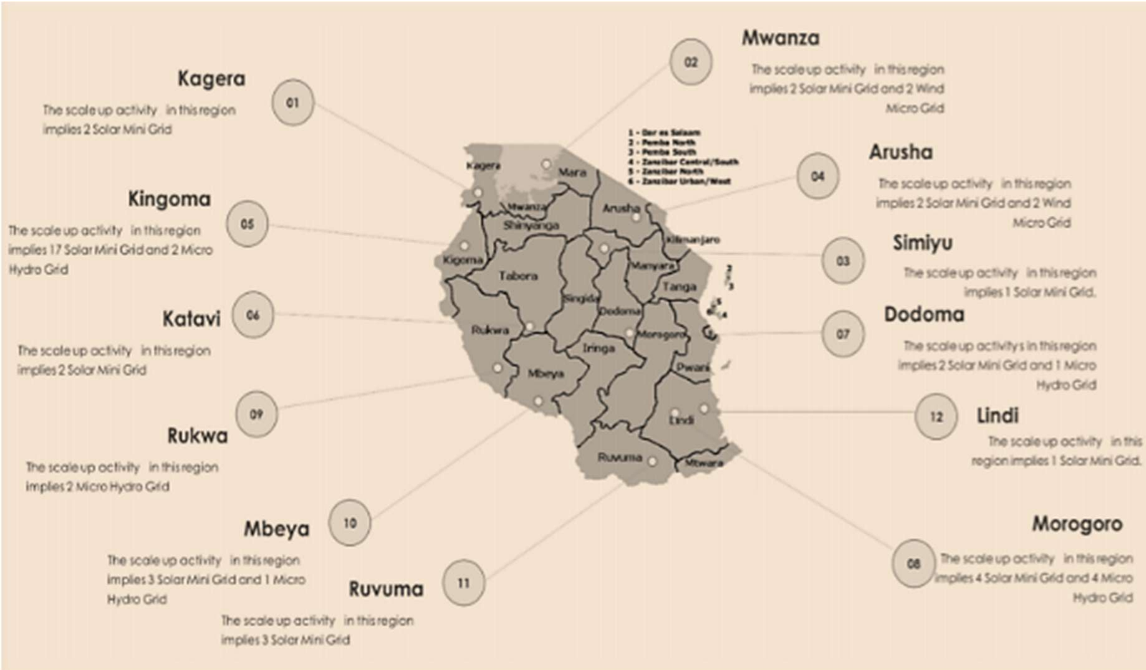


Figure 26 - Scaling up project at country level (Tanzania). Source: OpenEconomics [50].

REGION	Hydro mini-grids	Wind mini-grids	PV mini-grids
KAGERA	0	0	2
MWANZA	0	2	2
SIMIYU	0	0	1
ARUSHA	0	2	2
KIGOMA	2	0	17
KATAVI	0	0	2
DODOMA	1	0	2
MOROGORO	4	0	4
RUKWA	2	0	0
MBEYA	1	0	3
RUVUMA	0	0	3
LINDI	0	0	1
TOTAL	**10**	**4**	**39**

Table 7 - Overlook of scale up projects.

The total number of projects to implement was determined as per 39 solar mini-grids, 10 hydro mini-grids and 4 wind mini-grids (Table 7), for an overall total of 53 installations, with investment costs (including the water and food component) as presented in Table 8.

Project	Unitary Cost (Usd)	Replications	Total Investment Costs (Usd)
Solar Mini-Grid	3,500,000	39	136,500,000
Hydro Mini-Grid	2,950,472	10	29,504,720
Wind Mini-Grid	3,300,000	4	13,200,000
Water Project	337,232	53	17,873,296
Food Project	493,427	53	26,151,631
Total			**223,229,647**

Table 8 - Activities and related investment costs.

3.3.7. Macroeconomic impact assessment

On the basis of the microeconomic analysis's results (see section 3.3.5), the macro impact analysis of the Ikondo-Matembwe project has been carried out, as the flow chart in the Figure 27 shows, by using a dynamic Computable General Equilibrium (CGE) model backed by a Social Accounting Matrix (SAM) [101]. This methodology constitutes an evaluative international best practice of increasing use by international organizations and multilateral agencies, including, in particular, the World Bank. This model is part of the latest generation of analytical tools applied in the evaluation of the indirect and induced effects of large investment projects and their macroeconomic impacts. CGE models are believed to be one the most reliable tool to investigate the policy options for an economy; advantage of using CGE lays on the general equilibrium assumption, assisting the adjustment of policy issues.

The general equilibrium represents a condition where all markets are in a state of equilibrium from the point of view of demand and supply, according to the Walrasian general principles [102]. It concerns three different circles of causation:

- between demand and supply of goods and services on one hand, and prices and incomes on the other;
- between the formation of incomes from demand and supply of factors of production and their prices, and
- between the initial resource endowment and the redistribution caused by productive choices and institutional transfers.

CGE incorporates all the interactions that are market-based, and results generated, suggesting which kind of policy would be more appropriate for a certain economy. It simulates the behaviour of the observed economy, in response to external stimuli of various nature, entity and temporal extension created by the considered investment. The factor behind the more appropriateness of CGE than all its linear predecessors is that it eliminates the linearity constraint found in all the previous models. Such methodology can simulate the functioning of the economy on the basis of the interdependent relations among local stakeholders and among all market's components.

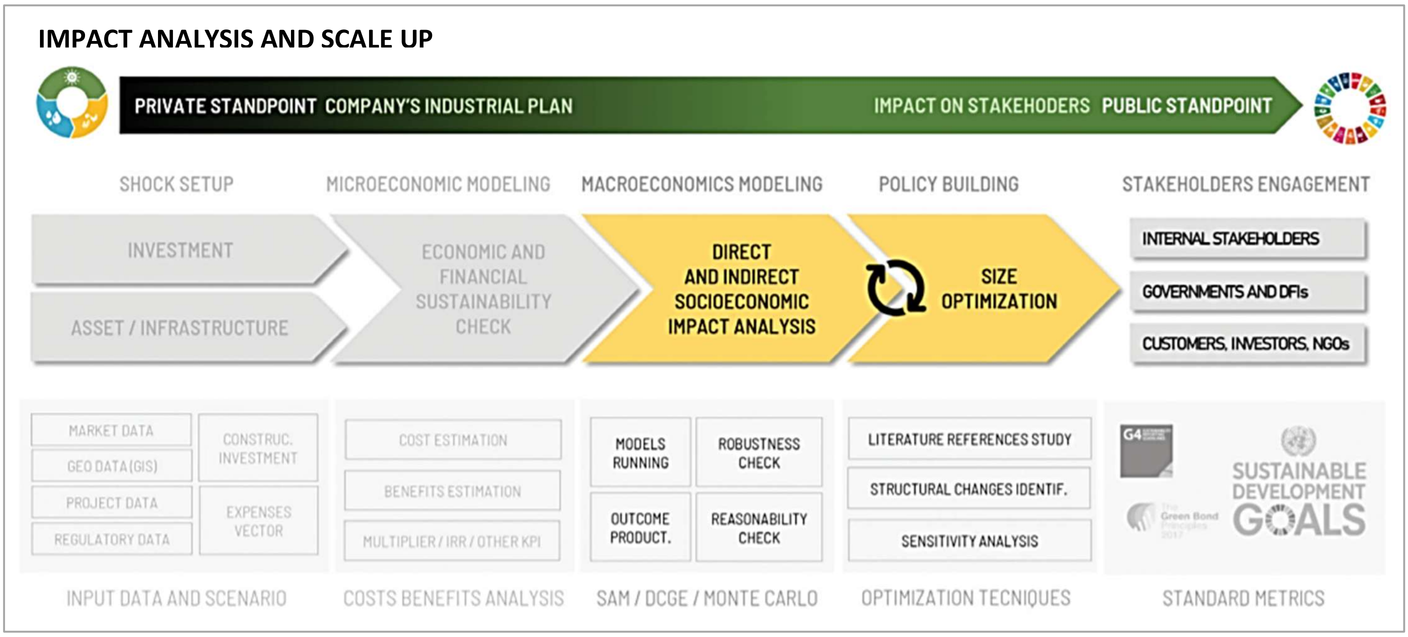


Figure 27- Macroeconomic modelling. Source [50]

The socioeconomic impact of the integrated project scale up confirms the results of the pilot project. If the outcomes of the comprehensive project are compared with those related to the sole energy component, it is possible to verify the impact differences that are more favourable to the integrated solution. As said, the WEF nexus results complete the range of benefits brought by the stakeholders and wide up the recipients including among the direct beneficiaries (therefore those mostly impacted by the project) all the local communities englobed in the initiative. The Figure 28 clearly shows the main results given by the evaluation, comparing the energy component outcomes with those related to the integrate project as described in this document.

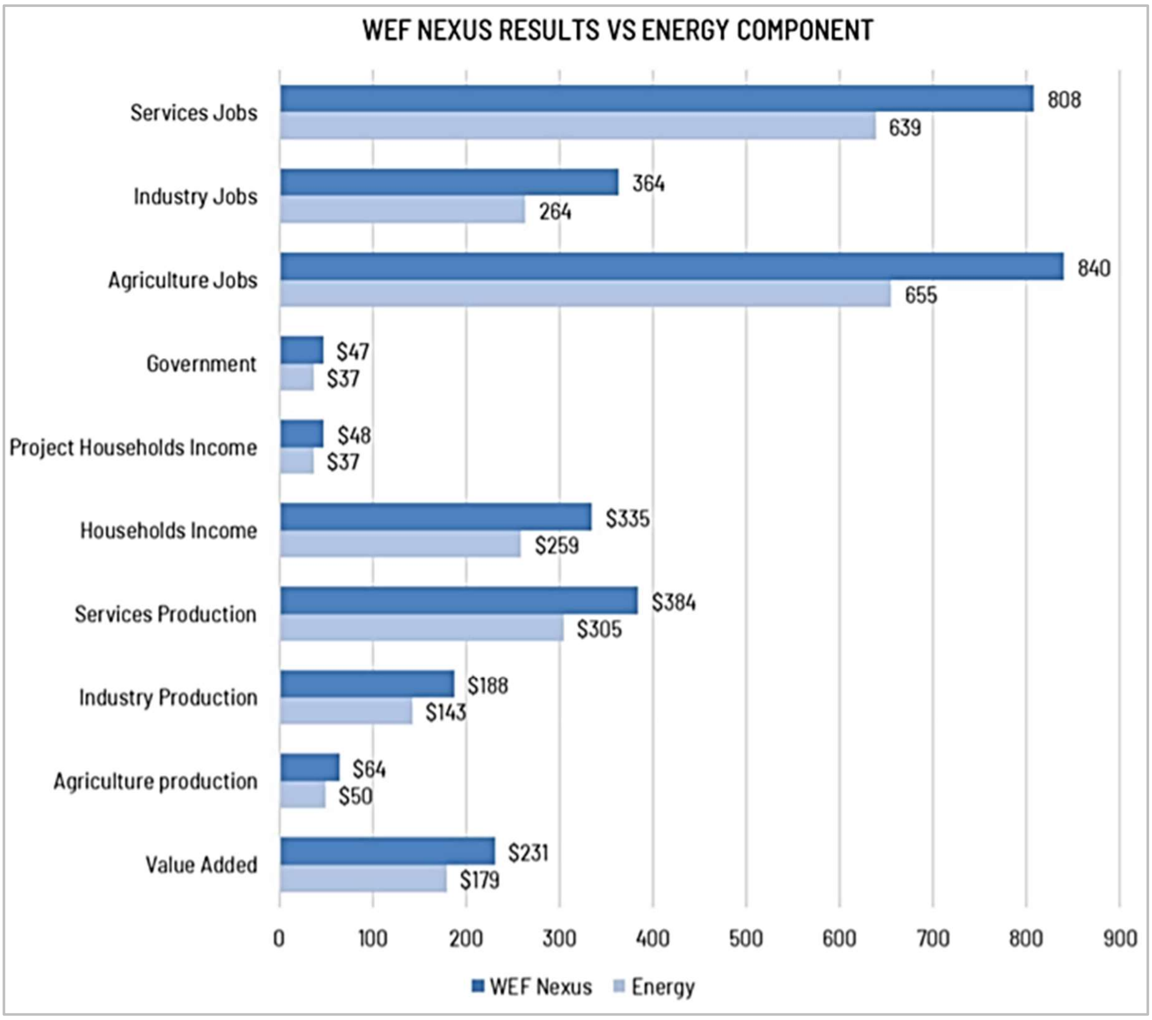


Figure 28 - WEF nexus results compared to the energy component results. Note: Service, Industry and Agriculture jobs are express in unit while all the other indicators are expressed in USD million. Source: OpenEconomics [50].

3.3.8. Policy recommendations

Tanzania's Development Vision 2025 seeks to transform Tanzania into a middle income and semi-industrialized nation in 25 years. To achieve this goal, it is crucial that effective stakeholders are engaged in investment devoted to encouraging economic growth and social cohesion. Planning an appropriate resources allocation strategy aimed to achieve social goals through a quantum jump in technology adoption is crucial to foster development actions.

For this purpose, the results of this assessment suggest the following policy recommendations:

- ***Animation and participation:*** the diffusion of project patterns and its transformative success depends on a dynamic process of adoption and diffusion that can only occur if communities embrace the project goals and solutions and participate in adapting them to the local context through adaptation and innovation. Activities of animation and participation of local communities may thus be crucial actions to achieve widespread adoption of the new technologies and the business model fostered by the project.

- ***Increase policy synergies among key sectors:*** transformative investment requires a holistic approach aiming to link general purpose and enabling technologies with product and process innovations fuelled by higher level of human and non-human capital.

- ***Improving information on the project:*** in order to ensure project success both in its initial and scaled up mode, it is vital ensure an adequate amount of information of the stakeholders involved as well as all local population on the goals, the logic, the features and the WEF nexus project. Both project stakeholders and people not directly involved in fact have a potential role in promoting the success of the projects and investments in a specific area, so that by providing adequate information it is possible to improve the efficiency of the actions performed and engender the transformation that the project aims to achieve. Information should be diffused, accessible, of high quality, and such as to engender engagement and confidence. Governments may also help in this, by furthering knowledge sharing activities using specific programs as well as the media.

- ***Promote trans-boundary activities:*** in a globalised world, decisions cannot be taken alone. Regional and international integration is crucial in order to promote trans-boundaries activities to enhance and spread the benefits deriving from a WEF nexus project while promoting optimal resource use and equitable distribution.

- ***Create a favourable environment for investment:*** WEF nexus projects are positive both for those implementing them and for local societies. For this reason, governments should create a favourable environment for investments by supporting business through an enabling regulatory environment, reducing bureaucratic obstacles to private initiative and foster market competition and innovation.

- ***Create a gender and children-equality environment:*** enhancing WEF related investments means promoting a gender equal environment. As water and fuel collection are currently feminine tasks, the WEF nexus project promises to improve the quality of life of girls and women. In addition, in order to increase long run incomes and opportunities, project implementation should be combined with policies that ensure that children will not be forced to work to contribute to the family wealth, but can attend school, widening their skills and knowledge.

3.4. Case study analysis of 21 RE mini-grids: aggregate and correlation analysis of business model indicators.

3.4.1. Introduction

The main obstacles retaining private investments in mini-grids are usually identified in the financial, technological and institutional areas, accounting for high initial costs and difficulty in access to finance due to the perceived high-risks of investments, low and unpredictable demand patterns, reduced ability to pay and low tariffs and weak policies, among others [9].While these factors are generally present in SSA, they are found declined differently in every specific context, resulting in a lack of a proven business model that can be easily replicated [10]. While private developers are operating and maintaining existing projects and installing new ones, there is not a proportionate stream of data and analyses to capture the current situation and trends. Lack of data and communication is in fact recognized as another key challenge for the mini-grid sector [10], which can be eased by private sector associations that can aggregate information from their members [11].

The "lack of documented experiences, information, knowledge, and open source quality data on renewable mini-grids in sub-Saharan Africa", in the words of Moner-Girona and coworkers, affects as well energy planners and policy-makers [12].

This research, that I fully managed and performed together with Paolo Cherubini from University of Pisa, is intended as an extension of the research carried out within the broader data-driven study on business models for decentralized RE solutions promoted by RES4Africa Foundation and resulting publication “RE-thinking Access to Energy Business Models. Ways to Walk the Water-Energy-Food Nexus Talk in Sub-Saharan Africa.” [103] and the companion assessment specifically addressed the micro and macro-economic impact of a selected case study in Tanzania “Applying the Water-Energy-Food Nexus Approach to Catalyse Transformational Change in Africa.”[50].

3.4.2. The research objective

This research intends to produce a scholarly effort to analyze the extensive database coming from the 21 case studies gathered in the RES4Africa study and analyze them under a different light and by means of a more in-depth data analysis which has slightly updated the projects’ financial performance. While the publication in [103] aimed at modelling the financial profitability of the projects and assess the results vis-à-vis the business model structure adopted, here a set of 48 indicators has been identified, to characterize firstly at an aggregate level the mini-grid sample available, and then to search for emerging patterns and possible correlations among the indicators themselves.

The first objective of this work is to provide a picture, based on the available dataset, of different kind of electrification approaches adopted in SSA, starting from older projects commissioned in the mid-eighties, up to recent ones. Then, in addition to the descriptive aggregate analysis, the research seeks correlations among indicators with the aim to critically analyze in retrospective manner what is the state of the art of the mini-grid sector in SSA so far, and to provide practitioners and developers with evidence to actually support the design, develop and evaluate new projects.

Thus, this work is intended as a first step towards the development of a systematic framework for the comparative and aggregate analysis of mini-grid projects (see chapter 6), to overcome the limitations inherent to case-specific studies, to scope far-reaching findings that can unlock the scaling-up of mini-grid initiatives. Therefore, besides the data availability limitations for some indicators and the inevitable biases implicit in the type and kind of sample selected, the proposed framework of indicators can be populated with a larger and diverse set of data, and as such is a contribution that, in itself, can hopefully benefit academics and practitioners alike.

3.4.3. Methodology of the case studies analysis

This research has been conducted by means of a descriptive analysis which has consisted of the process of gathering and interpreting data to describe what is the state of the art of mini-grids in operation in SSA.

3.4.3.1. General assumptions in the data analysis

The data analysis has been done on 21 mini-grid projects in SSA, identified among 32 pre-selected cases on the basis of selection criteria detailed in Table 9.

Scope	**Criteria**
Geographic position	• sub-Saharan African countries
Location	• rural • peri-urban
System type	• decentralized RE solution (grid connected systems were considered if they included independent generation and distribution)
Services provided	• energy supply (electricity, heating, cooling, etc.) • water related services • food processing and conservation • energy/water/waste management • others (telecommunications, health, housing, etc.)
System sizing	• > 10 kW
Energy sources	• at least one renewable source in the power generation mix
Status	• operational for at least 2 years

Table 9 - Criteria for selection of case studies

Exceptions

The model was created starting from the eligibility criteria of case studies, thus having in mind mini-grid projects that comprise a central generation plant with a distribution system, possibly integrated with the supply of other services and associated revenue streams.

However, 2 business cases developed in South Africa and based on decentralized RE solutions have been included even if not in compliance with the eligibility criteria, being in operation for less than 2 years and based on residential nano-grids, where a small power station interconnects groups of a dozen households. They have been considered to include potentially disruptive new business models, that even if nascent or at pilot stage are worthy of consideration even if their performance cannot be analyzed with the criteria used for the rest of the case studies.

3.4.3.2. Data collection

The data collection activity was carried out from December 2018 to March 2019. As Table 10 shows, 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. The raw data has been used to derive key parameters for the analysis (such as IRR, NPV and payback period), following the methodology described in section 3.4.3.3.

Scope	**Data type**
Business model	- sales model; - type of services; - ownership; - other.
Business plan	- CAPEX; - financial structure (equity, debt, grant); - other.
Operating data	- date of commissioning; - current status; - actual investment (real CAPEX); - revenues, over the operational time; - tariff, over the operational time (with type of tariff plan); - OPEX, with breakdown costs when available; - repowering, if any (not referring to spare parts but to increase/modify generation, storage, etc.); - electricity production in the operational phase (kWh produced and with reference to RE share in the energy mix; - amount of not served energy (kWh);

	- sales volume (for additional services provided: amount of product sold depending on the business: electricity, litres of water, Kg of food processed, etc.); - continuity/discontinuity of the service over the operational time; - number of customers (e.g. connections, etc.); - potential direct market (number of households or population); - other.

Table 10 - Types of data collected from the 21 case studies.

3.4.3.3. Data analysis

The data analysis of the inputs collected were mainly processed in three phases, outlined below and discussed in detail in the following sections:

Phase I: Case-by-case analysis

- a master Excel sheet was developed for the case-by-case analysis;
- data entry and processing were carried out in an Excel Sheet per each case;
- assumptions and projections were included to align all cases and estimate missing data, where needed to get key financial parameters;
- a justification sheet was created to explain all detailed assumptions and calculations;
- cross-checking: results of disaggregated data analysis were compared.

Phase II: Aggregate analysis

- key indicators were identified;
- data from case studies, already processed in the previous phase, were used to calculate indicators case-by-case;
- indicators' values were aggregated;
- statistical results on each indicator were provided as the output of the aggregate analysis output.

Phase III: Correlation analysis

- indicators values were compared to suggest correlations by using both aggregated and disaggregated results;
- suggested correlations are verified case-by-case;
- if any, extra-information was taken into consideration to justify inconsistent results;
- suggested correlations were confirmed or denied and are provided as the correlation analysis' output.

The methodology is explained in detail hereafter.

Phase I: Case-by-case analysis

In the first phase, an Excel model was created starting from the development of a master Excel sheet for the case-by-case analysis. The master structure was that of a business plan for energy-related projects 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 such as the NPV and the IRR, which were included over a 20-year financial plan.

The values of all the financial data have been kept in local currency, and adjusted for inflation, using a ten-year average of the inflation rate registered in the country according to World Bank data source. The IRR was calculated with reference to the local currency, while the NPVs have been converted to USD for ease of comparison of all projects (even those commissioned before the introduction of the Euro in 1999), using the exchange rate of the 31st of December of the year of commissioning.

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. However, data on projects financial structure has been analyzed separately. To discount future cashflows, the average Weighted Average Cost of Capital (WACC) for utilities in each country has been used [104].

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 modelization 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 an evident growth in the historical trends, a reference curve for consumer takeoff 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.

A justification sheet was created to explain all detailed assumptions and calculations in order to fully understand the insights given by the data analysis.

Lastly, to find out any discrepancy, mistake and inconsistency, the results of disaggregated data analysis were compared and cross-checked.

Phase II: Aggregate analysis

In the second phase, data from case studies, already processed in previous phase, were aggregated, by identifying key descriptive indicators.

Bearing in mind this research was conducted within a broader study on access to energy business models, the selection of indicators revolved around "burning issues" in the mini-grid sector for access to energy. Unlike in the original study in [103], the business model classification is not the preeminent criteria to evaluate the features of the various case studies; here, it's only one among the various indicators, so that, in an academic perspective, specific characteristics of each mini-grid are not necessarily "lumped" into a given business model, and the study can be as analytical and granular as possible. That is why business model-related issues are allocated into clusters within a framework of analysis' indicators (see section 3.4.5), used to give both aggregate and correlation analysis' results.

Phase III: Correlation analysis

In the third phase, the relationship between pairs of indicators has been explored, combining the disaggregated and aggregated results obtained for all the indicators reported in Table 16. Given the diversity of the indicators, for their practical significance and data availability, and also considering the exploratory nature of this work, potential correlations have been evaluated by pairing selected indicators together, thus exploring only a meaningful and reasoned subset of 342 pairwise correlations among the 1152 potential ones.

To evaluate them, the criteria adopted is summarized in Table 11:

CRITERIA for the correlation analysis
In case both **indicators assume numerical values**, the correlation is ranked according to the coefficient of determination R^2: Strong correlation ($R^2>0.8$) Moderate correlation ($0.5<R^2\leq 0.8$) Weak correlation ($R^2\leq 0.5$) Not available
In case one or both **indicators assume categorical variables**, the correlation is ranked according to the following criteria: Strong correlation: all the cases verify the correlation (1 exception is admitted only if duly justified) Moderate correlation: all the cases verify the correlation with 1 exception per category. Weak correlation: all cases verify the correlation with 2 or more exceptions per category.
ASSUMPTIONS for the correlation analysis
- Minimum quantity of available cases (per each indicator) to assess a correlation is 2. - "Not available" correlation means that (i) the minimum quantity of available cases is not reached or (ii) the correlation is not relevant. - Mini-grid in steady loss is assumed with -100% IRR.

- Mini-grids 100% funded by local Government are included under the "grant component" indicator. - IRR is calculated over 20 years by using local currencies and do not take into account the financial structure (e.g. grants or debts) to allow a comparative assessment of the projects' financial performance.

Table 11 - Criteria and assumptions for the correlation analysis.

3.4.4. Business model classification

To provide a full description on the methodology adopted, it is relevant to specify how case studies were classified in terms of business models. Such classifications were adopted along the entire research project, not only in this aggregate and correlation analysis.

There are different criteria to classify business models (BMs) for mini-grids. The most common ones are based on ownership, payment systems, distribution strategy, financial structure, operating entity, scalable approach as well as multi-criteria classifications.

The business models that result particularly interesting from a mini-grid developer point of view and that best fit the business cases selected for this analysis as well as the WEF nexus, are the ones based on:

- services provided,
- operating methods,
- ownership.

Classification based on services provided

This study aims at exploring effective solutions to foster the deployment of decentralised RE solutions in SSA. Since the analysis of correlations between integrated business models, the application of the WEF nexus and business financial sustainability are at the core of this study, the business model classification based on services provided is instrumental to present the analysis' results.

This criteria defined three classes as shown in the Table 12.

BM classification based on services provided
Electricity supply (only)
Electricity supply & other energy-related products/services
Electricity supply & other WEF nexus-related services

Table 12 - BM classification based on services provided.

The difference between the two classes including other services in addition to electricity supply (and thus apply an integrated business model) lays in the fact that projects providing

"Electricity supply & other energy-related products/services" deal with other energy-related products/services, such as sale or facilitation in purchasing of electrical appliances and technical services, while projects providing "Electricity supply & other WEF nexus-related services" deal with WEF nexus-related services and therefore integrate the nexus approach in their business' value proposition.

Thus, mapping energy-related products/services and WEF nexus-related services enables the identification of service integration and provides an overview of potential correlations, as Table 13 shows.

	Types of BM based on services provided		
Services provided in detail	**Electricity supply**	**Electricity supply & other energy-related products/services**	**Electricity supply & other WEF nexus-related services**
Electricity supply	**V**	**V**	**V**
Provision of electrical appliances		V	V
Technical services		V	V
Water supply			V
Irrigation and land cultivation			V
Forestry and wood processing			V
Ice production			V
Livestock			V
Animal feed production			V
Meat processing			V
Dairy production			V
Other food production/processing			V
Micro-credit services		V	V

V = mandatory; V = optional

Table 13 - Mapping potential services provided in a mini-gird project.

Taking into consideration the 4 projects that provide WEF nexus-related services, the following activities can be noticed:

- 1 case on electricity supply and water supply;
- 1 case on electricity supply, water supply, forestry, livestock and animal feed production;
- 1 case on electricity supply, water supply, forestry, jam production and cattle meat rearing;
- 1 case on electricity supply and ice production.

In this study, considering on one hand that only a few cases integrate electricity supply with other services in a single business, and on the other hand that all of them run water-related services as not-for-profit public services (such as water supply at a social tariff just to cover maintenance costs or free ice provision), it is interesting to investigate whether such approach, usually developed by non-governmental organizations (NGOs) and public entities, could be integrated in a business strategy adopted by a private entity. In other words, could water-related services, and in particular water supply, be provided not-for-profit by a private entity as well? If such services came at a financially sustainable cost, could they represent an added value for the developer since they sustain local development and ultimately may lead to customers' improved quality of life and ability to pay?

Classification based on operating methods

In order to define a tailored classification based on operating methods, the classes identified by a World Bank's study on mini-grids [105] have been integrated with two additional classes to best describe the following aspects: (i) projects with Power Purchase Agreements (PPAs) or Public Private Partnership (PPPs), which should fall in class A ("build, own, operate") or the new one F ("build, own, operate, transfer") and (ii) projects developed by non-profit actors, which should fall in the new class E ("build, short-operate, transfer"). The latter addresses the peculiarity of non-profit developers to shadow the start-up phase of the project (sometimes even for 6-12 months or more) and to assign the ownership to a local association/cooperative/community-based organization. It is usually a project partner in the development phase, so that the non-profit developer is not the owner at any stage of the project, but instead there is an actual transfer of responsibility as planned in the project design.

This criteria defined six classes for electricity supply. Furthermore, in order to give more prominence to the additional services provided beyond electricity supply and thus clearly identify the projects that apply an integrated business, a second level of classification for such additional services, based on the same criteria of operating methods, is added as shown in the Table 14.

BM classification based on operating methods	
Supply of electricity	Supply of other services
A. build, own, operate	1. build, own, operate
B. build, own, outsource	2. build, own, outsource
C. build, own, lease	3. build, own, lease
D. build, sell	4. build, sell
E. build, short-operate, transfer	5. build, short-operate, transfer
F. build, own, operate, transfer	6. build, own, operate, transfer
	7. none

Table 14 - BM classification based on operating methods.

In this study, 3 out of 4 cases applying the WEF nexus approach (see results in sections 3.4.6, 3.4.7) are implemented through a build-short operate-transfer business model, which identifies projects developed by non-profit actors in this BM classification. This highlights how, among all the other criteria to classify a mini-grid project, the issue of ownership stands out as one of the most interesting, also considering its relevance in the operating methods. That is the reason why it is selected as the third BM classification criteria in this study, as explained in the next section.

Classification based on ownership

In general terms, the ownership structure of a mini-grid should fit in one of the following models: community, public utility, private company or hybrid, featuring for instance a PPP [10]. This criteria defined four classes as shown in the Table 15.

BM classification based on ownership
Public
Private
Community
Hybrid

Table 15 - BM classification based on ownership.

Case studies classified according to criteria of "services provided" and "operating methods" can be read in correlation with the "ownership model".

Taking into consideration at the history of rural electrification, many individuals and communities in rural areas have spontaneously taken it upon themselves, or have done so supported by NGOs, to construct their own rudimentary electricity distribution system supplied by isolated power sources [106]. Once the centralized generation paradigm was challenged and the space for mini-grids was recognized, more structured actions were undertaken to assure a higher standard of service and safety, in which NGOs acted as project developers and transferred the asset and its management to recipient communities.

The **community ownership model** is represented in this analysis by case studies that show the effectiveness of such model if developed by non-profit actors, while providing energy access within a long-term integrated programme that aims at empowering the communities through capacity building, provision of other services and stimulation of productive uses of energy.

The **private company model** is emerging and it can be compared to community models in quantitative terms. This is not an unexpected result, since the approach to the problem of access to energy has gone through a profound change in the last decade during which cooperation development agencies, that usually supported only non-profit actors in the rural electrification sector, are now targeting private investors and consider them eligible for funding. The necessity of involving private capital to reach a wider impact of the international action comes from the high ratio between project budget and beneficiaries in mini-grid projects: public finance is not available to justify high grant funding on large scale programs and non-profit actors cannot afford such important co-contribution [97]. This political and financial framework has encouraged private developers and hampered non-profit actions in the last years. In fact, as this study shows, projects developed by private actors were commissioned after 2016 whereas those developed by non-profit actors were commissioned before 2016. However, it must be underlined that pilot projects are testing partnerships between profit and non-profit actors, where the latter usually play the role of local partners which facilitate preliminary studies and community inclusion by means of complementary activities (see section 3.2.4), with or without providing a financial contribution. In fact, enabling the local environment is one of the key barriers that private developers have to face. However, it may not be the main one: all of the private initiatives featured in this study, except one, have been relying on grants (see results in 2.4.6) which reveals that it is fundamental to reach an acceptable return of investment (ROI) to make the project feasible in a piloting phase and support the scaling-up phase to reach a commercial financial sustainability of the business to justify its replicability.

On the other hand, local governments have also made efforts to increase energy access without solely resorting to grid extension. However, the **public utility model** is represented by case studies with poor technical and financial performances and severe sustainability problems, because (i) they often apply national tariffs which are usually very low, especially if compared to those awarded to private operators after negotiation and licence procedures, (ii) use diesel as a main power source, (iii) have poor community involvement and lack of a more comprehensive approach to support access to energy.

Lastly, hybrid models are a promising alternative as they exploit fruitful cooperation of public and private actors within a clear and established electrification pathway and regulatory framework. Among the case studies analysed, the Monte Trigo micro-grid in Cape Verde was built combining a grant with an investment from the local municipality [7], which partnered with a private actor to create a mixed company that is in charge of O&M and owns the movable assets of the plant, whereas the municipality retains ownership of the distribution grid and power room.

3.4.5. Framework of the analysis' indicators

Business model-related indicators are allocated into the following clusters, used to give both aggregate and correlation analysis' results:

1. Context data
2. Power generation systems
3. Business model and PUE
4. Financial features
5. Electricity market dimensions
6. Electricity tariff and expenditures

The 48 indicators identified are given in Table 16, divided into the six groups outlined above; each one is identified by a number in square brackets, which will be used to refer to them in the remainder of the document. For each indicator, the following measures of position were analyzed to get the key results: arithmetic mean, quartile, minimum and maximum. In Table 17, the frequency distribution of available data presented, which is used to rate the reliability of the results obtained.

Context data

[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]
Country	Location type	System type	Start date	Current status	Actual years of operation[1]	Climatic zone	Settlement type

Power generation system

[9]	[10]	[11]	[12]	[13]	[14]	[15]
Solar PV power installed	Wind power installed	Hydro power installed	Diesel generator installed	Storage capacity	Yearly Energy Produced2	Share of energy from RE2

Business model and productive use of electricity

[16]	[17]	[18]	[19]	[21]	[24]	[25]	[26]	[27]	[28]	[29]
Services provided	Type of PUE service	Low Quality of service[3]	Marketin g campaign	Ownership	Payment systems	Operationa l structure	Complement ary activities	Share of revenues from yther Services than electricity	Operating Method for Electricity Supply	Business Model Classificati on[5]

Financial features

[20]	[22]	[23]	[41]	[48]
IRR[8]	Develope r's assumpti on for the financial plan	Mini-grid in steady loss[4]	OPEX per unit[2]	Grant component

Electricity market dimensions

[30]	[31]	[32]	[33]	[34]	[35]	[36]	[37]	[38]	[39]	[40]	[46]	[47]
Market size -total HHs	Market Penetrati on rate - Total	Connecti on rate trend - HHs[6]	Connecti on rate trend - Others[6,7]	Share of HH consumpti ons - First Year	Share of HH consumpti ons - Last Year[2]	HH yearly consumpti ons (and Tiers) - First Year	HH yearly consumption s (and Tiers) - Last Year[2]	BUS yearly consumpti ons - First Year	BUS yearly consumpti ons - Last Year[2]	Yearly Energy Produced[2] / HH	Share of BUS custome rs - First Year	Share of BUS custome rs - Last Year[2]

Electricity tariff and expenditures

[42]	[43]	[44]	[45]
HHs expendit ure for electricity[2]	HH average tariff[2]	BUS expendit ure for electricity[2]	BUS average tariff[2]

[1] up to 2019
[2] ref. to the last year of data availability
[3] problems reported in detail
[4] not able to cover OPEX
[5] including supply of electricity and other services
[6] over 10 years
[7] businesses, public services
[8] calculated over 20 years of operations, without including grant component to align all projects in the financial performance assessment

Table 16 - Indicators of aggregated data analysis.

Number of data points available for each indicator												
Context data												
[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]					
21	21	21	21	21	21	21	21					
Power generation system												
[9]	[10]	[11]	[12]	[13]	[14]	[15]						
21	21	21	21	21	21	21						
Business model and productive use of electricity												
[16]	[17]	[18]	[19]	[21]	[24]	[25]	[26]	[27]	[28]	[29]		
21	21	14	21	21	21	21	21	21	21	21		
Financial features												
[20]	[22]	[23]	[41]	[48]								
21	21	21	21	21								
Electricity market dimensions												
[30]	[31]	[32]	[33]	[34]	[35]	[36]	[37]	[38]	[39]	[40]	[46]	[47]
15	14	6	6	13	13	13	13	11	11	13	13	13
Electricity tariff and expenditures												
[42]	[43]	[44]	[45]									
13	13	11	11									
Legend												
	High reliability of results											
	Mid reliability of results											
	Low reliability of results											

Table 17 - Frequency distribution of available data.

3.4.6. Aggregate analysis' results

All the indicators presented in Table 16, after being calculated case-by-case, were aggregated to provide statistic results on each indicator as aggregate analysis' output.

The main results are discussed by grouping them into the six typical topics introduced in section 3.4.5, whereas all the details on the aggregate analysis' results are enclosed hereto as Annex 1.

Context data

The 21 case studies are from Tanzania, Ghana, Kenya, Zambia, South Africa and Cape Verde. Thus, according to the world maps of Köppen Geiger climate classification [107], the majority are found in equatorial areas (57%), while the remaining are developed in warm temperate areas (29%) and arid areas (19%).

Most sites are located in rural areas, with the exception of two cases of peri-urban installations in South Africa, which only represent 10% of the total. Considering the settlement type, most projects target moderate scattered settlements (52%) while the others are divided between scattered (24%) and intensive settlements (24%), where scattered is defined as one house in a radius of >100m on average, moderate scattered as one house in a radius falling in a range of 100-30 m on average, and intensive as one house in a radius of <30m on average.

Regarding the age of the projects, the slight majority (52%) have been commissioned between 2016 and 2018, followed by those commissioned between 2011 and 2015 (29%) and those commissioned before 2011 (19%), among which the oldest mini-grid has been operating since 1987.

Power generation systems

The 21 case studies are all isolated off-grid systems with the exception of 1 case which is grid connected, only to sell to the local utility the energy not consumed by the mini-grid's off-takers.

According to the selection criteria in Table 9, all case studied are powered by renewables, and specifically 71% by solar PV with an average installed capacity of 42 kWp, 19% by hydroelectric with an average installed capacity of 275 kW and 10% by wind power only or hybrid wind-PV.

Even if the majority of case studies include a diesel component (57%), the share of RE in the energy generation mix is quite high with an average value of 86%. Electrochemical energy storage represents a relevant component of the systems, with an average capacity of 278 kWh installed in almost all the solar-PV systems, with 2 exceptions only.

Business model and productive use of electricity

The analysis of business models are classified according to the approach described in section 3.4.4 with a the three-level classification method, as it is able to describe mini-grids as well as the WEF nexus by considering separately the services provided, operating methods and ownership, as summarized in Table 18.

Classification based on SERVICES PROVIDED				
				n° of cases
Electricity supply				14 (67%)
Electricity supply & other energy-related products/services				3 (14%)
Electricity supply & other WEF nexus-related services				4 (19%)
Classification based on OPERATING METHODS				
	Supply of electricity (class)	n° of cases	Supply of other services (class)	n° of cases
build, own, operate	A	7 (33%)	1	3 (14%)
build, own, outsource	B	9 (43%)	2	-
build, own, lease	C	-	3	-
build, sell	D	-	4	-
build, short-operate, transfer	E	5 (24%)	5	4 (19%)
build, own, operate, transfer	F	-	6	-
none			7	14 (67%)
Classification based on OWNERSHIP				
				n° of cases
Public				9 (43%)
Private				6 (28%)
Community				4 (19%)
Hybrid				2 (10%)

Table 18 - BM classification methods and results.

In terms of **services provided**, most of the projects only provide an "electricity supply service", accounting for 67% of total case studies, while only 33% of cases provide other services in addition to electricity supply and thus apply an integrated business model. Among them, 4 cases (19%) provide "WEF nexus-related services" and therefore integrate the nexus approach in their business' value proposition, whereas the other 3 (14%) deal with "other energy-related products/services", such as sale or facilitation in purchasing of electrical appliances and technical services [103]. Considering the quality of the electricity supply service, only a minority (24%) records a low quality of the service, even if the data is not available for a third of the total case studies.

In terms of **operating methods**, a tailored classification method has been adopted (see 3.4.4), describing separately the method adopted for electricity supply (classes A-F) and to the supply of other services (classes 1-7), as detailed in Table 14.

Considering the **electricity supply**, the 21 case studies only fall in 3 operating methods: 43% of cases are operated through a build-own-outsource (class B), 33% of cases are operated through a build-own-operate (class A), and 24% of cases are operated through a build-short operate-transfer (class E). The latter addresses the peculiarity of non-profit developers to shadow the start-up phase of the project (sometimes even for 6-12 months or more) and to assign the ownership to a local association/cooperative/ community-based organization. Considering the related O&M, half of the projects applied a local maintenance and local management whereas the other half applied a local maintenance and remote management.

In terms of **additional services**, most of the case studies fall into class 7, so no additional service is offered, clearly corresponding with the 67% figure obtained for the sole supply of electricity in the classification based on services. The build, short-operate, transfer method for additional services (class 5), is typical (3 cases out of 4) in the provision of WEF nexus-related services, while the build, own, operate one (class 1) is adopted in 2 cases out of 3 for the supply of non-WEF energy services [103].

In terms of **ownership**, 43% of the mini-grids analysed have a public ownership, followed by 29% having a private ownership and 19% having a community ownership, while only 10% have a public-private ownership.

Focusing on PUE, one should distinguish the actual compatibility and services provided to support PUE, since they are strictly correlated to the mini-grid business model [103](RES4Africa Foundation et al., 2019). PUE can be defined as agricultural, commercial and industrial activities involving electricity services as a direct input to the production of goods or provision of services [86]. PUE are considered a driver to boost local economy, reduce investment risk and enable customer willingness of more sustainable and advanced business activities.

According to the PUE classification used in the RES4Africa research this work refers to, the level of PUE compatibility & integration can be outlined as follows:

Type I. Restricted compatibility with PUE: the use of electricity to feed limited equipment and appliances in terms of technical specifications or time of use, which are often not compatible with productive uses in rural areas. E.g. DC supply which implies specific DC devices for PUE and/or low thresholds per customer in terms of power peak and electricity consumption.

Type II. Full compatibility with PUE: the use of electricity to feed equipment and appliances for productive uses carried out by off-takers, allowing AC and DC supply, power peaks of machineries commonly used by business off-takers in rural areas and time of use for PUE.

Type III. Full compatibility with integration of PUE in the business: the use of electricity for productive uses as part of a single integrated business case. It powers PUE carried out by off-takers, as defined in II, as well as by mini-grid developer, which adds revenue streams to the sole provision of electricity.

The type I characterizes projects with small size installed capacity or DC distribution, and it is only represented by the minority of cases analyzed (19%, however this data has to be evaluated considering that the selection criteria excluded power plants smaller than 10 kW). The type II represents the majority of the case studies analyzed (62%): the PUE is included as project's result since it is widely recognized that access to reliable and affordable electricity supports the local development. The type III, still a market niche, accounts for 19% of the total case studies analyzed.

Financial features

As extensively discussed in the RES4Africa study this research refers to [103], the financial analysis of the 21 projects confirms that existing mini-grids have been mostly relying on grants (76%) to fund their investment while the others were fully funded by governmental agencies (public funds or energy funds at the national level) or did not receive grants (only for the two projects apply a very peculiar business model based on DC distributed nano-grids in South Africa), as summarized in Figure 29. Among those with grants, 11 have a grant component at 90% or more, whereas 2 at a percentage between 75% and 90% and 3 under 35%.

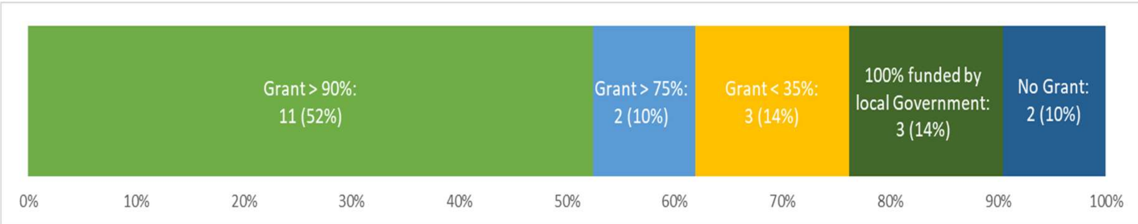


Figure 29 - Project's financial structure - adapted from [103].

Regarding the financial performance, the IRR has been used to rank project profitability and it is calculated by using local currencies while the NPV is converted in USD in order to gain comparable results among projects from different countries.

Results of the financial analysis of the selected case studies should carefully be read taking into consideration that the financial structure (grant, equity, debt, others) is not applied to calculate the financial performance indicators: all projects are aligned on a fully equity structure. Only 19% of case studies are able to achieve a positive IRR within 20 years of operation, followed by 38% of case studies working with operating cost-reflective tariffs that are meant to compensate for OPEX, while the others (43%) operate in steady loss.

Additionally, the share of revenues from other services than electricity is only recorded in 6 cases (28% of total cases), but only 2 cases (10% of total cases) actually record a significant share around 60-70%. However, all these projects provide "WEF nexus-related services" or "other energy-related products/services", with reference to the BM classification of services provided in section 3.4.4. Please note that cases with a share of revenues is 6 instead of 7, since there is 1 project providing "WEF nexus-related service" for free and thus there is not accounted.

With regard to OPEX, the average value per electricity unit produced is 0.36 Euro/kWh; however, it is relevant to report high variations with the first quartile of only 0.11, while the second and the third ones are close to the average value with 0.32 and 0.41, respectively.

Electricity market dimensions

Data on the electricity market dimensions notably differ among case studies analyzed and the frequency distribution of available data is not high so that a mid-reliability of result is estimated (see Table 17). That is the reasons why also quartiles are reported in this section.

The average target market is composed of 3,589 households; however, the first quartile is only 515 while the second and the third ones nose up 2,655 and 3,931, respectively.

The total market penetration rate is 24% on average at the 1st year of operation; however, the first quartile is only 4% while the second and the third ones are 14% and 30%, respectively. The penetration rate rapidly increases up to the 5th year, reaching 44% on average and a notable gap among quartiles: the first quartile is only 8% while the second and the third ones are 51% and 65%, respectively. Values remain quite stable up to the 10th year, however it must be specified that only half of projects with available data for this indicator are actually running for more than five years, whereas projections were carried out for the other half.

To full describe the mini-grid off-takers, the share of business connections is an interesting indicator. The average share is 12% at the 1st year of operation, even if it relevant to report that values are gradually distributed in a range of 0% to 29%, and the average share slightly decreases at the last year of operation with a value of 11% and the same gradual distribution.

The overall indicator of the yearly energy produced per household, which us referred to the last year of operation, reveals that the average values is 386 kWh/year per household; however, the first quartile is only 235 whereas the second and the third ones are 361 and 524, respectively.

Electricity consumptions are described through a set of indicators, which distinguish between households and business activities, whereas data for public services are not available. However, it must be highlighted that the last year of operation, which is mentioned hereafter, varies case-by-case: as shown in Table 17, these group of indicators are available for 13 cases and the last year of operation falls between 3 and 15 years in these specific projects.

The share of household consumptions out of the total energy consumed is 71% on average at the 1st year, with values of 73%, 80% and 85% for the first, second and third quartile, respectively. The indicator is analyzed in the last year of operation as well, with a slight increase of the average value up to 78%, mainly due to variation of the first quartile.

The household yearly consumptions at the 1st year of operation fall in Tier 2, with the exception of the first quartile in Tier 1, according to the World Bank MTF for measuring access to household electricity supply classification [108], and almost all the project remain in the same Tier in the last year of operation as well, with two exceptions in Tier 3 only. In terms of energy, the average value at the 1° year of operation is 174 kWh/year; however, the first quartile is only 114 while the second and the third ones nose up 169 and 233, respectively. Increasing lower than 20% is recorded at the last year of operation, with an average value of 204 kWh/year and values of 158, 182 and 244 for the first, second and third quartile, respectively.

Regarding business yearly consumptions, the average value at the 1st year of operation is 658 kWh/year; however, the first and second quartiles are very close with 414 and 466 kWh/year respectively, while the third one noses up 662. A slight decreasing lower than 3% is recorded at the last year of operation, with an average value of 639 kWh/year, mainly due to variation of the third quartile.

Electricity tariff and expenditures

As for the data on the electricity market dimensions, both average and quartiles are reported in this section since data on electricity tariff and expenditures notably differ among case studies analyzed and the frequency distribution of available data is not high so that a mid reliability of result is estimated (see Table 17).

The household's expenditure for electricity is 96.9 Euro/year on average; however, high variations are recorded with the first quartile of only 45.2, the second one of 75.9 and the third one of 150. As expected, the business's expenditure for electricity is notably higher with a value of 273.2 Euro/year on average; however, the first quartile is only 150.2 while the second and the third ones are very close with 204.9 and 258.6, respectively.

In all the projects the electricity tariffs differ between household and business off-takers. The average electricity tariff for households is 0.8 Euro/kWh, even if a notable gap is recorded between the first and second quartiles, giving a value of 0.3, and the third one which reaches 1.1. The average electricity tariff for businesses is 0.5 Euro/kWh and only the first quartile get a lower value of 0.3 while the second and third ones fall around the average value.

3.4.7. Correlation analysis' results

As discussed in section 3.4.3, potential correlations between the 48 indicators identified for this research (Table 16), have been explored by an expert selection of indicator pairs. Out of the 1152 potential correlations, 342 have been investigated, excluding the remainder due to the minimum quantity of available cases not being reached or the correlation was not relevant. A summary of the results is presented in Table 19 and Figure 30: the correlation analysis reveals 66 strong correlations, 85 moderate correlations and 185 weak correlations.

Item	Quantity
Indicators	48
Potential correlations	1152
Analysed correlations	342
Results	**Quantity**
Strong correlations	66
Moderate correlations	85
Weak correlations	185

Table 19 - Summary of the correlation analysis results.

Considering the large quantity of information, the correlation analysis' results are described in this document through a selection of the correlations which are considered relevant for a broader discussion, beyond peculiarities of case studies analysis. When considering a pair of indicators, the respective identifying numbers, as reported in Table 16, will be reported in square brackets in the format [X-Y].

The strong correlations are analyzed first in section 3.4.7.1, analyzing the relationships between indicators belonging to the six fundamental thematic groups outlined in section 3.4.5. Moderate and weak correlations are discussed in section 3.4.7.2 and 3.4.7.3 respectively, going through the insights they suggest highlighting further investigation needs.

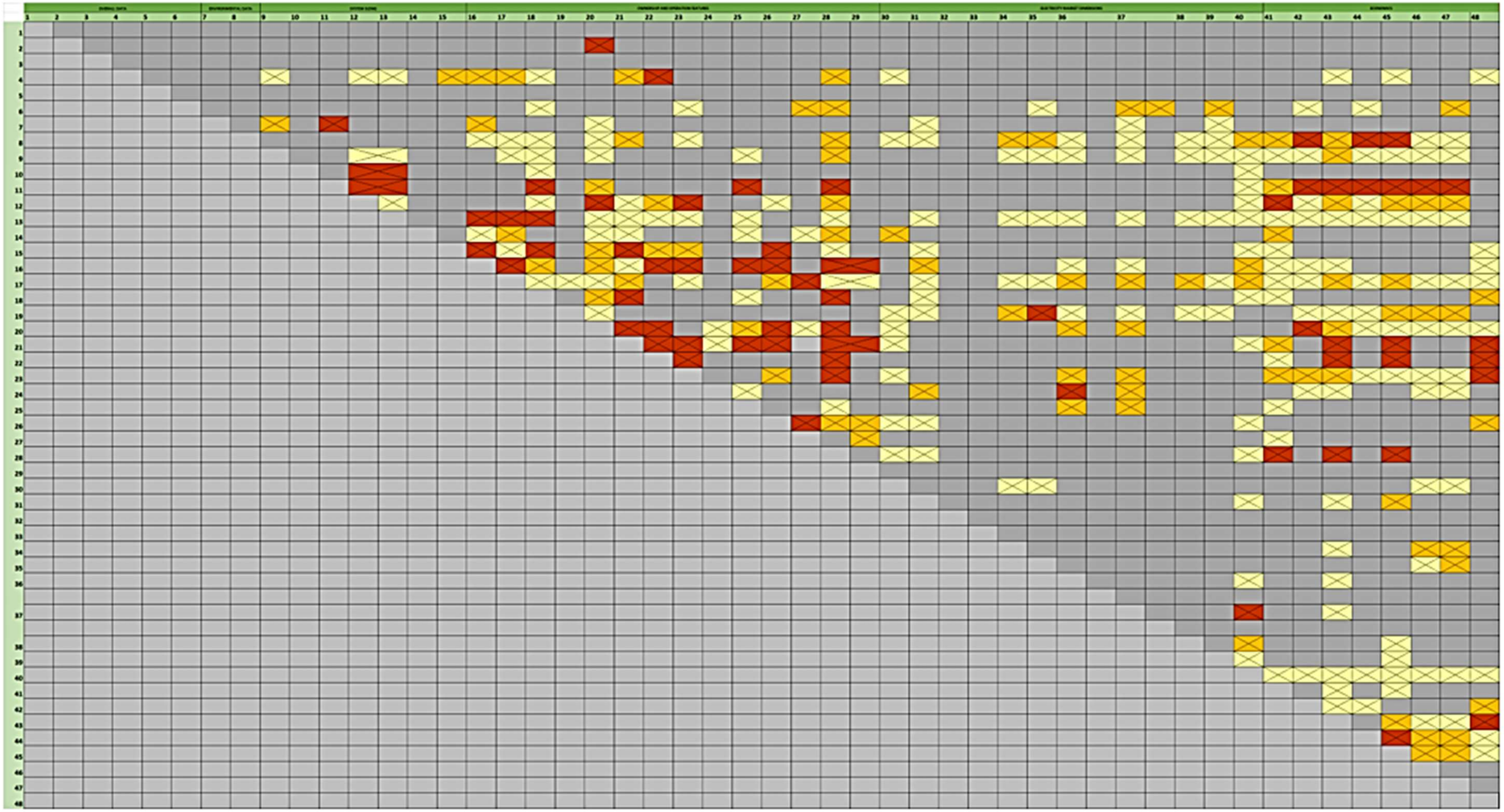


Figure 30 – Matrix of correlations between indicators.

Legend (as per the criteria reported in Table 11):

Strong correlation

Moderate correlation

Weak correlation

Data not available/not analyzed

3.4.7.3 Strong correlations

As mentioned above, the discussion on strong correlations will follow a structured approach, considering firstly the ones among indicators belonging to the same group, and then correlations belonging to different groups, as summarized in Table 2020. Among the 66 strong correlations identified, 35 have been selected for discussion as the most insightful and noteworthy. The table also reports the section number in which the correlation is discussed, for ease of consultation.

Correlations between indicators of the same group		**Quantity**
1.Context Data		0
2.Power Generation Systems		0
3.Business Model and PUE		5
4.Financial Features		3
5.Electricity Market Dimensions		1
6.Electricity Tariff and Expenditures		1
Correlations between indicators of different groups		**Quantity**
1.Context Data *and*	**2.**Power Generation Systems	0
	3.Business Model And PUE	0
	4.Financial Features	0
	5.Electricity Market Dimensions	0
	6. Electricity Tariff and Expenditures	2
2.Power Generation Systems *and*	**3.**Business Model And PUE	8
	4.Financial Features	3
	5.Electricity Market Dimensions	0
	6. Electricity Tariff and Expenditures	0
3.Business Model and PUE *and*	**4.**Financial Features	6
	5.Electricity Market Dimensions	1
	6. Electricity Tariff and Expenditures	2
4.Financial Features *and*	**5.**Electricity Market Dimensions	0
	6. Electricity Tariff and Expenditures	5
5.Electricity Market Dimensions *and*	**6.** Electricity Tariff and Expenditures	0
	Total:	**35**

Table 20 - Strong correlations selected for discussion.

Business Model and PUE – correlations between indicators of the same group

Case studies classified according to the operating method criteria can be read in clear correlation with the ownership model [21-28-29]:

- all the 9 public ownership projects operate through a build-own-outsource business model;
- all the 6 private ownership projects operate through a build-own-operate business model;
- all the 4 community ownership projects operate through a build-short operate-transfer business model;
- hybrid ownership projects, represented by only 2 cases, apply a build-own-operate or a build-short-operate-transfer business model.

Additionally, the operating method is also correlated to the quality of service, since all the projects applying a build-own-outsource operating method record low quality of the service [18-28]. On the other hand, all the projects recording low quality of the service have a public ownership or a hybrid public-private ownership [18-21].

Another method applied to classify the business models is by considering the types of services provided, which revealed interesting evidence if correlated with (i) the operating method and (ii) PUE. Regarding the operating method, as shown in Table 2121, all the 9 projects applying build-own-outsource business model provide electricity supply only, while 3 out of 4 cases applying "electricity supply & other WEF nexus-related services" are implemented through a build-short-operate-transfer business model, which identifies projects developed by non-profit actors; weak correlation is given for all the other projects [16-28-29].

Operating method for supply of electricity	N° of cases	Operating method for supply of other services	N° of cases	Class code	Services provided
A. build, own, operate	7 (33%)	1. build, own, operate	3 (14%)	A.1	**2 (10%)** electricity supply & other energy-related products/services
		7. none	4 (19%)	A.7	**1 (5%)** electricity supply & other WEF nexus-related services
B. build, own, outsource	9 (43%)	7. none	9 (43%)	B.7	**9 (43%)** electricity supply
E. build, short-operate, transfer	5 (24%)	5. build, short-operate, transfer	4 (19%)	E.5	**1 (5%)** electricity supply & other energy-related products/services **3 (14%)** electricity supply & other WEF nexus-related services
		7. none	1 (5%)	E.7	**1 (5%)** Electricity supply

Table 21 - Correlation between operating method and services provided – adapted from [103]

Regarding PUE, strong correlation is recorded only for cases providing full compatibility with integration of PUE in the business (Type III as defined in section 3.4.6): all of them apply a business model which provides "electricity supply & other WEF nexus-related services". Weak correlation for all the other cases providing restricted compatibility with PUE (Type I) or full compatibility without integration of PUE in the business (Type III) [16-17].

Moreover, the correlation between the level of PUE compatibility & integration and the BM classifications based on criteria of services provided: 3 out of 4 cases having full compatibility with integration of PUE in the business (Type III) and providing "electricity supply and WEF nexus-related services" are owned by community entities [17-21].

Financial Features – correlations between indicators of the same group

As expected, IRR reflects the developer's assumption for the financial plan: projects designed to operate for profit result in higher IRR [20-22] and thus they are not among those working in steady loss [22-23].

Specifically, the 6 projects working with a kind of commercial purpose, employing a tariff that is designed for profit, at least in principle, should be able to achieve a pay-back period during the commercial operation of the plant. However, the financial analysis reveals that 2 of them do not reach a payback period within 20 years of operation.

In the other 15 projects, which operate non-for-profit, the developer designed a financial plan that does not intend to recover the CAPEX. Among them, only 6 cases work with operating cost-reflective tariffs that are meant to compensate for OPEX, which means that they adopt at least an operational sustainability. Remarkably, 4 out of 6 are developed by NGOs, showing how such grant-funded projects can serve as pilots to demonstrate, albeit partially, the financial sustainability of energy access initiatives.

Additionally, the 9 projects unable to cover running expenses, and thus operating in steady loss, were almost fully funded either from grants or public funds [23-48] and specifically:

- 6 have a grant component at 90%,
- 3 are 100% funded by local government,
- 1 has a grant component at 75%.

Electricity Market Dimensions – correlations between indicators of the same group

The only one strong correlation revealed that higher households' energy consumptions are recorded in projects producing more energy per household (calculated as the total energy produced/household as indicator of the amount of available energy in the target market). In other words, domestic consumptions increase where there is more energy available [37-40].

Electricity Tariff and Expenditures – correlations between indicators of the same group

The only one strong correlation revealed that business expenditure for electricity and electricity tariff are clearly and positively correlated [44-45], as shown in Figure 31. The result is given only if the highest expenditure of 998 Euro/year is excluded from the R^2 calculation.

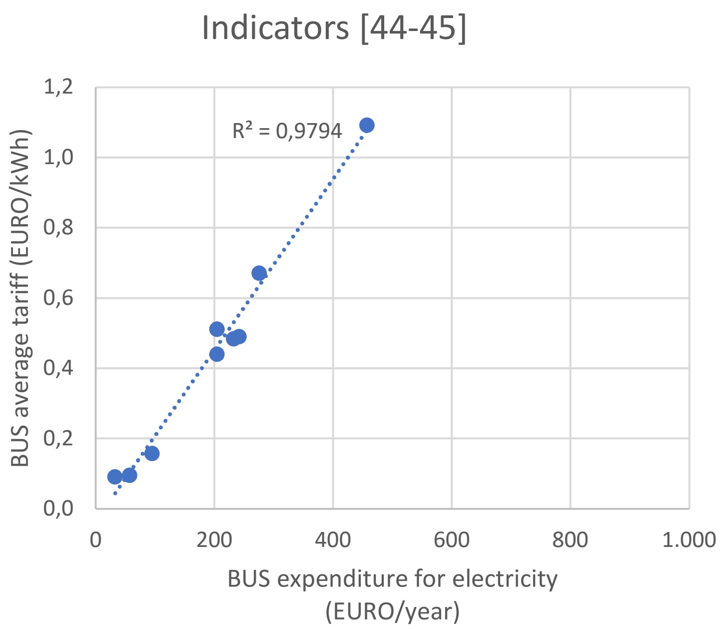


Figure 31 - Correlation between Business Average Tariff and Business Expenditure for electricity

Context Data in correlation with Electricity Tariff and Expenditures

Context data are in strong correlations only with indicators on electricity tariff and expenditures: both household and business expenditure for electricity increase with the intensity of settlement [8-42, 8-44] whereas only business average tariffs increase with the intensity of settlement [8-45].

Power Generation Systems in correlation with Business Model and PUE

Matching indicators on power generation systems with the ones on business model and PUE resulted in many strong correlations; we will discuss eight of them in the following.

Firstly, they regard hydroelectric power projects: among 4 projects analyzed, all of them do not report low quality of service [11-18]. This positive data should be read together with another evidence: all the hydropower projects apply a build-short operate-transfer (class E) business model [11-28]. The result could be justified considering that such model addresses the peculiarity of non-profit developers to shadow the start-up phase of the project (sometimes even for 6-12 months or more) and to assign the ownership to a local association/cooperative/community-based organization. It reflects 2 relevant issues for non-profit actors: 1) hydropower project are preferred because the solar-PV projects' LCOE is usually higher with respect to hydropower ones and thus the ratio budget/beneficiaries is higher (meaning lower impact with a given budget); 2)there is no storage system, and related replacement costs, in hydropower plant and this favours a longer operating life (if locals are properly trained and supported, even after the plant commissioning).

Secondly, an interesting evidence is given with a focus on storage systems. Among 18 projects with storage or hydroelectric power component (that can potentially work 24/7 even without storage):

- 7 (39%) don't have data available,
- (11%) report low quality of service and
- 9 (50%) do not report low quality of service [13-18].

Additionally, all the cases providing services beyond the sole electricity supply (including cases applying a WEF nexus approach) have installed storage systems or count on hydroelectric power components [13-16] and they have a ratio between net yearly storage capacity - assuming 50% depth of discharge (DOD) and 1 cycle/day - and yearly energy produced of at least 1. Specifically, results are interesting if they are disaggregated into cases providing "electricity supply only" and cases providing "electricity supply & other WEF nexus-related services" or "electricity supply & other energy-related products/services". Among 14 cases providing "electricity supply only", 11 (79%) have a storage system, while among 7 cases providing "electricity supply & other WEF nexus-related services" or "electricity supply & other energy-related products/services", all have a storage system (3, accounting for 43%) or hydroelectric power component (4, accounting for 57%) installed.

Still remaining on the storage indicator, there is a strong correlation for cases providing full compatibility with integration of PUE in the business (Type III of PUE service) only, with a ratio between net yearly storage capacity (assuming 50% DOD and 1 cycle/day) and yearly energy produced of at least 1. There is a weak correlation for all the other cases providing restricted compatibility with PUE (Type I of PUE service) or full compatibility without integration of PUE in the business (Type III of PUE service) instead [13-18].

Lastly, interesting results arise on the share of RE in the energy mix. Projects with lower share of energy from RE apply a business model which provides "electricity supply only" [15-16]. The correlation is clear both considering projects with share of energy from RE < 95% of the total yearly energy produced and projects with share of energy from RE close to 99%. Even if the latter does not seem to be relevant, it reveals the approach applied by the project developer: mini-grids designed to run almost 100% from RE requires highest investments and were probably funded by impact funds/ international cooperation/ development banks require to pursue SDGs and thus low carbon emissions and high socio-economic impact and boosted business models providing further services than electricity supply.

Considering the business model classification based on ownership, the 3 projects with the lower share of energy from RE have a public ownership, followed by 1 of the 2 projects with a hybrid PPP ownership, whereas all the projects with private or community ownership have a share of energy from RE of 99-100% [15-21].

The last strong correlation regards projects with lower share of energy from RE, which record low quality of the electricity supply service [15-18]. The correlation is clear for projects with share of energy from RE < 95% of the total yearly energy produced. At a first glance, the correlation should be reduced due to a project with 100% energy from RE recording low quality of service as well, but it is a plant in Zambia which was negatively affected by several factors and lost about 50% of its customers after the two first years of operation due to generation curtailment, lack of community involvement and of a clear and coherent tariff plan.

Power Generation Systems in correlation with Financial Features

Strong correlations between power generation systems and financial features are all related to the diesel component. All the projects with diesel component result to have worst financial performance, except one: 11 out of 12 cases are included in the worst-13 ranked models [12-20]. It is evident that the larger the diesel generator installed, the higher are the OPEX [12-41]. Additionally, all the projects operating in steady loss, except one, are mini-grids with a prevalent diesel generation component. The exception is a project mainly powered by genset that records a very bad financial performance (IRR<-50%) thus it confirms the correlation even if it does not reach the steady loss stage [12-23].

Business Model and PUE in correlation with Financial Features

The mini-grid financial performance is clearly correlated to the business model applied and the three classifications (services provided, operating methods, and ownership) adopted in this research are useful to describe such interactions.

All the mini-grids in steady loss provide "electricity supply service" only, except one [16-23]. The main reasons for this exception, which is related to a project providing "WEF nexus-related services" lie in the fact that (i) the WEF related activity (ice production) is not-for-profit which means that no additional revenue stream supports the mini-grid business even if the asset and operational costs of an ice machine are consistent and (ii) the usage of diesel in support of the renewable power plant increases the OPEX and causes the steady loss of the business plan.

Furthermore, correlation [23-28] reveals that 8 out of 9 projects with a build-own-outsource business model operate in steady loss, thus there is 1 project with a build-own-outsource model recording better financial performance. It is also evident that 8 out of 9 projects operating in steady loss apply a build-own-outsource business model and the remaining 1 project applies a build-own-operate model instead.

Moreover, all the projects with public ownership, except one, operate in steady loss [21-23] and such projects were almost fully funded either from grants or public funds [23-48]. It is also relevant to highlight that 8 out of 9 projects in steady loss are fully owned by public entities, while the remaining one by a hybrid public-private ownership.

The ownership model clearly affects the IRR as well: projects with the highest IRR have private ownership, followed by those having community ownership [20-21].

At the same time, there is a strong correlation between IRR and the operating method [20-28], as shown in Figure 32:

- the top-11 (in blue) apply a either a build-own-operate model (class A, as per the classification detailed in Table 14) or a build-short operate-transfer model (class E);
- the worst 10 (in orange) ranked projects apply a build-own-outsource model, with a single exception of a build-own-operate model;

- all the 5 cases applying a build-short operate-transfer operating method (code E) are ranked in the top-11 (4 out of 5 are developed by NGOs while the fifth is a hybrid public-private initiative) and
- the remaining 6 cases apply a build-own-operate model (code A) and are all developed by private actors.

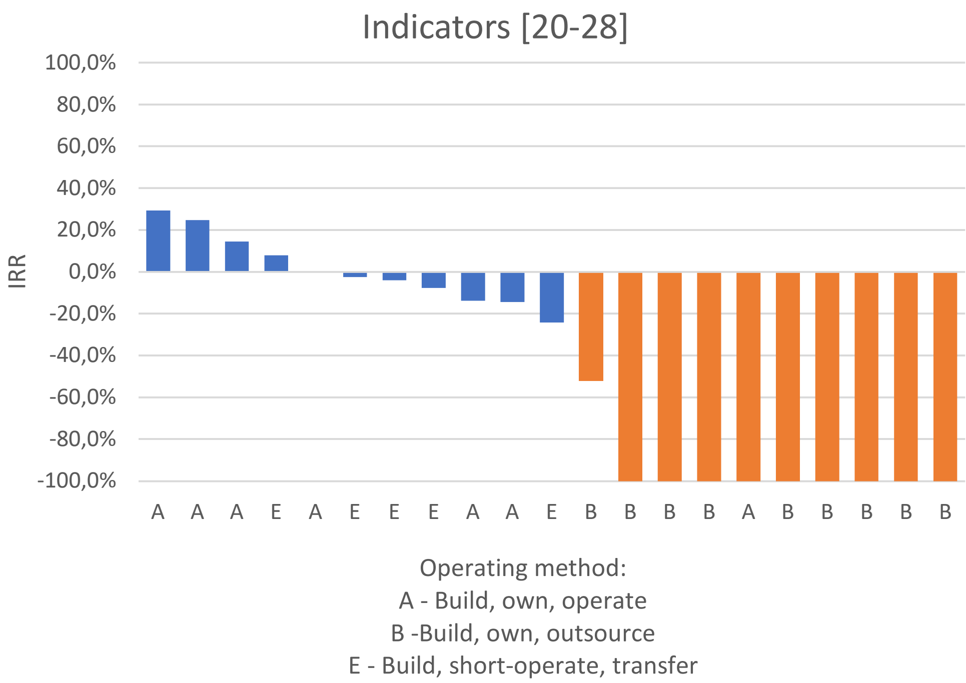


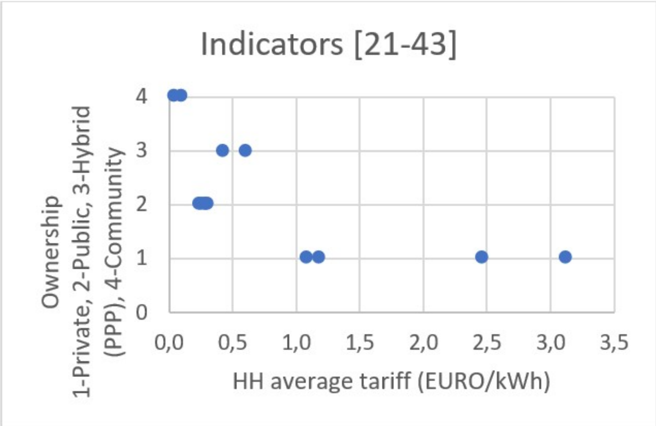
Figure 32 - Correlation between IRR and Operating Method

Business Model and PUE in correlation with Electricity Market Dimensions

The only one strong correlation revealed that all the projects applying PAYG systems record higher households' energy consumptions than those projects applying monthly payments [24-36].

Business Model and PUE in correlation with Electricity Tariff and Expenditures

Figure 33 shows strong correlations where, on one side, the lowest household electricity tariffs are applied in projects with community ownership, followed by projects with public, hybrid and private ownership, in this order [21-43]. On the other side, the lowest business electricity tariffs are applied in projects with community and hybrid ownership, followed by projects with public and private ownership, in this order [21-45].



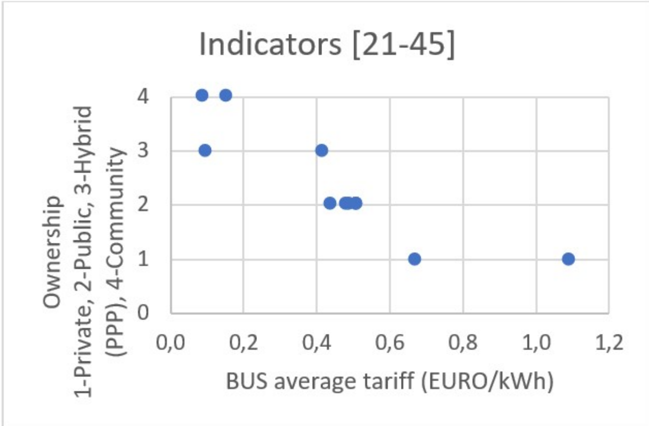


Figure 33 - Correlation between HHs average tariff and owneship model (left). Correlation between Business average tariff and owneship model.(right).

With regard to operating method instead, there are the two following evidences on both household tariff [28-43] and business tariff [28-45]:

- projects operating with build-own-operate business model apply higher tariffs than other projects;
- projects operating with build-short-operate-transfer business model apply lower tariffs than other projects, with one exception for household tariff.

Financial Features in correlation with Electricity Tariff and Expenditures

Projects with higher IRR record higher expenditure for electricity per households, except one [20-42]. The exception is the same one justified in the previous paragraph about correlation [16-23].

It is also evident that projects where developer's assumption for the financial plan declare a for profit initiative apply the highest household electricity tariffs [22-43] and business electricity tariffs [22-45].

3.4.7.3 Moderate correlations

Beyond strong correlations, other moderate correlations can feed an interesting discussion. The most interesting ones are selected and discussed hereafter.

A moderate correlation suggests **that IRR is positively correlated to the WEF nexus approach** [16-20]. Considering the IRR ranking from the point of view of the business model classification based on services provided (Figure 34), the top-11 present a balanced mix of the three classes. However, the IRR ranking reveals another interesting evidence looking at the top-11, which includes:

- all the projects applying a business model based on "electricity supply & other energy-related products/services" (3 out of 3);
- all the projects applying a business model based on "electricity supply & other WEF nexus-related services" except one (3 out of 4); the exception is the same one justified in 4.3.1.8 about correlation [16-23].

•   36% of projects applying a business model based on "electricity supply" only (5 out of 14).

Thus, cases applying the WEF nexus approach showed encouraging financial performance while cases fully focused on the electricity supply are lower ranked in the large majority, even applying higher electricity tariff for business customers [16-45] whereas there is a weak correlation with the household tariff [16-43]. Additionally, 3 out of 4 cases applying the WEF nexus approach are implemented through a "build, short operate, transfer" business model (see strong correlation [16-28-29]), which identifies projects developed in this classification by non-profit actors. All of them ran water-related services as not for profit public services – such as water supply – at a social tariff just to cover maintenance costs. This suggests that developers focused on the socio-economic benefits of the beneficiaries have exploited innovative solutions to integrate food and water-related services into their energy supply business models, demonstrating their actual feasibility [103].

These results suggest that business models applying integrated services should be further investigated.

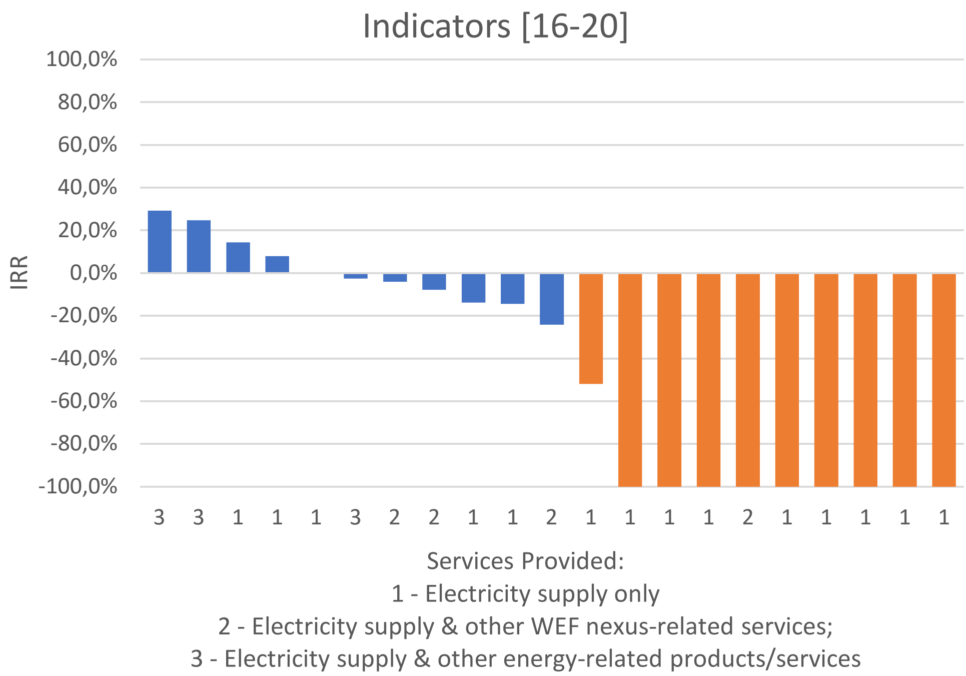


Figure 34 - Moderate correlation between IRR and services provided.

Looking at the ranking based on IRR, the top-11 ranked projects have a share of energy from RE of 99-100% [15-20] and those with lower share operate in steady loss [15-23], however such correlations are moderated by the fact that there are projects with the same share which are differently ranked as well.

Still remaining on financial performance but with a **focus on OPEX**, projects operating at a steady loss (meaning that the revenue streams are not able to cover the OPEX) record the higher OPEX per electricity unit, mainly due to fuel expenditures or simply to staff and other O&M costs. In such cases, the choice of adopting a national electricity tariff plan, giving up on cost-reflective tariffs or subsidized tariffs, denotes the acceptance of economic losses from local utilities [103]; among those not operating at a steady loss, 2 projects with highest OPEX per unit are exceptions since they are justified by applying very high household and business electricity tariffs.

About the **PUE indicator**, the Table 22 shows the correlation between the level of PUE compatibility & integration and the BM classifications based on criteria of ownership [17-21]. It highlights that, firstly, almost all public mini-grids (8 out of 9) are fully compatible with PUE (type II), which could reflect public policies to foster rural development. Secondly, there are no public and private mini-grids that have full compatibility with integration of PUE in the business (type III), which could reveal the challenges beyond such approach as well as the innovation it represents in the rural electrification sector. Lastly, 3 out of 4 cases having full compatibility with integration of PUE in the business (type III) and providing electricity supply and WEF nexus-related services (as per BM classification on services provided) are owned by community entities. This factor could suggest that partnership with local cooperatives and associations structured or empowered during the project development phase is key to successfully carried out high-impact and viable rural electrification projects [103].

Level of PUE compatibility & integration	N° of cases	BM based on services provided	BM based on operating method	BM based on ownership
Restricted compatibility with PUE	4 (19%)	2 cases electricity 2 cases electricity & energy-related products/services	1 case E.7 1 case B.7 2 cases A.1	1 case public 1 case hybrid 2 cases private
Full compatibility with PUE	13 (62%)	1 case electricity & energy-related products/services 12 cases electricity	1 case E.5 4 cases A.7 8 cases B.7	1 case community 4 cases private 8 cases public
Full compatibility with integration of PUE in the business	4 (19%)	4 cases electricity & WEF nexus-related services	1 case A.1 3 cases E.5	1 case hybrid 3 cases community
Total	**21(100%)**	**21**	**21**	**21**

Table 22 - Correlation between level of PUE compatibility & integration and BM classifications.

Still remaining on PUE, lower compatibility of the system with PUE results in both lower household yearly consumptions [17-36] and business yearly consumptions [17-38]. Thus, there is a correlation between PUE and domestic use of electricity as well as business use of electricity beyond PUE (e.g. commercial or artisan activities). Evidence seems to increase in projects providing "full compatibility with integration of PUE in the business" (type III) as well as along the operating life for households [17-37] while evidence for business in the first year of operation is not confirmed over the operating life [17-39]. Further investigation is suggested.

Additionally, lower compatibility of the system with PUE results in lower yearly energy produced/HH [17-40], where household is used as reference term for the market size. As above, evidence seems to increase in projects providing "full compatibility with integration of PUE in the business" (type III).

The sixth one is related to electricity consumptions and expenditures and the most relevant moderate correlations are the following:

- [6-37] suggests that household yearly consumptions (kWh/household) increase over the time, even if it mainly happens within Tiers 2 and 3;

- the share (%) of household consumptions is higher in moderate and intensive settlements than in scattered ones, both in the first year of operation [8-34] and in the last one [8-35];

- the total yearly energy produced (kWh/household, where household is used as reference term for the market size) increases with increasing the intensity of settlements [8-40];

- projects with higher IRR record lower household yearly consumptions [20-36] and the correlation is confirmed over the operating life [20-37];

- projects with higher share of household yearly consumptions (with respect to business ones) have a smaller cluster of business customers [34-46]. in other words, there is a positive correlation between the share of business customers and share of business consumptions. It implies that there are no or few anchor loads able to shift business consumptions in rural areas. The correlation is confirmed over the operating life [34-47, 35-47];

- higher business energy consumptions are recorded in projects producing more energy per household (calculated as the total energy produced/HH as indicator of the amount of available energy in the target market) [38-40]. In other words, where there is more energy available, business consumptions increase;

- the smaller is the genset size, the higher is the share of business customers, both in the first year of operation [12-46] and in the last one [12-47]; unlike the hydroelectric projects, this share remains quite stable over the time, meaning that there is not a notable increase of the household penetration rate as recorded in other projects analyzed, while it confirms that the business market is rapidly reached despite the household market.

- business expenditure for electricity and share of business customers are negatively correlated [44-46]: projects with higher business expenditure for electricity record lower share of business customers and the correlation is confirmed over the operating life [44-47];

- the share (%) of business customers decreases over the time [6-47] since their absolute value is quite stable whereas the household penetration rate increases, as shown in Figure 35.

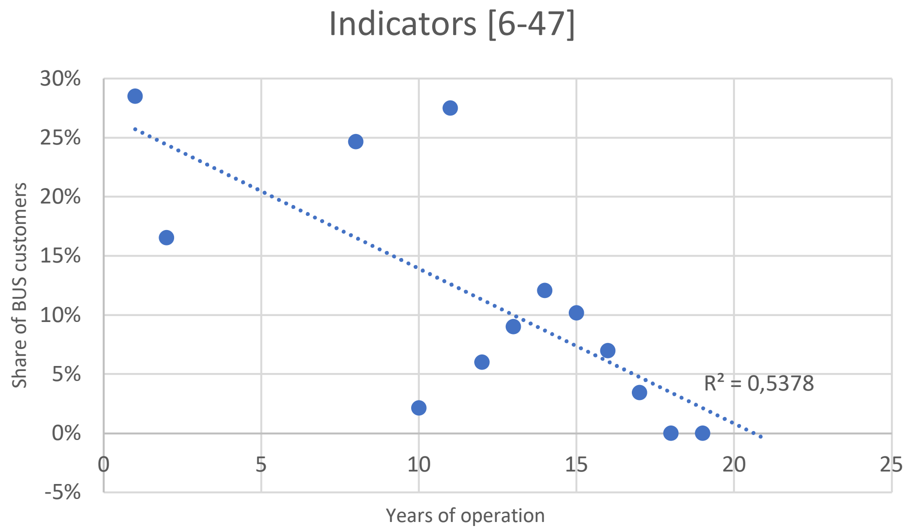


Figure 35 - Share of business customers over the time

All these indicators should be read together since they might affect several factors, such as: (i) moderate and intensive settlements might imply a larger domestic market to be managed, associated with related risks [109]; (ii) higher quantity of connections might not imply higher electricity consumptions (and related revenues) if the PUE component is not relevant and properly supported by complementary activities [103]; (iii) the project impact in term access to electricity might not be proportional to the system size since small systems might favour business connections to be sustainable and less access for households; (iv) even if distribution costs are lower in moderate and intensive settlements, they should be analyzed together with the last-mile connection costs (connection from the grid to the house, including meter) and who pay for them and how in case of subsidies, since inability to pay for the full connection fee is a major barrier to access to electricity [110].

The last one is related to the **electricity tariff** and the most relevant moderate correlations are the following:

- lower compatibility of the system with PUE (types I and II as per classification of the "level of PUE compatibility & integration" in 3.4.6) results in higher household tariff [17-43]; it may depend on the need to compensate the low ability to pay and to consume of domestic customers, however the share of household consumption does not confirm such hypothesis, thus further investigation is suggested;

- full compatibility with PUE (type II) without integration in business results in a higher business tariff [17-45]; it may depend on the need to recover high CAPEX to assure reliable supply for PUE in projects which can only count on the revenue stream of electricity sale;

- projects with higher IRR apply higher household tariffs [20-43] whereas projects operating in steady loss apply the lowest household tariffs [23-43] and record a prevalent diesel generation component that have confirmed to be unsustainable with a uniform national tariff plan not able to cover the fuel expenditure [103];

- electricity tariffs increase with the intensity of settlement (correlation for business tariff [8-45] and moderate correlation for household tariff [8-43], which is actually decreased due to and strong, however the correlation for households is reduced due to an exception with high tariff in moderate settlement applied in a peri-urban South African location);
- electricity tariff plans apply proportional household and business tariffs [43-45];
- business electricity tariff and share of business customers are negatively correlated [45-46]: projects with higher business tariff record lower share of business customers and the correlation is confirmed over the operating life [45-47].

3.4.7.3 Weak correlations

Beyond strong and moderate correlations, some weak correlations can feed an interesting discussion. The four most interesting ones are selected and discussed hereafter.

The first one suggests that, despite the expectations, **project profitability** is independent from the settlement type [8-20]. It means that the fact that a target community lives in a scattered settlement instead of an intensive or moderate settlement (intensive main road/scattered surroundings) does not mainly affect the IRR. The result does not contest that intensive settlements have clear economic advantages in terms of lower distribution cost, but it reveals that such advantage is easily lost whether other internal or external conditions are not leveraged. Thus, private actors should carefully take it into account as this research confirms that private ownership is only present in moderate and intensive settlements [8-21], as expected.

The second one suggests that the amount of **storage installed** is not correlated to the amount of diesel component installed [12-13]. It was considered the ratio diesel/PV installed in correlation with the ratio storage/PV. The result shows that the RE power generation mix with storage is not driven by a system optimization approach in the most of case studies but by other financial or operating issues instead. That is quite unexpected if considering that the majority were strongly funded by the international cooperation and local governments, which should have been aligned with MDGs/SDGs.

The third one suggests that, despite the expectations, there is not a strong correlation between the **share of energy from RE and OPEX** [15-41], while it was expected that a higher share of RE would correspond to lower OPEX. Such result is not justified even considering whether case studies providing further services beyond the electricity supply might have affected the results (including additional costs in OPEX to run additional services). The reason could lay in the operating method, since the majority of cases with diesel component apply a build-own-outsource model [12-28] and probably an O&M in outsourcing encompasses basic activities that come at a low-cost. However, further investigation is suggested due to this inconsistence result.

The fourth one suggests that there is no clear correlation between **services provided and OPEX** [16-41], meaning that OPEX of case studies are heterogeneous and do not actually reflect the business model. The reasons could lay in the variables of fuel expenditure and O&M costs, with represent notable costs even in projects providing electricity supply only and that reflect the business model based on operating method. As above, further investigation is suggested.

3.4.8. Discussion and highlights

The results of the aggregate analysis that was carried out help depict a picture of the mini-grid development scene in SSA for the past 30 years, including projects with different share of RE and application of the WEF nexus approach in different environment and business models.

However, in this work we tried to go beyond the depiction of a static portrait of the rural electrification market in SSA, aiming at seeking correlation factors between indicators to gain potential explanatory evidence of the operating behaviour of off-grid systems.

Considering generation technologies, the 21 case studies show an increasing presence of RE, with diesel generation prevailing in older installations developed by national utility companies. This approach is associated with revenues not even covering the running OPEX, matching the inefficient management of utility companies in SSA [111], and with the provision of electricity only instead of an integration with additional services.

The integrated presence of PUE is still not so widespread in the sampled cases but is positively associated with the presence of RE in the energy mix, which possibly depends on financing mechanisms for more recent projects, which are required to achieve multiple positive impacts and enhanced environmental sustainability. This is prominent in the projects developed by NGOs, which included WEF nexus related services as well. This evidence, and the associated business model (the new class "build-short operate-transfer", as per the proposed classification based on the operating method), suggests that an approach based on PUE and WEF nexus should not be disregarded as it could benefit also ensuring the profitability of private projects, even if it is heavily focused on community engagement, which has been in fact recognized for playing a key role in project development [112], [113]. The analysis reveals that a high level of PUE compatibility & integration is recorded in project owned by community entities, meaning that were developed by NGOs. This factor could suggest that partnership with local cooperatives and associations structured or empowered during the project development phase is key to successfully carried out high-impact and viable rural electrification projects.

It is crucial to highlight that PUE and other WEF-related services can be a source of additional revenue streams in the business plan, and the resulting integrated projects can have a broader impact on local development [103] as well as better financial performance.

With specific reference to WEF projects, albeit they would not achieve full financial bankability (also due to the no-profit operation of water access provision, for instance), they can also make a case for policymakers, considering their extremely positive economic impact at local and national level, as examined quantitatively in [50].

Consequently, such interest can turn into source of financing and private capital since investing both in energy and in other complementary sectors allows developers to cover the whole chain – energy supply and its productive use – with revenues from both types of activities and increase project's financial performance. However, this model brings additional challenges, as it (i) increases CAPEX, (ii) requires knowledge on other business sectors, and (iii) could lead to conflict with local communities (e.g. on land issues). Partnerships between private companies and local communities could mitigate these risks [103].

The financial analysis on the case studies in fact confirmed that, so far, mini-grids in rural areas are not viable without appropriate subsidies, subsidized tariffs or loans, even if there are exceptions applying nascent business models that target more affluent population segments, such as the ones inhabiting in peri-urban areas, therefore having a higher ability to pay, matched with lower CAPEX for leaner DC generation assets. In terms of operating method, the build-own-operate model results in the most promising business model for private developers.

Electricity tariffs are in fact one of the keys to guarantee financial viability through cost-reflectiveness; in some cases analyzed, the uniform national tariff has been imposed by the government without a project design adopting measures to mitigate poor financial performances.

This analysis reveals a clear correlation between the (i) financing structure, (ii) the operational strategy and (iii) the type of developer: projects with a strong grant-based structure apply a financially unsustainable O&M plan (except those developed by non-profit actors) and are mostly developed by public entities [103]. In other words, publicly-owned projects show low level of performance, both in terms of economics and quality of the electricity supply service.

Thus, firstly, focus should be on sustainable OPEX for off-grid projects, not only on viable CAPEX, as proved to be the public approach, and thar can be pursued by hybridizing genset with RE systems. Hybrid systems helps to reduce investment costs and address the intermittency of some types of RE, however, the diesel generation component should be carefully balanced, considering that fuel expenditure can highly affect the economic and environmental sustainability of the electricity supply service, as this study reveals that all the mini-grids operating in steady loss have a major diesel generation component.

Secondly, focus should be also on delivering a good quality of service: the quality was lower than expected from customers, and that the installed asset did not run at full capacity mainly because of poor O&M management operated in outsourcing.

4

Action roadmap to sustain the development of mini-grids

4.1. Action strategy

Looking at 2030, universal access to electricity will remain an African issue. Considering the policies and implementing measures adopted as of mid-2018 along with relevant policy proposals announced, the IEA estimates that the world will count 650 million people with no electricity in 2030, 90% of which in SSA, and mostly living in rural areas. Promoting private sector's investments is now recognized as fundamental to accelerate access to electricity. This urges governments to strike a balance between ensuring affordable and equitable access to energy to rural people, and favouring a low risk environment to developers and investors. The main issue lies in the fact that rural electrification is more expensive than the electrification of high-density and well-connected urban areas, and this applies to grid extension, micro-grid electrification and isolated systems. Therefore, to reach rural areas and provide access to affordable, reliable, sustainable and modern electricity to low income people, it is necessary to fill the gap between possible revenues from off-takers and the costs of rural electrification.

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. This study analyses access to energy business models with a focus on the productive use of electricity, excluding captive projects with a unique industrial off-taker since their financial feasibility is already demonstrated and they represent a notable potential market in developing countries, even though still relatively untapped.

An analysis of the technical, regulatory and financial challenges and opportunities was carried out 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 SSA analysed in this study give a picture of a growing and innovative sector with heterogeneous experiences. Process for identification of the most promising business models has gone through the analysis of these case studies, which have been classified on the basis of three criteria: (i) services provided, (ii) operating methods and (iii) ownership.

Results suggest that investing in energy and in other complementary sectors, such as food and water, allows developers to add and diversify revenue streams, strengthen customers' ability to pay and increase energy demand, as well as enable the improvement of the socio-economic environment. Agri-food processing, cooling services and ice production, for instance, can represent new revenue streams and produce a positive impact on local economy, in addition to the electricity supply for domestic and business use, so to strengthen resilience to market price fluctuation (e.g. crop), increase communities' income and reduce agricultural waste.

Furthermore, the provision of electrical appliances (selling, renting or leasing), especially in the first operational phase of micro-grid projects, can boost energy demand and promote energy efficiency, providing valuable services to customers as well as ensuring the use of equipment compatible with the installed energy systems.

An approach that integrates clean water supply, irrigation, and agro and fish-processing activities, can capture different types of value: needs-based irrigation increases food producers' resilience against droughts and breaks the cycle of seasonal income, just as ice production allows for a more efficient value chain for fish production. 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 the economic sustainability of off-grid projects by supporting energy consumption. However, this approach comes at a cost. Developers and investors should assess both corporate and market benefits, but also risks: developing integrated projects usually (i) increases CAPEX, (ii) requires knowledge of other business sectors, and (iii) could lead to conflict with local communities. Partnerships between private companies and local organizations are suggested to mitigate those risks.

Even if this study analysed projects operating for years by applying such approach (the oldest mini-grid has been operating since 1986), this is yet to be tested at scale as most off-grid systems don't provide integrated services yet. The present study highlights four business models 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. On one side, in order to be effective and viable, integrated approaches need to be tailored to community's needs and focus on local market strengths and opportunities for growth. On the other side, they can be managed to shape the best business model for a given developer, in a given country, with a given investment ticket or capability of fundraising.

So far, energy investments in mini-grids with a full equity structure are not viable, and governments struggle to support them because of public energy companies' poor balance sheets and political priorities, which are often linked. Rural electrification alone will not be able to support local development and create its own energy demand. However, if rural electrification is integrated with investments along the food value chain and other productive uses of energy, it can bring substantial development results and thus attract the attention of governments, international development agencies and investors, who pay attention to impact objectives and indicators.

In recent years, the majority of funding programmes led by international cooperation agencies, development banks, foundations and public institutions have recognized energy and its productive uses as key drivers for local development. In this perspective, the more a developer is able to prove the effectiveness of its strategy to ensure both the business sustainability and achieve a notable impact on the ground, the more it increases its competitiveness in accessing finance. Building energy projects and services around productive uses of energy, and leveraging on positive spill-overs of the WEF nexus approach, can support developers in attracting blended finance. On the other side, in order to stimulate access to electricity and PUE, governments and donors should establish credit schemes and concessional loans, as well as test innovative finance instruments such as results-based financing and targeted subsidies.

Governments, private sector actors, international financing institutions and development agencies are called to collaborate to: (i) ensure clear and effective policies and regulations, (ii) provide access to the right finance, and (iii) prove business models. The in-depth analysis of these three dimensions reveals that the current vision is partial, or at least too sectorial. Accelerating rural electrification also depends on the capacity to support local socio-economic development, and it requires energy and non-energy players to go beyond their comfort zone, working and investing together.

4.2. Highlights and recommendations for enabling the environment

4.2.1. Technical and technological issues

1. It is crucial to ensure an adequate energy supply to the energy demand through:

- ENA, to properly estimate the current demand and foresee how it will evolve over the operational period. It is crucial to verify the financial viability of the project with a view to pursue the techno-economic optimum design;
- multi-year planning of the mini-grid, including possible upgrade or extension of the power generation and distribution systems, as the demand grows and uncertainties in the load become clearer;
- DSM, which combines strategies and technologies in order to reduce the cost of energy supply by optimizing the usage of available assets and deferring further investments in generation capacity. DMS should be embedded in the planning and design phase, and be part of the business model itself, since it allows to achieve a

higher efficiency and profitability of the systems by optimally aligning generation and load.

2. Hybrid diesel-RE systems help to reduce investment costs and address the intermittency of some types of RE (solar and wind). However, two issues are key regarding such systems:

- taking into account the continuing reduction of the costs of renewables and storage systems, a technical design with increased solar-PV generator and battery storage capacity, without diesel generator in the energy generation mix but only as backup system, could be a potential solution;
- the diesel generation component should be carefully balanced, considering that fuel expenditure can highly affect the economic and environmental sustainability of the electricity supply service, as this study reveals that all the mini-grids operating in steady loss have a major diesel generation component.

3. Mini-grid systems should be compatible with the grid system in order to be interconnected with the national grid, if needed.
4. A trade-off analysis between installation costs and the battery lifetime must be carried out in the technical design, in order to improve optimal lifetime and techno-economic performance of the generation plant as a whole.
5. A remote management system is an essential part of any mini-grid project. It is used to measure, monitor and control the electrical load together with the generator and energy storage system, as well as to track the system's dynamics through advanced smart metering systems.
6. With a focus on the WEF nexus approach, it is key to co-locate food, water and energy infrastructure, where possible, to allow the waste stream of one to be utilised by the other(s), thus reducing by-products, minimising transportation costs, and lowering energy and water requirements.
7. PUE and other WEF-related services, in particular regarding agri-food chains, help managing supply and demand of energy by shifting part of the demand for energy to daytime.
8. It's important to promote well-proven technologies in all the WEF sectors. Social acceptance, risks, workloads and opportunity costs have to be sufficiently taken into account when promoting these technologies.
9. Adding provision of electrical appliances to electricity supply ensures their compatibility with the installed energy systems and promotes energy efficiency (in particular in case of DC distribution). However, this requires a careful assessment of the ability and WTP for such appliances from the users' side.

4.2.2. Integration of PUE and WEF nexus

1. Agri-food chains play a crucial role in the development of rural areas throughout Africa, and they probably represent the most relevant and widespread PUE in these areas, from which integrated projects and innovative partnership could be built.

2. There is a positive correlation between the agri-food and energy business: reliable and affordable electricity supply allows to improve food production and makes the agri-food business more profitable, thus strengthening energy demand.

3. Giving due consideration to complementary activities to energy supply, in particular those related to a productive use of energy, significantly enhances the financial and overall sustainability of the project, as well as local people's livelihoods and project acceptance.

4. PUE and other WEF-related services can be a source of additional revenue streams for the energy operator, and the resulting integrated projects can have a broader impact on local development.

5. The water component in a WEF project is responsible for important indirect benefits, as its adequate quantity and quality is crucial for good health as well as agri-food activities, and can therefore indirectly contribute to jobs and income generation.

6. Enabling viable water projects by integrating the water component in wider programmes is key: water alone, especially in rural areas of SSA, is a "risky" sector because it depends on erratic rainfalls and encompasses the right of all people to access to an essential good like safe water, with related issues such as scarcity, low quality and political interests.

7. The social, environmental and economic impacts when evaluating investments in the decentralised RE sector can be monetized through the SROI analysis, which is a systematic approach to holistically include them in the existing financial model. SROI stands as a powerful tool for an in-depth analysis of the overall impacts of projects, bringing an innovative outlook to highlight hidden impacts and therefore involve other stakeholders and sources of finance.

4.2.3. Environmental and socio-economic impact

1. Ensuring adequate access to modern energy services, in particular from renewable sources, has a positive influence on several SDGs, in particular those related to poverty, food security, water, health and climate change. However, while RE has significant advantages in terms of sustainability, in particular in relation to climate change, the production and use of RE are not sustainable *per se*. Awareness on the possible positive, synergistic interactions, as well as the negative ones, is important to ensure that collectively the greatest benefits are generated and negative impacts are minimized when developing and deploying mini-grids from renewable sources.

2. The assessment of the sustainability of mini-grids associated with PUE is both complex and multifaceted, and different aspects in both supply and demand/use sides have to be considered. As a result, beyond sustainability principles, conclusions about the sustainability of mini-grids cannot be generalised. The assessment of their sustainability should rather be context-specific and integrate all social, environmental and economic aspects related to their implementation.

3. Trade-offs and synergies, especially when it comes to the use of water and energy to produce food, should be considered: (i) solar irrigation bears the risk of over-pumping; (ii) biogas production requires quite some water; (iii) land-based energy (in

particular bioenergy) can lead to inadequate land use and/or competition between different uses of the biomass, (iv) the disposal of the materials used in solar and wind energy systems can pose significant environmental risks.

4. Linking energy supply to the enhancement of local livelihoods is key for the financial viability of the energy business model as well as for local development. This requires a shift from a focus on energy supply objectives (supply side goal) towards objectives related to support to local services and livelihoods (demand side goal).

5. It is crucial to adequately involve energy users (in particular local communities and farmers, if appropriate) in the decisions related to the planning and implementation of project development. This allows for bottom-up solutions, knowledge sharing and conflict mitigation, which, in turn, facilitates collaboration and commitment from user communities in handling O&M activities.

6. Complementary activities (e.g. businesses incubation, capacity building, microcredit support, etc.) strongly contribute to ensure the sustainability in a mini-grid project: they represent a means for engaging local communities, promoting community inclusion and ownership as well as supporting the electricity demand pattern.

7. Gender considerations should permeate decisions throughout the project cycle. Women have a key role to play in the energy supply as well as in PUE, particularly when related to food production and food value chain.

8. Sustainability requires that potential environmental and social risks and opportunities are identified through an initial screening analysis and an in-depth Environmental and Social Impact Assessment (ESIA) to be conducted in the early-stage project design. ESIA is essential to secure both local permits and project bankability, since developers are required to be able to demonstrate their capability in managing environmental and social issues throughout the life of a project.

4.2.4. Policies and regulations

1. The rural electrification process faces two main challenges: (i) it is significantly more expensive than the electrification of high-density and well-communicated urban areas, and (ii) it serves the lowest income people in developing countries with related lower ability to pay for electricity. The combination of these facts leads to a gap between possible revenues from off-takers and the costs of rural electrification systems. This, in turn, creates a major challenge for governments: they need to strike a balance between ensuring affordable and equitable access to energy to rural people, and ensuring profitability and low risk investments. Policies and regulations can help to address this challenge in different guises.

2. An integrated electrification plan for all the supply modes (grid extension, mini-grid and individual systems), a sound regulatory framework, and an effective institutional organization chart to avoid overlapping of responsibilities between government agencies, are the backbone of an effective institutional framework to foster access to energy.

3. An enabling regulatory framework to accelerate rural electrification and private sector investments should:

- provide regulations that facilitate the bankability of electrification projects;
- ensure a comprehensive and stable framework with a segmented approach, according to the size of energy projects, the type of energy source and the supply modes;
- consider the impact of both the iron law (the fact that rural electrification is significantly more expensive than the electrification of high-density urban areas) and the viability gap (difference between what the business models can collect from the customers and the total cost of supplying the electricity service) in the allocation of funding, resources and subsidies, with an adequate calculation of the cost of service of off-grid least-cost alternatives;
- offer fair electricity price to the most impoverished population in isolated off-grid rural areas through cross-subsidized tariffs as for grid-connected customers, wherever they are located, also thanks to additional direct subsidies from the national budget or electrification funds from international development banks and agencies.

4. In countries that have specific regulations for mini-grids, the process for obtaining licences is often lengthy, costly and sometimes unclear [114]. In this context, governments could: (i) provide the possibility to acquire provisional licences, (ii) centralize the procedure in one government organization, such as the AMADER in Mali and (iii) create dedicated portals (e.g. in Tanzania). On the other side, developers could work also on mini grids smaller than the size under which licences are required (when allowed, for instance up to 100 kW in Tanzania and 20 kW in Mali). This latter solution bears the risk of not being able to support productive loads while scaling up might prove rather costly. An existing phenomenon consist in going illegal, especially for small size systems, making informal agreements with community leaders. Governments should oppose this phenomenon by providing clear, transparent and operative regulations.
5. Mini-grids can be a permanent or a transitory solution for the electrification of islanded areas, and therefore grid expansion is a major concern for mini-grid developers. The risk of grid expansion varies across countries: in theory, the shorter the distance between the national grid and the mini-grid, the higher the risk. The review of regulations carried out on five countries (Kenya, Zambia, Ghana, South Africa and Ethiopia) undertaken in Chapter 6 shows that this risk is often not well-addressed, if at all, in government regulations. Ways to address this risk include:

- master energy plans about planned grid extension should be accurate, available and updated in order to provide guidance to rural electrification projects and plan how investment should be amortised by the time the grid arrives;
- developing mini-grids so that they are technically compatible with national grids to avoid competition but rather facilitate integration when the grid arrives;
- offering concessions that ensure sufficient time to amortize investments (typically 15-25 years) and that foresee compensation or interconnection mechanisms in case the grid arrives earlier than planned, such as [114]:

- three types of interconnections: (i) the mini-grid operator continues to generate and sells electricity in bulk to the grid as a "small power producer" – this requires PPAs, special FiT for mini-grid projects, and a clear outline on how to implement the interconnection; (ii) mini-grid operators continue to serve retail customers with electricity bought from the national grid as a "small power distributor" – this requires additional legal provisions and tariff regulations; (iii) the mini-grid operates as a "service quality guarantee" by providing power integration and backup component, running as stand-alone system – this requires specific regulation on the energy management and proper control systems installed (this model has a good potential in large areas that are connected to the grid but still underserved);
- compensation mechanism for the main-grid operators for the residual value of the assets rendered uncompetitive by the main grid – this requires that depreciation times for fixed assets (e.g. distribution grid) are set according to the main-grid connection risk and financial plan. This option is more challenging because often not well-defined, however Rwanda provides an example in SSA where compensation for relocation is included in government regulations.

4.2.5. Access to finance

1. There is no one-size-fits all financial mechanism for mini-grid development, be it from the supply side (energy operator) or the demand side (energy user). Solutions often depend on conditions related to the energy supplier, energy users, local context and international support.
2. For small-size mini-grids1 in developing countries, there is often a lack of suitable financing options from the national commercial banking system, and high transaction costs for project finance. This means that it is unlikely that mini-grid business models for access to electricity (excluding captive projects with a unique industrial off-taker) can be developed without public finance support in the form of grants or subsidies.
3. Enabling large deployment of mini-grid projects mainly lies in reducing upfront costs for both the energy supplier and the energy user (e.g. connection fee or PUE equipment). In this view, financial mechanisms can allow the energy supplier to de-risk investments and reach financial viability, and the energy user to access electricity and pursue local business activities.
4. Grants to CAPEX or investments should be limited in order to avoid later energy market distortions, and thus only be applied in pilot projects and early stage market phases. That said, most mini-grid cases analysed in this study (76%) have used grants to cover their CAPEX, at least partially; grants to OPEX are risky, because of the likelihood of their discontinuity due to unforeseeable circumstances, and unwise as do not encourage to find the most efficient way to run operations.
5. Grants should be combined with mechanisms to leverage commercial financing and to buy down the risk with first loss guarantees. Minor contributions should also come from target communities (e.g. in form of in-kind).

[1] Power generation of at least 10 kW.

6. Not limiting the business plan to energy supply, but rather including PUE and in particular food production, has proven to significantly improve the financial viability of mini-grid in rural areas.

7. A few instruments (some new) exist to ease private sector access to capital, such as equity financing, debt capital or local currency lending structures.

8. Prepaid systems, in the form of PAYG or fee for service, have been quite successful in making energy from micro-grids more affordable in rural areas. But using these mechanisms also means that the energy operator must have enough capital to withstand segmented/non regular payments.

9. Provision of energy appliances, for instance through a leasing mechanism, promotes energy consumption and therefore positively affects both the cash flows for the mini-grid operator and local productive activities. Bearing in mind that food production is usually the main source of revenue in rural SSA, a positive effect on the whole local economy is expected. But, in the case of solar mini-grids, it should mainly concern appliances used during daytime in order to reduce evening use of energy and costs related to energy storage.

10. Regarding the electricity tariff, an approach tailored to the purchasing power of the energy user is effective for catalysing private sector investment in mini-grids. In this case, public finance (e.g. feed-in-tariff) should be needed to make up for the financial shortfall and enable the project viability.

11. Business plan evaluation from financing entities and governments should allow complementary activities (e.g. businesses incubation, capacity building, microcredit support, etc.), to be eligible in capital and operating costs as they represent a means for engaging local communities, promoting community inclusion and pursuing the project sustainability.

4.3. RE-thinking Access to Energy Business Models

In order to seize opportunity of investing in rural electrification sector, it is necessary to analyse mature business models as well as explore emerging ones. As discussed in previous chapters, this study has highlighted how integrated projects, if properly designed, can contribute both to business viability and local development which, in turn, further support the sustainability of the project, in a sort of virtuous cycle. This chapter is aimed at providing developers, investors and decision-makers with the most promising integrated business models to be explored in mini-grid projects for rural electrification.

Process for identification of the recommended business models has gone through the analysis of case studies' results, which are classified on the basis of three criteria: (i) services provided, (ii) operating methods and (iii) ownership (see section 3.4.4). 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: (iv) ways to apply a WEF nexus in the project, (v) community categorization in terms of local economy, type of PUE and ability to pay, (vi) type of mini-grid operator(s), (vii) the required regulatory framework and (viii) the correlation between investment size-profitability-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:

1. **Electricity supply & appliances provision**: a private operator owns and operate small RE power units providing DC electricity and small appliances to customer clusters.

2. **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.

3. **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 appliances and retail.

4. **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.

Matrix of features and trade-offs of selected BMs	BM 1: Electricity supply & appliances provision	BM 2: Electricity supply & agri-food production	BM 3: Electricity supply & water-related services	BM 4: 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 or hydropower	solar, biomass or hydropower

Table 23 – Matrix of key features and trade-offs of selected business models.

The Table 23 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.

4.3.1. Business Model 1: Electricity supply & energy-related products

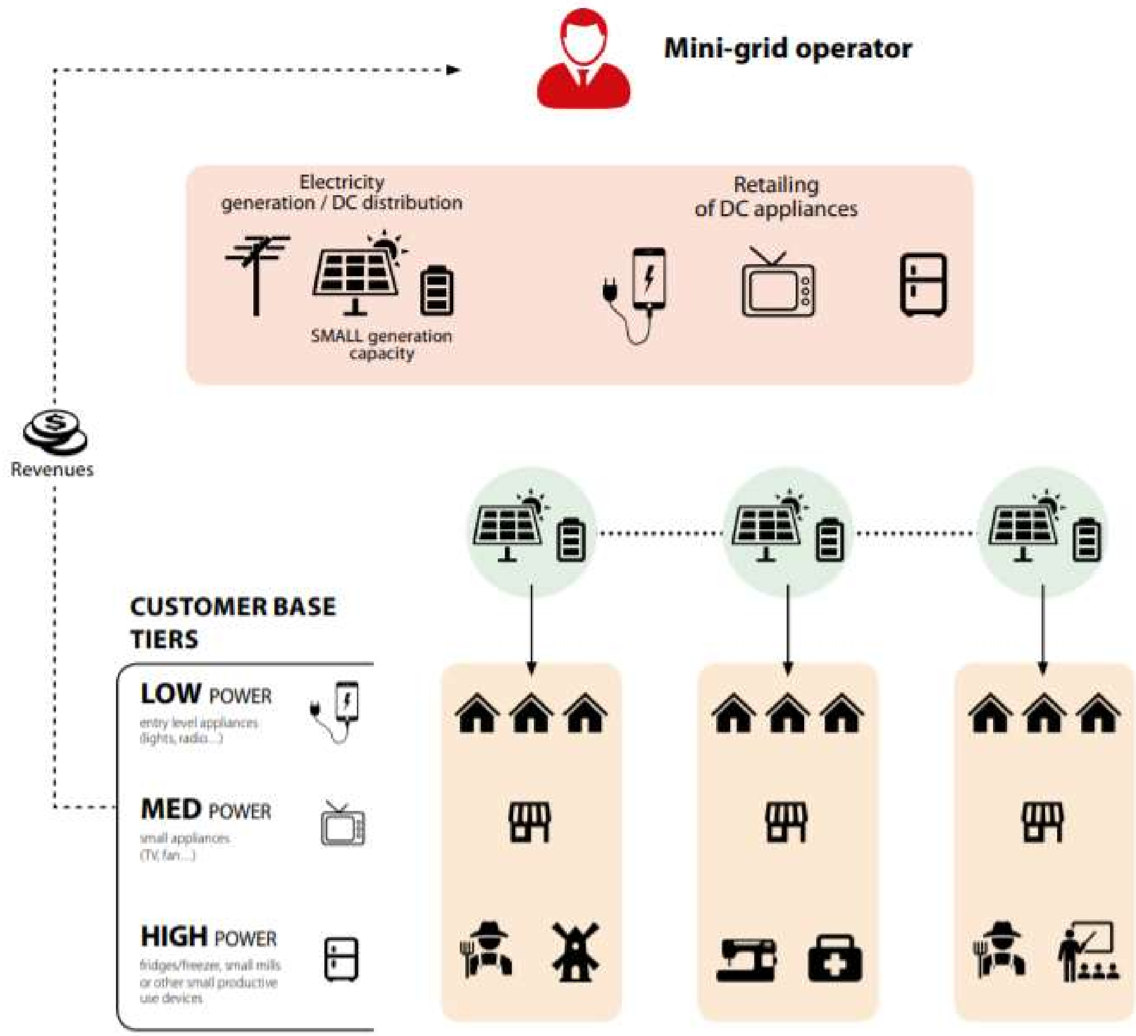


Figure 36 - Business model 1

Overview

The BM1 features a single private owner which operates the mini-grid. Generation is distributed through several small renewable power units providing DC electricity to customer clusters. PUE are restricted to relatively small appliances, such as fridges/freezers or little electric mills. Likewise, the only basic level of service can be provided to public institutions such as schools or rural health centers. There are only two revenue streams (electricity sales and provision of appliances), but at the same time minimal assets are needed, with low capital investment per connection, which is appealing for accessing finance. Furthermore, the operating cost structure is limited to local sale and ordinary maintenance, easily managed remotely.

How it works

The small power units, which serve 10-12 customers each, allow for high flexibility in terms of load management and distribution: they can operate independently or be interconnected where needed (e.g. PUE requiring a peak power not available from a single power unit) and thus allows for inexpensive coverage of isolated customer clusters. Expansion of the plant is also easy to perform, given the ‘plug-and-play’ nature of the generation units, the installation of which can be phased based on financing availability and the market’s demand evolution. The customer base, limited to households, small productive activities and basic public services can be segmented in “tiers” of power available depending on the type of subscription. Provision of DC appliances (through leasing, rental or sale mechanisms) is relevant to sustain electricity consumption and thus the viability of such small-scale mini-grid business model.

Key partners

The **key partners** include (i) a provider of DC electrical appliances, which the operator can either resell, rent or lease - depending on this commercial partnership they can be considered as part of the assets of the operator or not, (ii) a mobile money integrator to manage electricity and appliances payments.

4.3.2. Business Model 2: Electricity supply & agri-food production

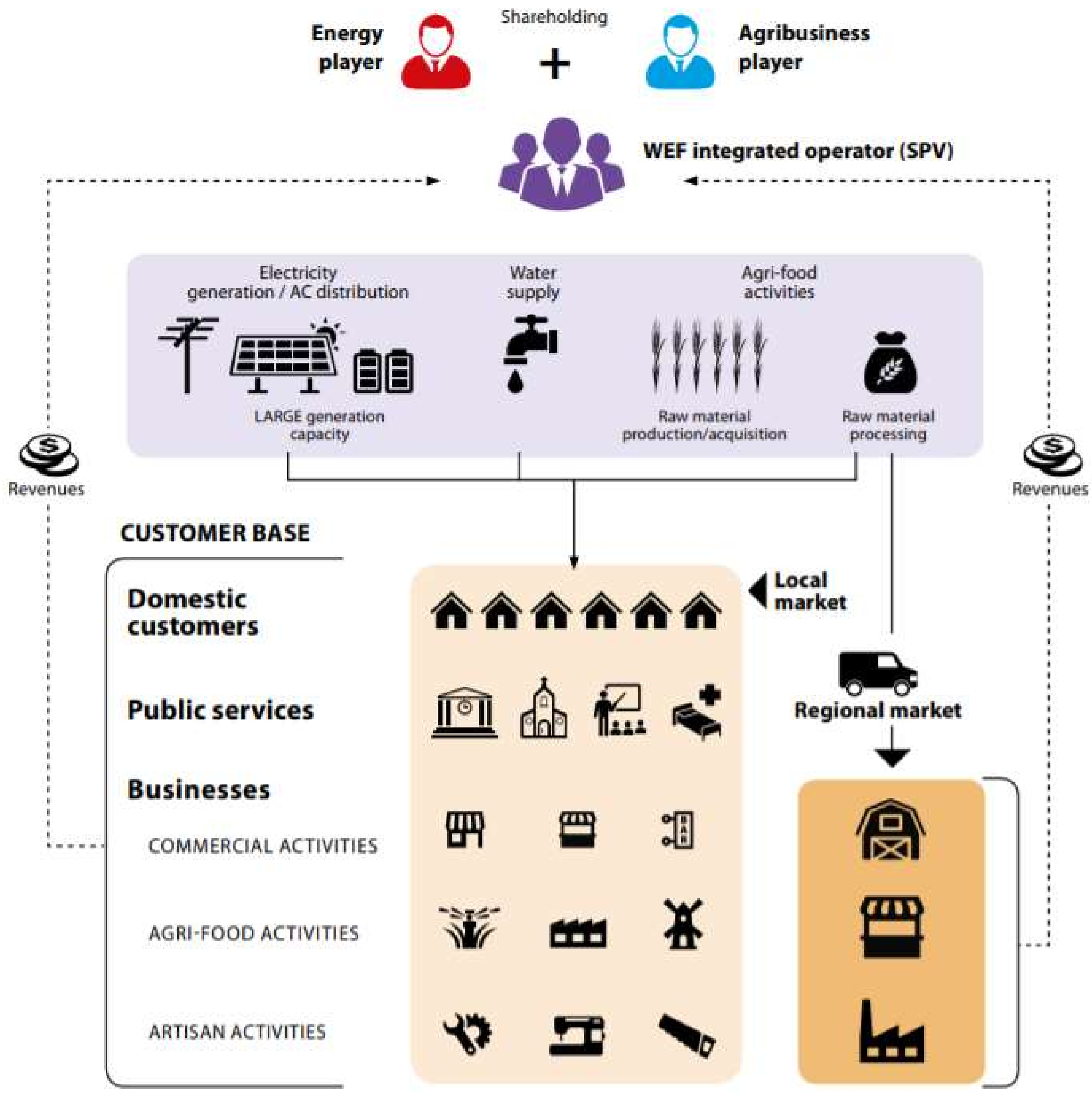


Figure 37 - Business model 2

Overview

The BM2 fully embraces the WEF nexus approach. An SPV is created between a private energy player and an agribusiness entity, that could be either a private company or a community-based organization, as shareholding company. The SPV operates with a WEF nexus integrated business that relies on a large generation capacity to provide electricity and water to the local customer base of connected users, and to power its own agri-food production and processing facilities. In this scenario, the agribusiness shareholder brings the experience to acquire or produce raw materials as well as process and retail agri-food products. Selling products not only to the local market but also to the regional and national ones allows the SPV to enlarge the market segment by sector and geographic scope. Investing through this model expects to gain relevant profit share from the agri-food business, as well as high development impact at the local level.

How it works

A multi-utility structure is established, supplying electricity and water-related services, which also produces and sells agri-food products. On the one hand, the business development involves a high level of complexity: the SPV with hybrid ownership, a high CAPEX due to multiple assets in energy and agri-food sectors, an O&M structure that requires a multi-skilled staffing with local management and remote supervision. On the other hand, the BM2 can result in an interesting business since the SPV directly manages both energy supply and anchor load (agri-food) activities, reducing off-taker risks. In this BM, the energy supplied to the agri-food activities directly managed by SPV does not provide cash flow, whereas it enables revenues from agri-food product sales. Thus, BM2 allows for various and differentiated revenue streams coming from electricity and water supply as well as the sale of agriproducts on a local and regional scale. The local customer base can include a wide array of local businesses, since the plant can power high-energy intensive PUE such as large mills and other agri-food factories in the target area, and irrigation systems for local farmer associations. Thus, it has a broad impact on the development dimensions and long-term sustainability, which is a peculiar value proposition for access to finance. However, the water supply management can be implemented only if permitted by the country's regulations. If the water management cannot be privatized, a partnership with the authorized local entity (i.e. water users association) could be promoted.

Key partners

The **key partners** include (i) local agribusiness association(s)/cooperative(s), which can be the suppliers of the agricultural raw materials which the SPV will process and retail, (ii) a distributor for the processed agri-food products to reach the regional/national market, (iii) a water users association if water management by private entities is not admitted by law, (iv) a mobile money integrator to manage electricity and appliances payments.

4.3.3. Business Model 3: Electricity supply & water-related services

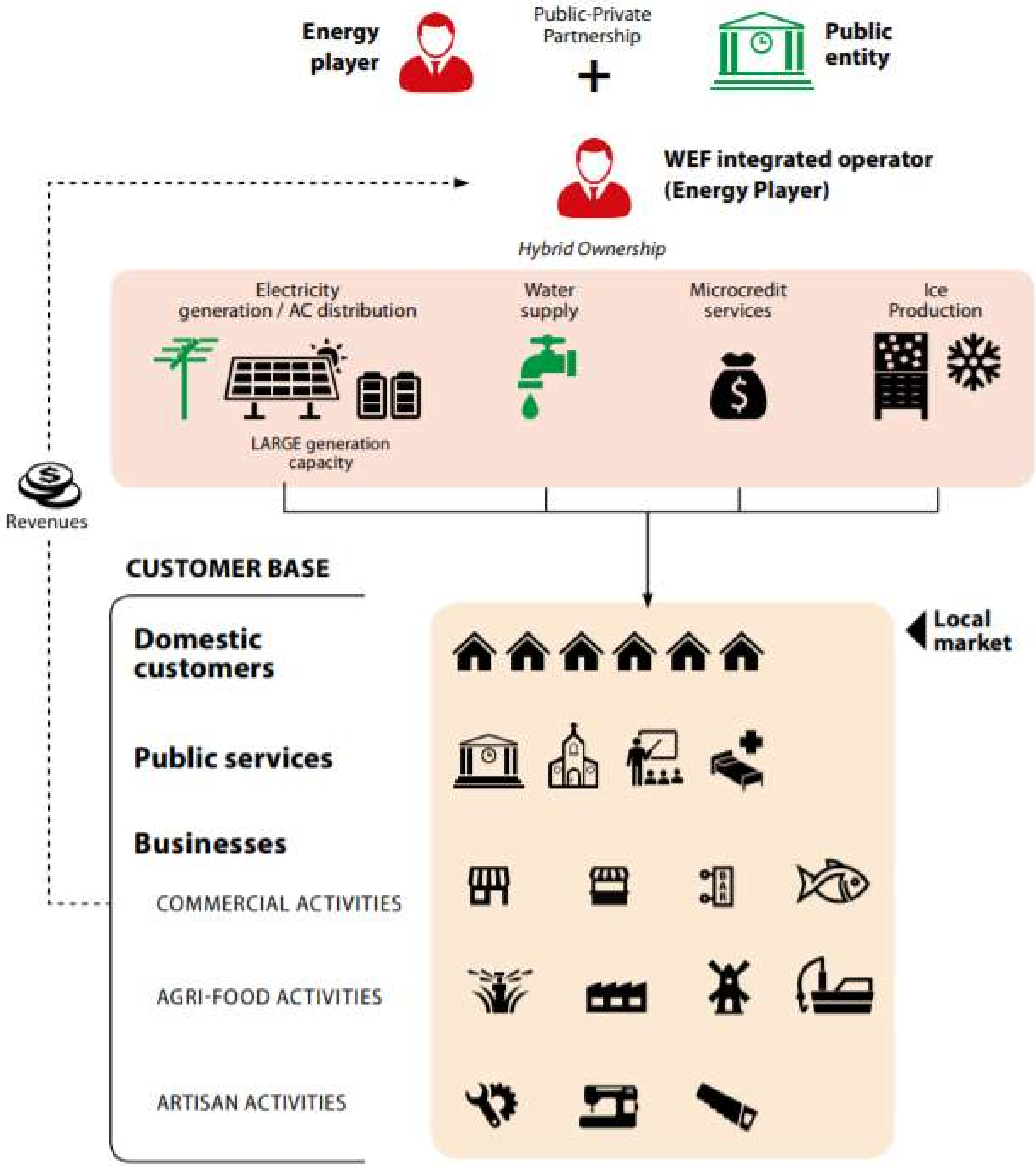


Figure 38 - Business model 3

Overview

The BM3 emphasizes the water component of the WEF nexus approach, and it is particularly suitable for specific contexts in which there is a vibrant fishing-based local economy along with an enabling regulatory framework which allows a private water supply management or a partnership with the authorized local entity (i.e. water user association).

A public-private-partnership is established between a private energy player and a public entity (e.g. national energy distribution company, water user association), with a hybrid ownership where the latter maintains a separate asset property, usually the energy distribution network and/or water supply system. In this scenario, the private energy player operates with a WEF nexus integrated business that relies on a generation capacity large enough to support ice production, and manages electricity and water supply as well as ice production and retail. Microcredit services are a key financial tool to mitigate off-taker risk by sustaining customers in purchasing electrical appliances and in developing local business activities. This, in turn, also allows to achieve a higher project impact.

How it works

In the BM3 a multi-utility structure that supplies electricity and water-related services, and also manages to produce and sell ice, is established. This means a lower level of complexity compared to the BM2, due to the ice business instead of agri-food ones, and a single operator – which can use or not an SPV – instead of a shareholding company. Consequently, on the one hand, CAPEX are lower and the investment risk is therefore reduced – since distribution assets are owned by the public entity – and the O&M structure is slimmer compared to BM2. On the other hand, the BM3 can result in an interesting business since the operator directly manages both the energy supply and the anchor load (ice factory), reducing off-taker risk. As in the previous model, BM3 allows for various revenue streams coming from electricity and water supply as well as ice sale in the local market. The local customer base can include a wide array of local businesses, since the plant can power high-energy intensive PUE such as large mills and other fish-related activities as well as agri-food factories in the target area, if any.

Additionally, offering dedicated microcredit finance services can help the spread of domestic appliances –without having the operator engaged in appliance retailing – and sustain the development of local business activities. This will also lead to (i) an additional revenue stream thanks to microcredit interests and (ii) increased electricity sales thanks to the use of electrical appliances. The project impact is notable and attractive for access to finance, and can be further increased if the water service also supplies irrigation systems.

Key partners

The **key partners** include (i) local fishermen association(s)/cooperative(s), which would be the main customer for the ice sale, (ii) a microcredit operator in order to offer tailored microcredit services through a commercial partnership, (iii) a water user association if water management by private entities is not admitted by law, (iv) a mobile money integrator to manage electricity and appliances payments.

4.3.4. Business Model 4: WEF multi-service supply

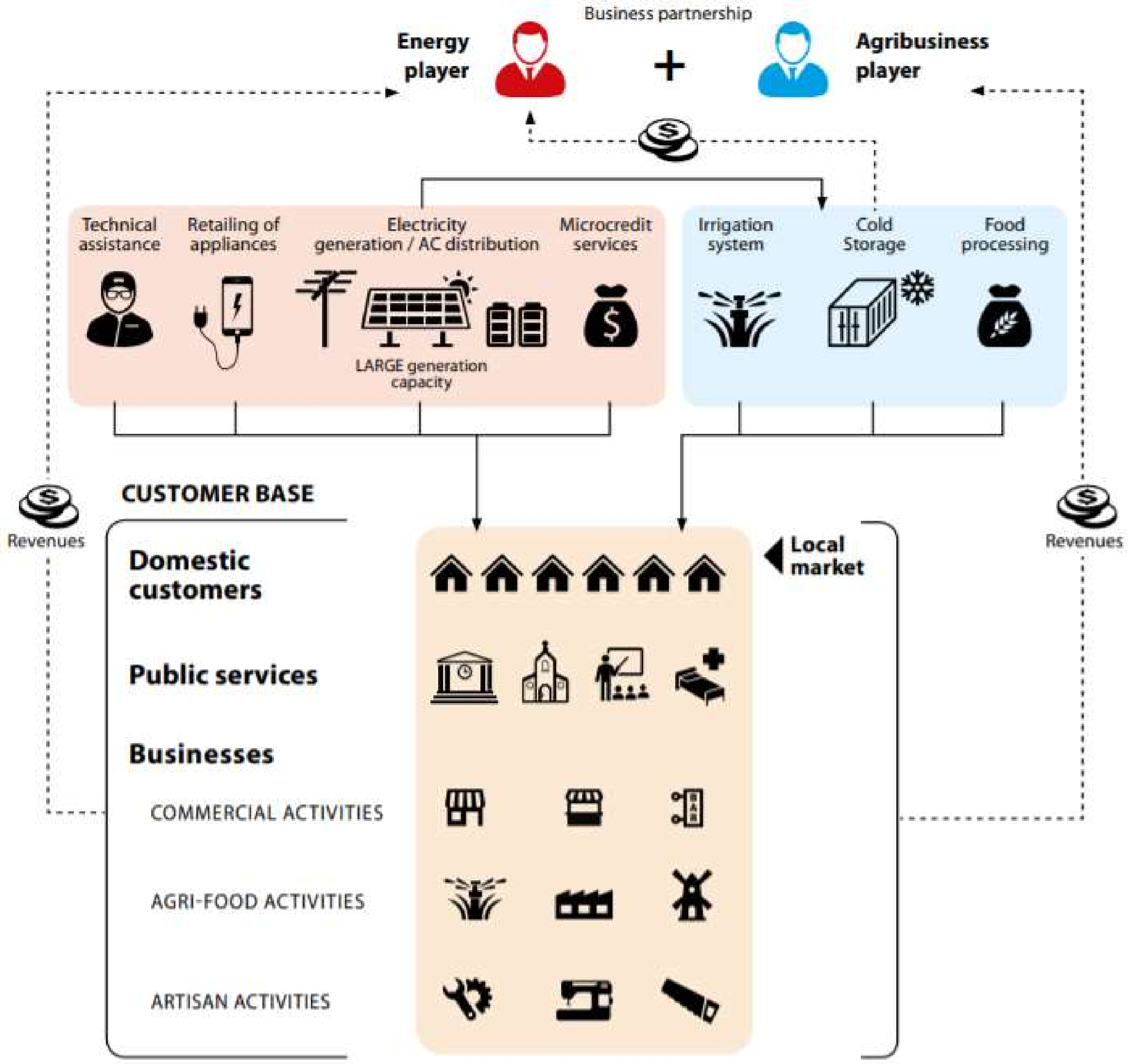


Figure 39 - Business model 4

Overview

The BM4 fully embraces the WEF nexus approach as BM2 but it is focused on a multi-service approach: electricity and water supply along with agri-food processing services devoted to the same customer base. It is particularly suitable for contexts where there is a variety of running agricultural activities, with production volumes high enough to justify the installation of dedicated processing facilities.

In this case, two private entities operate a WEF nexus integrated business in partnership, without creating a joint SPV and maintaining the energy asset separated from the agri-food asset in a hybrid ownership model. The energy player operates the electricity supply, along with other energy-related services: retailing of small electrical appliances, microcredit services and technical assistance thanks to a skilled technical team. As in BM3, the microcredit services are key financial tools to sustain the development of local business activities and acquisition of PUE equipment, such as welding machines or laundry-related ones, which are not included in retailing of the small electrical appliances (e.g. TV, radio, shaver, fridge) mentioned above.

The agribusiness company provides agri-food facilities instead, offering equipped rental space or storage and processing services (depending on the context: milling or drying unit, cold storage services for dairy products, fruits, meat, etc.). The two partners operate interlinked businesses since the mini-grid operator sells electricity through a private-PPA to the agri-food facilities, which sells services to a common customer base.

This model allows the sharing of investment risks between two players as well as mutual benefit of specialized expertise. Even if it integrates WEF components, this BM allows players to operate in their core business only.

Optionally, the water supply management can be added by applying conditions described in BM3.

How it works

In the BM4, the joint value proposition covers for a wide range of needs of the customer base, while keeping asset ownership, CAPEX, OPEX and revenue streams separated. The energy player can make a broad-impact project without the need of in-house agri-business know-how and investment in local staff and assets, but benefits from its business partner that operates in this complementary sector, representing a reliable anchor load for the energy business. On the other hand, the agribusiness company can penetrate markets otherwise not accessible without power supply, without being directly involved in the production and distribution of agriproducts, but only offering the processing facilities as a service. While this aspect maintains its activities simpler, it also limits its market to the local one. In this case, the mini-grid operator differentiates its revenue streams by providing additional services, such as the provision of small electrical appliances, which is not a specific trait of BM1. Microcredit services can be present at the same time to stimulate electricity consumption for business, offering assistance for PUE equipment purchase. The novelty, as observed in real case studies, is the provision of technical assistance services by its skilled staff as a way to monetize the diverse expertise of the technical staff, already trained to operate the other services. The local customer base can include a wide array of local businesses, since the plant can power high-energy intensive PUE beyond the agri-food facilities.

Key partners

The key partners include (i) a provider of AC and DC electrical appliances, which the operator can either resell, rent or lease – depending on this commercial partnership they can be considered as part of the assets of the operator or not, (ii) a microcredit operator in order to offer tailored microcredit services through a commercial partnership, (iii) local agribusiness association(s)/cooperative(s), which can affect the productivity of local farmers – who are key users of agri-food facilities, (iv) a distributor for the processed agri-food products to reach the regional/national market with a view to favour agricultural activities, (iii) a water user association (if water management is included), (v) a mobile money integrator to manage electricity and appliances payments.

5

Methodology for the energy need assessment

5.1. Rationale behind a focus on energy need assessment and load profiling

Considering the premises described in 1.1 and results R1 and R2 of this research project, to successfully deploy a large number of decentralized energy systems, as required by the global market analysis conducted by IEA [115], standardizing effective methodologies and procedures to develop off-grid/mini-grid systems is fundamental. However, in order to develop financially viable projects, there are various barriers that have to be overcome to create an enabling environment for such investments that are related to the institutional and policy framework as well as to financial barriers and technical challenges. Among others, a key barrier to mini-grid proliferation is the uncertainty in predicting customer electricity consumption, which adds financial risk [116], and their WTP. In other words, since the profitability of a project is highly dependent on the amount of electricity that is produced and sold, uncertainty regarding electricity demand in micro/mini-grids represents a significant risk for investors [117].

Even if electricity demand is extremely hard to predict, especially in a village that has never had access to electricity [118], adequate market assessment, mainly based on energy need assessment (ENA) and its outputs such as load profiling and demand forecasting, is feasible and it is essential to define the baseline and deal with an effective project design as well as properly evaluate its impact. Thus, the approach for applying a proven methodology for the ENA of rural communities in developing countries to obtain reliable input data for the mini-grid development provided in this research can help 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.

Furthermore, since the economic viability of mini-grid projects highly depends on the size of the installed assets and the related investment, which needs to be backed by a payable demand in the years after commissioning, there is clearly a link between the ENA, the load profiling and engineering design of the off-grid systems: an undersized system will provide unsatisfactory service and will cause consumers dissatisfaction, whereas an oversized system will not recover the costs required to set it up [106].

In the development process of a mini-grid, several factors and data contribute to design a technical solution that is considered financially viable and the electricity demand pattern is necessarily affected by several factors including socio-economic and environmental factors by which the pattern forms various complex variations. Thus, first and foremost, it has to be highlighted that every target community differs from others in terms of needs and context conditions. Hence, the research describes an inclusive methodology that can be used and adapted case-by-case in order to bridge the gap between general recommendations and information provided by existing micro-grid literature and the lack of detailed information and guidance from practitioners [118] to boost toward a common overall objective of mini-grid's optimization methods and tools.

To analyze in depth the literature framework that support the actual need of an effective methodology for the ENA in rural electrification sector with a specific focus on to mini-grid development, the following section provide a comprehensive literature overview composed of the main issues behind this topic. Furthermore, a flowchart is reported below (Figure 40) where blue color boxes represent area of direct influence for the proposed methodology to show the correlation between the ENA, the load profiling and engineering design of the off-grid systems.

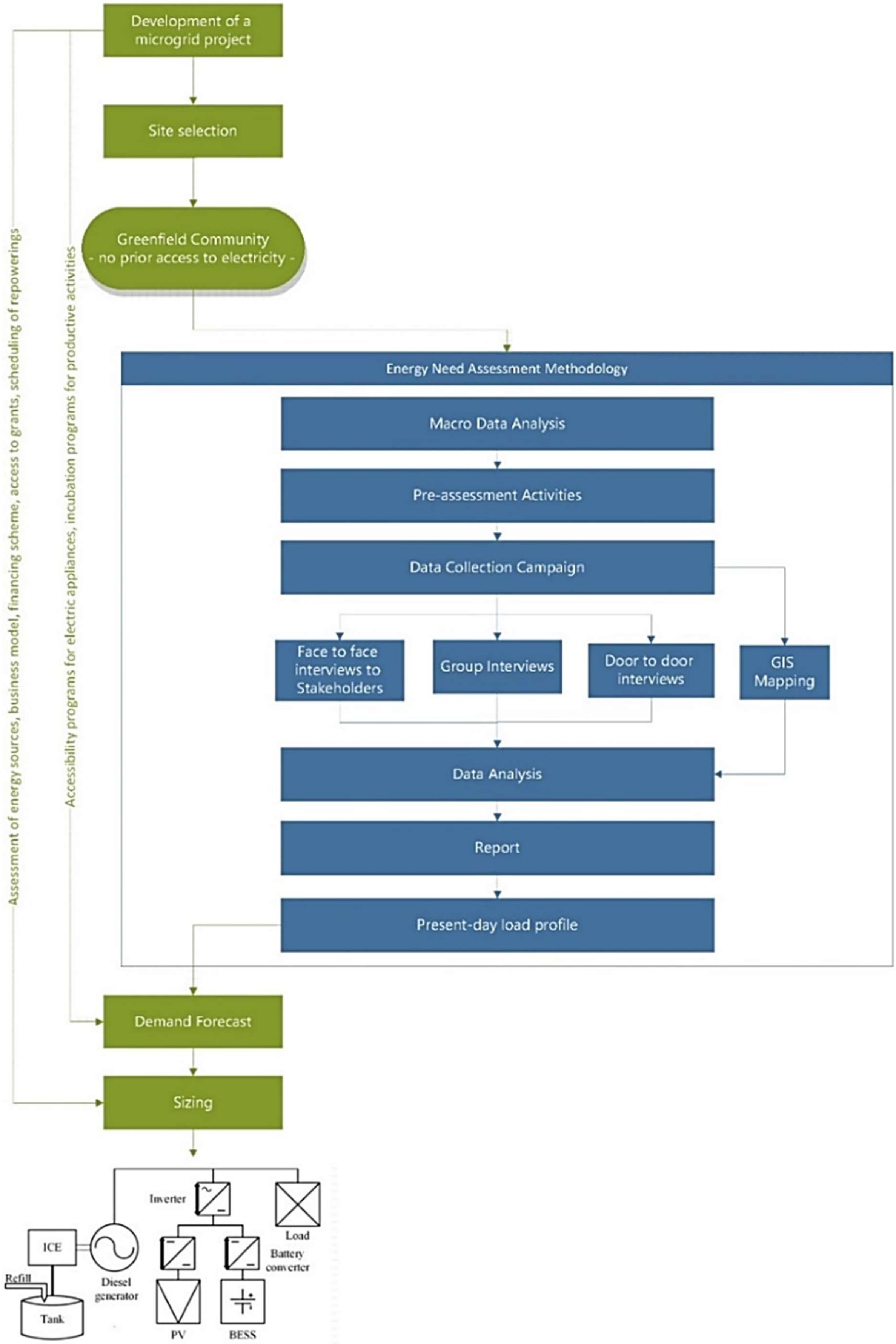


Figure 40 - Development process flowchart for greenfield mini-grid projects

5.2. Comparative Literature Overview

5.2.1. Load profile as input for sizing and optimization models

With the objective of reducing the viability gap of micro-grids as a means to provide energy access to communities which are not feasible to be grid connected, many models and software tools are being developed to size optimally a micro-grid and to operate it to serve the demand while minimizing running costs. A literature overview of the approaches used to optimize power systems with multiple energy sources can be found in [119].

Among the commercial software available for this purpose, the most known and utilized is HOMER [120], which can optimally size a mini-grid, simulate its operation, and perform sensitivity analyses, considering technical, economic and environmental aspects [121]. HOMER can also be used to evaluate poor design choices and operational issues in existing mini-grids [122]. Whereas HOMER considers a single deterministic scenario of load and RE generation, stochastic methods to cope with load and generation uncertainties have been proposed by other applied studies [123][124][119].

All the aforementioned software and models require the community load profile as input in order to run their algorithms. However, conducting surveys requires time, resources and specific competences. The simplest way of deriving a load profile for an unelectrified community would be that of combining data from other electrification projects in developing countries and adapting them to the context of operation with a number of assumptions. An example of this approach is given by Kolhe et al., [125], who investigated the optimal size of an off-grid energy system without conducting a primary data collection [126].

The effort of characterizing the load profiles of existing micro-grids to use as a improved input to simulation tools like HOMER has been pursued in [127], with respect to 11 micro-grids installed by Powergen in Kenya and Tanzania. Prinsloo and et al., developed a load profile "archetype" for rural micro-grids in Africa, by combining a variety of datasets found in literature, for the same purpose of improving inputs to computer models [128].

These approaches used to face the data input concerns are very valuable to gain a general understanding of the micro-grid sizing. However, when it comes to actually deploy a micro-grid project, with all its associated financial, technical and logistic concerns, a further deepening is required to bear the development risks.

5.2.2. The relevance of accuracy in the energy need assessment (ENA)

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 [129]. 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 the literature. In [130] 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 [129], instead, it can be found a discussion on the techno-economic consequences of estimation errors on energy consumptions of seven small-scale off-grid solar-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 USD1.92 to USD6.02 per watthour, whereas under-estimation can precipitously degrade reliability. Thus, the economic merit 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, as the authors claim.

In [116], 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 determine 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 ENA and, in addition to those mentioned before, it should be also consider 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 [131]. This work is not going to further discuss reasons for these discordances, but it does aim to highlight that there are many factors coming into play when explaining 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.

5.2.3. Process of load profiling in greenfield projects

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. It should be noticed that these studies, unlike this research, do not describe a tested and replicable methodology but just the chosen method to handle the scope of work.

Camblong et al., [132] 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 WTP and Substitutable Energy 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 [133], along with a design proposal.

More recently, Sandwell et al., [134] 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 [135] they represent the main sources of energy in unelectrified communities and complementary sources in those electrified. In the literature, there are studies that adopt this approach, such as a comparative analysis of the technology, economics and CO_2 emissions between kerosene-based lamps and modern bio-energy systems and solar PV, which considered fuel consumption, power rating, luminous flux, efficacy and useful life of devices [136].

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 [137]. 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.

5.2.4. Process of load profiling in greenfield projects

Among others, an important reference on survey methodology is the World Bank Living Standards Measurement Study (LSMS), being amply proven and implemented in over twenty developing countries. In the late 1970s, the lack for internationally comparable data to perform well-supported statements about world poverty [138] led to the establishment of LSMS in 1980 to improve the type and quality of household data collected by government statistical offices in developing countries [139]. The questionnaires inspected all major aspects of economic well-being at the household and community level [140] and featured novelties such as multi-topic questionnaires, rigorous quality control procedures and a pioneering use of computer software. The program also emitted specific guidelines on how to customize the questionnaires based on the social, economic and political context of the target country [140], [141]. The work cycle devised by the method was of 4 weeks to survey two locations [142], which makes LSMS questionnaires very time and cost intensive and as such not viable to conduct extensive energy policy analysis [143]. In [143] a comparison between LSMS and specialized household energy surveys can be found, highlighting how the latter are implemented to inform a particular energy policy or investment. For example, they are used to assess the efficiency and efficacy of fuel price subsidies or to establish baseline information and monitor rural electrification programs.

In the recent years, the MIT launched an initiative, the D-Lab, devoted to develop and advance collaborative approaches and practical solutions to global poverty challenges [144]. 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 [145], following a bottom-up approach, where local organizations active in a certain area or community drive the needs assessment, solution identification and project implementation [146]. Among its activities, D-Lab developed an Off-Grid Energy Roadmap, which first step consists in the assessment of energy needs and market opportunities [147]. At this scope a specialized set of tools was developed and published in 2017: the D-Lab Energy Assessment Toolkit (EAT) [146]. 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). 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 [148]. 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, has already been 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 [149]. 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 ENA, 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 WTP for a given service [150]. 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.

5.3. Methodology

5.3.1. Effective methodology for the energy need assessment (ENA)

The research objective aims at proposing an effective methodology for the ENA in rural electrification sector to obtain reliable inputs for load profiling and mini-grid sizing, with a view to characterizing the community's energy needs and exploring the viability of potential projects as well as optimization of operational energy systems.

An accurate and reliable ENA represents the preliminary and fundamental activity to design a rural electrification project, including both technical solutions as well as other ancillary activities in order to enable local communities to properly manage the electricity service and to boost their socio-economic development.

With a view to study all the factors affecting technical solutions, characterization of the community's energy needs is aimed at classifying the contexts of intervention in order to move toward a common overall objective of mini-grid's optimization methods and tools (see chapter 6). The main community's features are defined so as to guide the ENA methodology presented in this work. Such figures will be investigated through indicators and indexes that represent the objective of an ongoing study aimed at finalizing such characterization of target communities.

In order to address the requirements of mini-grid developers, the proposed methodology is specifically focused on the ENA 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 EAT developed by MIT D-Lab, 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.

5.3.2. Main phases of the methodology in brief

In brief, the proposed ENA 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.

To summarize the main activities that the ENA 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.

5.3.3. Macro-Data Analysis

As part of the first phase of the assessment, the aim of this activity is to examine and describe the context which the data collection campaign is going to be built upon. Preliminary macro-data analysis based on literature, publications and reports by accredited agencies and institutions is carried out at country, local level and sector level, such as off-grid systems and mini-grid outlook.

Specifically, the macro-data analysis is mainly focused on, but not limited to, relevant macro statistics and background data concerning demographic dimensions, economic data, access to public services, national grid masterplan, mapping of potential villages and their distance from the national grid (for greenfield projects), business activities the local economy is based on, medium-large farms, industries or companies (national or international), organizations active in the region (NGOs, UN field offices, etc.) and energy projects realized in the region.

The main outputs the macro-data analysis should provide to move forward are the following:

- administrative framework
- map of potential villages pre-selected (for greenfield projects)
- list of local stakeholders to contact
- list of organizations active in energy sector
- list of energy projects realized in the region
- list of potential local partners

5.3.4. Pre-Assessment Activities

As part of the first phase of the assessment, defining the specific objective of the ENA and formulating the key results accordingly should be a priority before proceeding with any practical activities. Such results in fact are given by the explanation of a set of key indicators, coming from the data collection. That is why a review of the standard data collection tools on a case-by-case basis is strongly recommended because questionnaires need to be checked before every application in order to best suit the given specific objective, results and context of intervention.

Actually, depending on the type of project (potential, existent, on-grid, off-grid, etc.) some indicators may be more relevant than others and some cannot be applied in a given context, such as existing and potential anchor loads with productive use of electricity, public infrastructures to be optimized through a reliable and/or more affordable electricity supply, market information and access to microcredit and banking services. This is one of the reasons why classifying the contexts of intervention with a view on the community's energy needs mentioned before can boost toward an optimization of methods and tools to develop rural electrification project.

Lastly, the pre-assessment activities are also focused on conducting a preliminary stakeholder consultation at national and local level to pave the way for the data collection campaign.

Particularly in rural areas of developing countries, consultations are an essential step to increase local understanding of the action, favoring a trustfully environment and collaborative approach and consequently and enhancing the reliability of assessment's results. Here follows a list of potential stakeholders to be contacted beforehand:

- political authorities at village/county/district level
- technical persons of relevant national agencies or local administrations
- representatives of local associations and financial institutions

5.3.5. 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 [151]. 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 [152].

Furthermore, the methodology emphasizes the importance of carrying out data collection activity with a focus not only on 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 [113]. 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 [113].

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, the following are the key features of data collection methodology 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 sections;
- 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. They are reported below at the end of each method's explanation.

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 PUE as well as public institutions and existing infrastructures requiring reliable electricity supply.

A 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 the main business activities, productive users of electricity and financial institutions.

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.

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 that it allows 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 [153]:

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

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 previous direct experience in rural areas of East Africa, we considered a ratio between small business activities and total households of 6–8%. With the aim of visiting all of them, the evaluation team should target to reach at least 80% of the total estimated number.

GIS Mapping

A GPS mapping of the main potential customers and village boundaries is carried out by using 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: infrastructure, 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.

5.3.6. Data Analysis and Reporting

The data analysis of the inputs collected during the second phase of the ENA 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:

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

5.3.7. Outputs of the energy need assessment (ENA)

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 and 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 ENA and its reliability is based on accuracy of results given by data collection and data analysis, representing the core phases of the ENA. It must be specified that forecast load curve is not included in this document since the optimization of its method of calculation represents an on-going research.
- 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.

5.4. Results

5.4.1. The methodology validation: case study in Rwanda

The presented methodology for ENA has been tested and improved time since 2012. So far, it has been applied in 9 data collection campaigns for a total of 42 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 ENA 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 consumption and expenditures and the assessment of current and potential anchor loads. With reference to the Village A (Table 4), 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 (PUE or other businesses with appliances requiring power over 5 kW and at least a consumption of 2 kWh/day), which are considered as stakeholders in the Table 24, whereas Table 25 summarizes the main survey figures considering gender balance and the sampling size.

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 24- Main survey figures of the data collection.

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 25 - Main survey figures considering gender balance and the sampling size.

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.

5.4.2. Results on socio-economic concerns

Local economy is based on farming and related commercial and productive activities, coupled with small livestock. Main crops cultivated are maize, beans, bananas, peanuts, manioca and sorghum, among which only maize and sorghum are currently processed by milling services.

Seasonality of business activities reflects dry seasons, which are harvest seasons as well: the "high season" periods, meaning when the business revenues are high, are from January to March and from June to August.

With regards to households income, population living in the targeted villages works 7.2, 7,0 and 7.7 hours per day on average in village A, B and C respectively, to earn 20,770 RWF, 26,256 RWF and 32,354 RWF per month on average.

Considering that access to microfinance is an essential factor to evaluate potential increase in energy demand and room of improvement of business activities, there are several saving groups in the targeted area (5, 23 and 13 in village A, B and C respectively).

The field mission disclosed a lack of access to water: the main water sources are unprotected springs (improperly called well or dam, or ibinamba in local language) that do not respect sanitation standards, and only few protected springs. However, during the dry season, the available water supply is not able to satisfy the needs of the entire population.

Furthermore, there is a fully convergence of data on sanitation concerns: 90% of the population uses private covered pit latrines (90%, 100% and 95% in village A, B and C respectively) with minor a percentage using uncovered pit latrines.

Additionally, a housing assessment was conducted to verify whether buildings meet the minimum safety criteria to be connected: spread of construction techniques with limited durability such as unburnt bricks with mud (representing 35%, 78% and 30% of buildings in village A, B and C respectively) suggests to verify case by case their eligibility for electricity connection.

Lastly, transports and energy used for cooking were investigated: the main mean of transport present is bicycle (owned by 70%, 60% and 54% of people in village A, B and C respectively) whereas only a few own motorbikes. Main cooking fuels are firewood and charcoal.

5.4.3. 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 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 41. 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 ENA, 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.

Current energy consumption and expenditures for lighting and electrical devices per customer represent two crucial indicators of the ENA, which are calculated separately per each customer group to favor the undertaking of specific actions (see Table 26 and Figure 42).

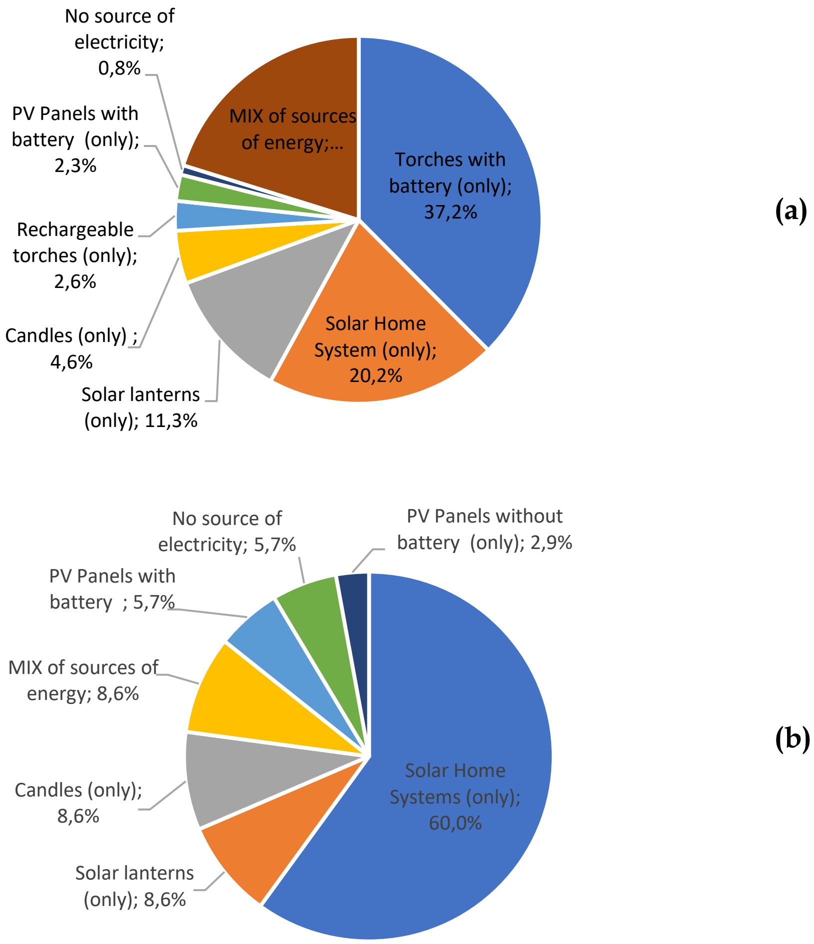


Figure 41 - Sources of energy current used per cluster of customers. (a) Sources of energy currently used by households. (b) Sources of energy currently used by small businesses.

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 26 - Average consumptions and expenditures for electricity substitutes per customer.

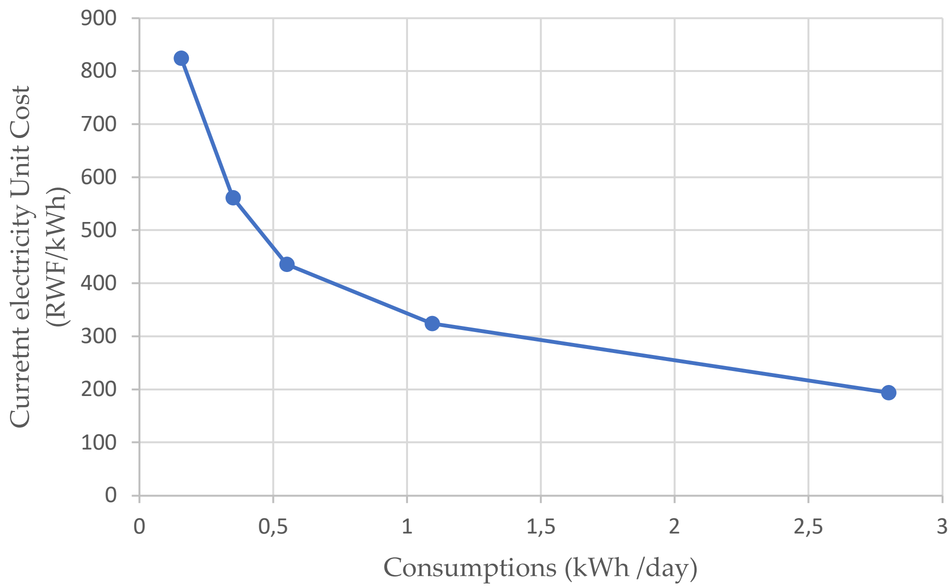


Figure 42 - Correlation between Current Electricity Unit Cost and Consumptions.

The first part of the ENA 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 [154], projections of rural population claim an increase of the size of rural population by 23.2% to 35% between 2012 and 2032. In contrast, 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 noted 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 required to assess the WTP, considering that previous studies have warned against the tendency of rural households to overstate their WTP, as mentioned in [155].

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 [156], 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 [7].

In the 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 [157]. This specific aspect can be quantified by considering the Ability To Pay (ATP), which is a parameter dependent on the income level of the interviewee, and it is directly related to the affordability of the tariff for the users [158]. WTP and ATP of rural household consumers are closely related since a higher (or lower) rate of WTP is strongly affected by the share of disposable income assigned to electricity as a service in the overall household income [158]. 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 sections, 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 Table 27.

5.4.4. Current energy load curves

The energy load profiling, which is considered as the current energy demand, and a detailed load profiling on possible sub-scenarios was carried out considering tentative electricity tariff plans. It must be specified that forecast load curve is not included in this document since the optimization of its method of calculation represents an on-going research.

To profile the load curves, a market penetration was assumed depending on the WTP as well as to change from SHS or PV panels with battery to reliable 24/7 energy supply. However, 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 (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 [29]:

$$Et = Eh \times C1h \times C2h + Eb \times C1b \times C2b + Ea \times C1a \times C2a \quad (2)$$

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)

First was shown 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 (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%.

Second, 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 27 below in terms of monthly flat tariff, whereas percentages represent the Commercial Demand Factor (C2) in the equation (2).

Market penetration considering the WTP: 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 27 - 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 WTP. 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 28 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	48,405	34%	30,403	26%	30,403	30%
Small business	49,783	35%	44,862	38%	26,510	26%
Anchor loads (mills)	43,469	31%	43,469	37%	43,469	43%
Total	141,657	100%	118,734	100%	100,382	100%

Table 28 - Current energy demand by type of consumer.

In conclusion, taking into account the market penetration reported in Table 27, the recommended flat tariff should be set below 2,940 RWF/month. The daily load profiles of the community with this flat tariff applied (Figure 43) 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.

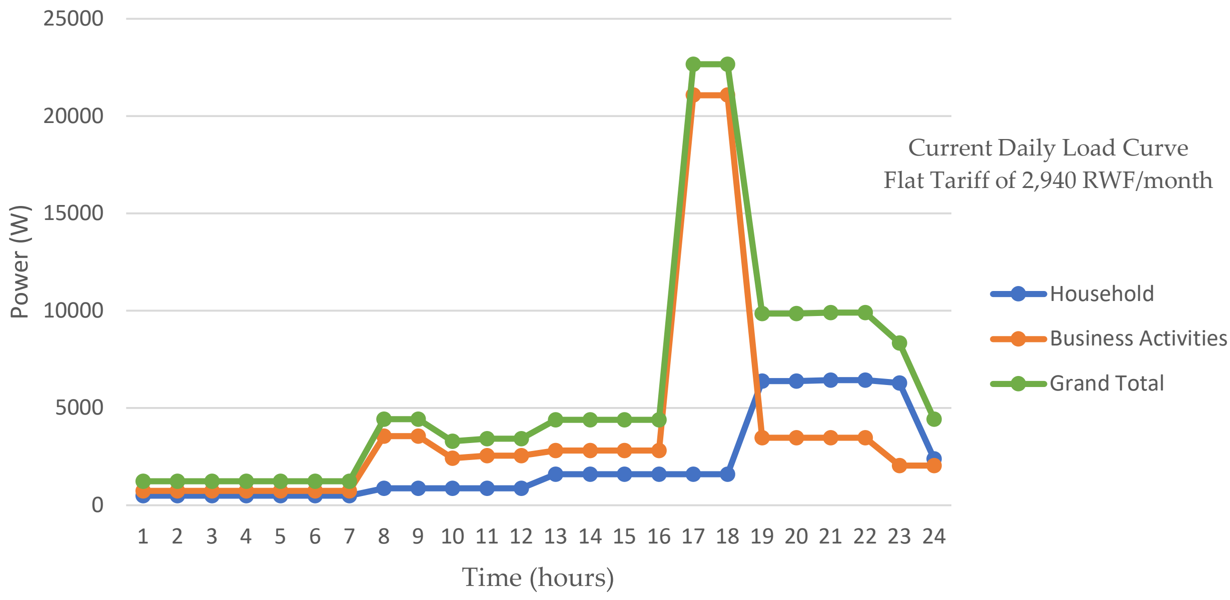


Figure 43 - Current daily load curves.

5.4.5. Sizing of mini-grid based on assessment results

Based on the output from the load profiling, we sized a mini-grid for the assessed village.

HOMER Pro Microgrid Analysis Tool 3.11.6 [159] is the simulation tool adopted for the optimization of the plant. This simulation tool assists in the planning and design of RE 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 section [122].

Detailed description on HOMER PRO software can be found in [120].

We considered solar irradiation as the only renewable source. 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 [160]. 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 44.

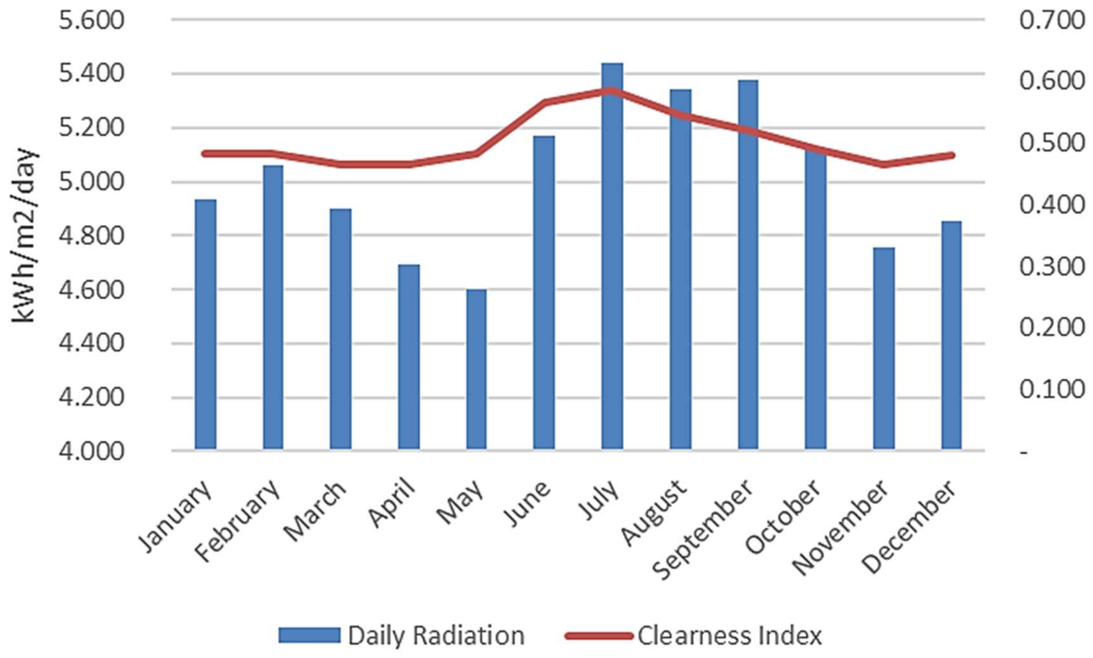


Figure 44 - Assumed average daily solar irradiation and clearness index for the plant location.

It was assumed to size a hybrid mini-grid composed by a PV plant, a Battery Energy Storage System (BESS) and a diesel generator (Figure 45).

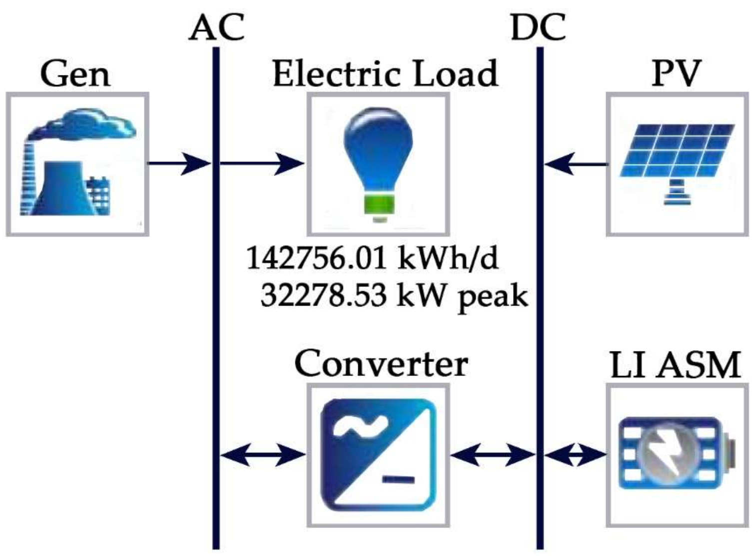


Figure 45 - Scheme of the Hybrid mini-grid.

The considered PV system and replacement cost is 2,200 USD/kWp. The O & M cost is set to 10 USD/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 USD/kW, and the efficiency is assumed to be 95%.

For the BESS, we considered a Li-Ion battery, with round trip losses of 8%, an estimated cost of 600 USD/kWh, an O & M cost of 10 USD/kWh/year, and a connection on the DC bus [122].

The cost of the diesel Generator is set to 500 USD/kW and the fuel price is set to 1.4 USD/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 COE of 0.447 USD/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.

5.5. Discussion

5.5.1. Strengths of the proposed methodology

The strengths of this methodology are that the use of different data sources:

- increases the results accuracy;
- allows an expert consultant to immediately bring to light relevant discordances and points of investigation to clarify during the field mission;
- supports in defining the current energy sources and expenditure for electricity substitutes by using a large sample size of the potential market (a crucial indicator to evaluate the real ability to pay of customers);
- helps to record perspective and detailed information from stakeholders and anchor users (fundamental qualitative data to customize the mini-grid project development);
- allows the project developers to lay the groundwork for a remote monitoring & evaluation framework over the project life, thanks to the use of GPS coordinates.

Lastly, it is important to highlight that it is based on the assumption that the key indicators are given by proxy variables since people that never had access to electricity and do not have regular income have little reliability in estimating their consumptions and expenditures as well as in predicting their future appliances purchases and their pattern of us [129], as recommended in the literature focused on mini-grid development [161].

5.5.2. Mini-grid sensitivity to inputs and assumptions coming from the energy need assessment (ENA)

The ENA is particularly important in the development of rural electrification project, especially in mini-grids, both from (i) a business perspective, which allows for reducing the investment risk and from (ii) a technical perspective, which allows for developing reliable load profiling and optimize the energy management systems. It follows from this that the accuracy of inputs used as well as assumptions selected directly affect the technical and financial feasibility studies. Results of the ENA 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, as discussed in [129], where the authors argue that 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. This issue has been investigated in detail also in [162], but the authors did not tackle the uncertainties in primary data acquisition and used a proxy method for getting "typical" classes of users based on their observations on already electrified peri-urban areas of Uganda. The same authors proposed a method to formulate load profiles for expected new customers in off-grid rural areas without prior access to electricity [152]. The method employs a bottom-up stochastic approach to take into account the variability of the overall time in which an appliance is functioning in a day and its functioning windows; but there is no insight on how to acquire the input data for it, and the model is validated on an already electrified site.

Another example of a tool dedicated to generating load profiles and estimate demand diversity is given in [163], but again the availability of reliable survey data is taken for granted. Thus, this study aims to contribute in bridging the gap between the development of modelling tools and the field challenges with a focus on uncertainties of remote communities.

5.5.3. Estimation of current average consumptions and expenditures for electricity substitutes

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

With respect to the literature, [164][165] 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. The matrix used to calculate average daily consumptions for electricity substitutes is reported in Annex 2 while the matrix used for the related monthly expenditure is reported in Annex 3.

6

Characterization of the community's energy needs

6.1 Rationale behind a focus on characterization of the community's energy needs in greenfield rural electrification projects

In order to develop financially viable projects, one of the major barriers to be overcome is the uncertainty in predicting customer electricity consumption, which adds financial risk [116], and their WTP. In other words, since the profitability of a project is highly dependent on the amount of electricity that is produced and sold, uncertainty regarding electricity demand in micro/mini-grids represents a significant risk for investors [117]. As discussed in a report on lessons from World Bank Group experience on off-grid projects [166] access to finance is directly linked to the risk profiles attributed to each mini-grid projects. Even with a pilot project, technical risk and cost estimates needed to be properly assessed and even if the probability of risk was low, the magnitude of impacts if the risk materialized needed to be examined and decision needed to be made accordingly, otherwise, there would be a waste of financing resources.

As claimed by GIZ [167], the initial demand assessment is reflected both in capital costs and revenue projections, and has a high potential for being inaccurate in the proposal phase.

Thus, there is a need to increase the accuracy of the proposal design to sustain both practitioners and financing entities in estimating and evaluating, respectively, the energy needs of a target community with a sufficient level of accuracy even in the project's early stage. That would allow to de-risk investments and secure finance to projects with a more reliable business planning.

Furthermore, with specific reference to off-grid micro and small projects in remote areas (ideally <50 kW), on one hand there is the need to secure a reliable project development as above, and on the other hand reaching the project viability is more challenging since the smaller is the project the highest is the percentage of development costs out the total capital costs [83]. Thus, conducting an adequate ENA with an expert data collection campaign and data analysis comes at a cost which is often not sustainable for a stand-alone project.

6.2 The research objective

This work is developed within a broader research to optimize the system design of RE mini-grids in developing countries, and to provide practitioners and developers with evidence to actually support the design, develop and evaluate new projects as well as the rural electrification planning.

Specifically, this work was born from two research activities, carried out during this comprehensive research project.

The first one was on the development of a "Methodology for the Energy Need Assessment to Effectively Design and Deploy Mini-Grids for Rural Electrification."[97] (see chapter 5), which aimed at proposing an effective methodology for an in-depth ENA to obtain accurate and reliable inputs for load profiling and mini-grid sizing, with a view to characterizing the community's energy needs and exploring the viability of potential projects as well as optimization of operational energy systems. In this methodology, with a view to study all the factors affecting technical solutions, the main socio-economic community's features were investigated and categorized through indicators and indexes, paving the way for this work as already stated in [97].

The second one was a case study analysis of 21 RE mini-grids in SSA, which firstly identified success factors and viable approaches to pursue the viability and replicability of rural electrification projects and resulted in the study promoted by RES4Africa Foundation "RE-thinking Access to Energy Business Models. Ways to Walk the Water-Energy-Food Nexus Talk in Sub-Saharan Africa." [103] (see chapter 4), and then feeds a scholarly effort focused on aggregate and correlation analysis of business model indicators [168] (see section 3.4). Results on weak, moderate and strong correlations among such business model indicators were particularly relevant to define the proposed framework of indicators.

The overall objective of this work is to overcome the limitations inherent to case-specific studies and to scope far-reaching findings that can unlock the scaling-up of mini-grid initiatives and sustain the rural electrification planning.

The specific objective is to develop a framework for characterization of the community's energy needs in greenfield rural electrification project. The framework tool aims to provide a proxy of an in-depth ENA by considering technical, environmental, socio-economic and business model-related parameters in an integrated manner in order to output the WTP for electricity as well as the shape and amplitude of load profiling (current and forecast), which are the key outputs of any ENA.

Thus, the framework tool is conceived to be adopted in two fields of application, which are actually interconnected.

The primary field of application is supporting the preliminary phase of mini-grid business development and/or small size projects not requiring an in-depth baseline in order to provide reliable inputs for business planning and systems design. In fact, the tool is formulated on the basis of a key assumption: it is expected to provide the user with outputs to design a mini-grid project which is economically sustainable, without taking into consideration external sources of finance, going beyond the scope of this work and being actually simulated to adjust the load profiles given by ENA in the real application.

The secondary field of application is optimizing the rural electrification planning tools. Developing a framework of indicators for individual systems, as the one proposed here, could be beneficial in a regional planning scenario to establish more evidence-grounded criteria for extrapolating proxy information.

This work is intended as a first hypothesis of a framework tool to be adopted by both academics and practitioners in understanding and fostering the large-scale development of off-grid systems. Therefore, besides the data availability limitations for some indicators and the inevitable biases implicit in a proxy assessment, as stated above, the proposed framework required to be tested and validated in the real environment.

6.3 Literature overview

As discussed in the previous paragraph, this work aims at bridging two research areas, on electrification planning and on framework of indicators for electricity projects in rural communities. As such, we will review here the most relevant works proposed in the literature on these two topics.

The stages adopted in the planning value chain, as discussed by Trotter et al. [62], go from obtaining preliminary demand estimates, to selecting producing electricity technologies, planning operations, designing T&D systems and finally the implementation. However, the term "planning" is referenced here with an ample scope, covering individual systems as well as regional, national and supra-national planification strategies, as done by Riva and coworkers in their review [169].

When considering individual systems, the demand assessment and load profiling steps are conducted usually with an engineering method, following the classification proposed in [151], meaning that in absence of historical consumption data for greenfield communities the final end-uses for electricity and consumption habits are estimated and modeled into a load profile curve. Notable examples developed for rural communities are LoadProGen [152] and EscoBox [170].

When considering regional planning, the demand assessment for greenfield communities is usually done with more coarse methodologies. OnSSET is an open-source tool [171] that uses GIS data to select an optimal electrification split (among grid connection, mini-grids and stand-alone systems) for off-grid communities of a given country. In so doing, no demand estimation step is performed, but a target expressed as a desired tier of access is simply set to evaluate a planning scenario [172], [173]. The Global Electrification Platform (GEP) is an evolution of the same tool, [174], which allows for a more refined scenario setting; it includes a bottom-up scenario that assigns a unique demand target (kWh/cap/year) in each settlement, based on local poverty rate and GDP level [175].

Such a "prescriptive" approach (i.e. externally setting a goal for the access level) it's an intrinsic limitation if considering only remotely accessible GIS data with no direct information about individual communities. Recently, USAID released a toolkit for estimating the addressable market for SHS in Mozambique, from the province to the single settlement level [176]. This toolkit uses a similar array of open-source GIS dataset as OnSSET and GEP, but is complemented by the results of a nation-wide survey report that determined the affordability percentage of population in each Mozambican province [177].

This combination of GIS and field data is adopted also by the REM, which is an electrification planning software developed by MIT and Comillas University [36], [178], [179]. REM, in performing demand estimates, relies on direct appliance pattern utilizations data complemented with proxy information obtained, for example, from grid connected remote communities.

This overview on local and regional planning methodologies is relevant to the extent of our work considering the following:

1. when planning for individual systems, it could be beneficial to locate systematically a set of data that can be accessed remotely, as done by regional electrification toolkits and discussed in [97], including GIS datasets, existing surveys and census information and so on. This to limit and streamline field data acquisition and fully exploit existing bodies of knowledge;
2. developing a framework of indicators for individual systems, as the one proposed here, could be beneficial in a regional planning scenario to establish more evidence-grounded criteria for extrapolating proxy information. That is, by building a sufficient dataset of indicators for rural communities, the criteria on which two greenfield communities are to be considered "similar" can more accurately and effectively be set.

Moreover, expanding on the point (1) above, given that our goal is to provide a tool to facilitate business development for mini-grid systems, it is key to not restrict the extent of the assessment to estimating the appliance ownership patterns and expected usage behaviour for load profiling. An attempt to integrate socio-economic indicators modelling, to obtain household appliance ownership projections, with load modelling tools was developed by Riva et al. in [180].

However, the project assumptions should be also incorporated in the analysis, such as ownership and operation features. These aspects are not commonly integrated into single-system planning methods, which focus more on the bottom-up estimation of the load profile, nor into regional planning ones.

Lorenzoni and coworkers [181] conducted a first exploratory study on the impact of external parameters on the load profile of mini-grid systems, such as the type of ownership and the tariff scheme, showing a clear impact on the demand characteristics of the communities. This experience substantiates the case for the development of a comprehensive framework of indicators that are expected to give us predictive abilities in terms of operating behaviour of off-grid systems.

Here, we borrow an approach based on indicators, which is typical of the development sector, including rural electrification. Indicators-based frameworks are usually employed for impact assessment [182], monitoring and evaluation [183], and, mostly sustainability analysis. This approach locates dimensions to analyze, which in turn are characterized through a set of measures, that are finally defined with clear and measurable indicators [184]. We employed a similar cascading structure for our framework, and albeit being oriented towards a techno-economic assessment, draws lessons and analogies from existing sets of indicators used for rural electrification projects.

Particularly, the work done by Ilskog [185] ,who developed a set of 39 indicators for the sustainability evaluation of rural electrification projects, illustrates clearly a methodology which resonates with the one proposed in the following. As shown in Figure 46, Ilskog tested potential indicators based on field suitability (A), re-evaluated them as being respondent to key criteria (simplicity, transparency, robustness, comprehensiveness and fairness – B), and iterating the process over existing literature (C). Furthermore, this framework has firstly been presented as a standalone research work [186] and then applied to case studies [187], much like the proposed work.

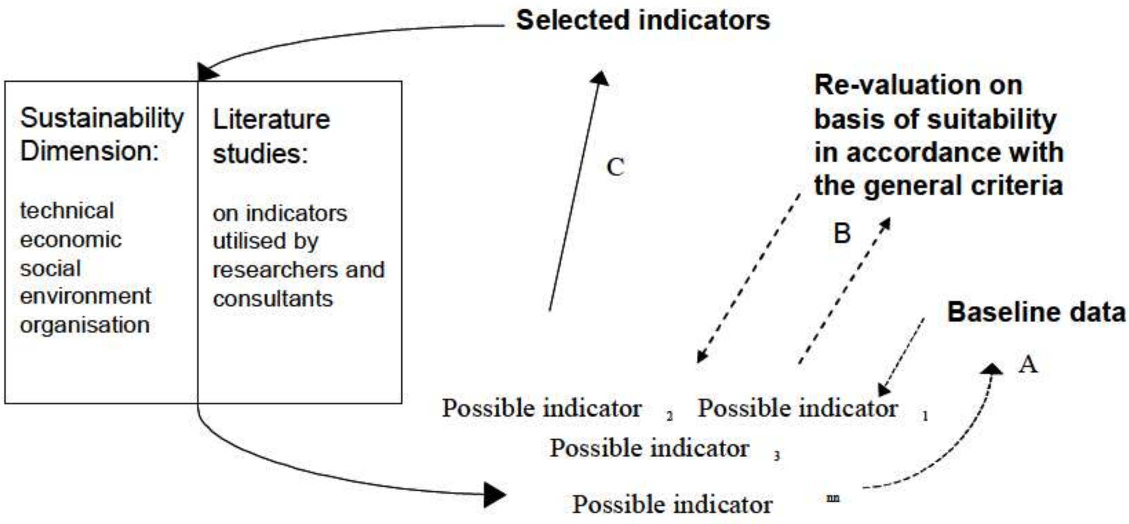


Figure 46 – Procedure of selection of indicators. Source: E. Ilskog [185].

Yadoo and Cruickshank built upon Ilskog's framework proposing 43 sustainability indicators, which were applied to case studies in Kenya, Peru and Nepal [188]. Their work has been used also by Lestari et al. in addition to the Institutional Analysis and Development (IAD) framework [189].

In the same spirit, Kabalan and Anabaraonye developed a set of 16 sustainability indicators to select the most appropriate generation technology (PV vs. micro hydro) for a rural village in the Philippines.

Obeng et al. proposed a framework of 34 indicators for rural Ghana, which was used to conduct a Principal Component Analysis (PCA) to compare the level of energy poverty in non-electrified versus solar-electrified households [190].

Neves et al. elaborated a list of 11 indicators for the characterization of communities and their renewable off-grid systems, which was applied to highlight similarities and differences of hybrid off-grid systems in small islands and remote villages [191].

Katre et al. developed a framework of 31 indicators for the sustainability assessment of community-owned mini-grids in India [184], with a clear and rigorous scoring system that has been was applied to 24 case studies [192]. A similar effort has been presented in [193] for 65 off-grid, community solar PV projects in Malawi, assigning scores to social, organizational, technical, and economic factors.

In addition to sustainability frameworks, one for the resilience of rural power systems is presented in [194], with 42 indicators covering technical, economic and social resilience.

For evaluation of planning strategies, in [195] a set of technical, management and regional scale indicators has been set up to compare the effectiveness of grid extension, mini-grids and standalone systems based on case studies in rural Mexico. Similarly, Juanpera et al. proposed a set of 28 indicators to evaluate the impact of different generation technologies and system types (mini-grid vs individual) for six rural Peruvian communities [196].

All the cited works dealing specifically with frameworks of indicators for rural power systems in developing countries have been considered in the definition of our own set of indicators, which is introduced in the following section. Albeit covering different objectives, this body of literature represents a fundamental basis to define suitable indicators that are able to "capture" and describe the key characteristics of rural communities, which are to be used, as in our case, as a first step to gain predictive capabilities in terms of the feasibility assessment for greenfield projects.

6.4 Methodology for selection of indicators

The proposed indicators' framework for characterization of the community's energy needs is defined on the basis of the following four types of input, which have been analysed firstly independently and then in an integrated manner:

a) literature analysis on indicators;

b) correlation analysis' results, as given by [168];

c) results given by the application of the ENA methodology in [97];

d) case studies, in addition to those analysed in [168].

About (a), the literature analysis on indicators is fundamental to leverage evidences already proven or at least justified by previous researches. The work was carried out searching for (i) similar framework tools, (ii) discussions on indicators for the ENA in rural areas of in developing countries and (iii) discussions on actual load profiles and operations in mini-grid projects.

About (b), potential correlations between 48 business model-related indicators have been explored by an expert selection of indicator pairs in [168]. Such indicators were managed in six clusters: 1.Context data, 2.Power generation systems, 3.Business model and productive use of electricity, 4.Financial features, 5.Electricity market dimensions and 6.Electricity tariff and expenditures. A summary of the results is presented in Table 19, revealing 66 strong correlations, 85 moderate correlations and 185 weak correlations.

Among the strong and moderate correlations, the proposed research identified those correlations affecting the ENA and the related indicator pairs were considered to be included in the proposed framework. Specifically, it was verified the frequency distribution of available data, given in [168]: they were not considered in case of low reliability of result (low frequency) and in case of discordance with other type of inputs, as defined in section 4.

About (c), ENA carried out according to the ENA methodology in [97] was taken into consideration. Specifically, the work analysed ENA reports related to 7 data collection campaigns carried out in 36 villages in Honduras, Uganda and Kenya in the period before the methodology's validation and 4 data collection campaigns carried out in 24 villages in Rwanda, Mozambique and Democratic Republic of Congo applying the ENA methodology validated for a total of more than 40,000 target people, and specifically:

- ENA campaign in 11 villages, province of Zambesia, Nampula, Manica and Tete (Mozambique). Total population of 13,230 people (3,000 households). Developer: RINA Consulting and EnGreen, funded by World Bank/FUNAE.
- ENA campaign in 2 villages, Idjwi island (Democratic Republic of Congo). Total population of 3,150 people (450 households). Developer: AVSI Foundation, EnGreen and Ministry of Environment of the DRC, co-funded by Italian Ministry of Environment.
- ENA campaign in 8 villages, province of Zambezia (Mozambique). Total population of 10,490 people (2,379 households). Developer: ENCO Consulting and EnGreen, funded by Enabel.
- ENA "validation" campaign in 3 villages, Eastern province (Rwanda). Total population of 15,780 people (2,818 households). Developer: AVSI Foundation and EnGreen, funded by Energy4Impact.

Such ENA was studied in order to find out which data result to affect (i) household's and business income (ii) energy consumptions and its evolution over the time and (iii) take-off of the community in terms of PUE and connections. Such data are required to compute the WTP and the load profiling and thus have a direct effect on the characterization of the community's energy needs in greenfield rural electrification projects.

About (d), this research leverages the research team' extensive experiences in the mini-grid feasibility study and execution as well as observation and data analysis in operation. The main mini-grid projects in operation which support this research projects to identify indicators to be included in the framework are the following:

- Increasing access to modern energy services in Ikondo Ward, Njombe (Tanzania). Rural electrification of 7 villages through a hydro-power generation of 430 kW. Developer: CEFA NGO, co-funded by European Commission.
- Sustainable energy services for Kitobo island (Uganda). 228 kWp solar PV with storage, diesel backup and LV distribution smart grid connection about 600 customers. Developer: Absolute Energy, in partnership with AVSI Foundation and CIRPS, co-funded by EEP.

- Solar hybrid mini-grid in the village of Rutenderi (Rwanda). 50 kWp solar PV with storage, diesel backup and LV distribution smart grid. Developer: Absolute Energy, co-funded by EnDev.
- Solar hybrid mini-grid in the village of Gatoki (Rwanda). 50 kWp solar PV with storage, diesel backup and LV distribution smart grid. Developer: Absolute Energy.
- Ilumina Project: access to energy for local development and women empowerment (Mozambique). 200 kWp solar PV with storage, diesel backup and LV distribution smart grid. Developer: AVSI Foundation and Tecnologie Solidali, co-funded by AICS.
- Sustainable energy Services for Idjwi island (Democratic Republic of Congo). 150 kWp solar PV with storage, diesel backup and LV distribution smart grid. Developer: AVSI Foundation, EnGreen and Ministry of Environment of the DRC, co-funded by Italian Ministry of Environment.
- Energy and training services for a sustainable growth in Bukasa island (Uganda). 100 kWp solar PV with storage, diesel backup and LV distribution smart grid. Developer: Absolute Energy, co-funded by AICS.
- Hydroelectric mini-grid for rural electrification of El Dictamo Village (Honduras). Developer: RETE and CIRPS, co-funded by EuropeAid.

6.5 Framework of indicators for characterization of the community's energy needs in greenfield rural electrification projects

The proposed framework of indicators is structured to clearly provide with the key information to understand how it should work, how it should be applied and how it is supported by the research process in its formulation. Specifically, Table 29 shows the framework structure, Table 30 shows at a glance the outside data, which are related to guess how the tool could be applied, and Table 31 represent the framework itself.

Please note that the full version of the framework is enclosed herto as the Annex 4.

The Framework Structure		
Item	**Options**	**Explanation**
Information category	Outside	"Outside" information is related to the project's side, and that should be provided by the potential user of the framework tool.
	Inside	"Inside" information is related to the data processing, dependency and correlation between indicators as well as references to justify the selection of indicators.
Sector	A.Electricity Market dimensions B.Technical Aspects C.Socio-Economic Aspects D.Habitat Aspects E.Ownership and Operation Features	"Sector" is referred to the overall sector the indicators are referred to.

Subsector	Several options as detailed in the framework.	"Subsector" is referred to the specific sector the indicators are referred to.
Indicator	Several options as detailed in the framework.	"Indicator" is specific and measurable and is able to describe the community and related mini-grid project in the time scale, as in [197].
Nature of data	Intrinsic	"Intrinsic" refers to essential data which characterize the community.
	Extrinsic	"Extrinsic" refers to external data pertaining to the project, but not characterizing the community itself.
Means of data acquisition	Desk	"Desk" refers to data available thought desk/remote analysis.
	Field	"Field" refers to data available thought soft field visit (e.g. local reference person / stakeholder/ unskilled partner)
Type of data	Input	"Input" refers to data gathered by means of desk or field activities, as defined in means of data acquisition.
	Derived	"Derived" refers to data computed from input data and/or other derived data.
	Assumption	"Assumption" refers to data given by the developer's project strategy and can be used for sensitivity analysis to provide different community's energy needs scenarios to support the business modelling.
Derived from	Other indicator(s)	"Other indicator(s)" is referred to those required to compute the given indicator, thus it is required in case of "Derived" type of data.
	Not applicable	"Not applicable" (n.a.) is applied in case of "Input" type of data.
Correlated with	Other indicator(s)	"Other indicator(s)" is referred to those resulted in strong or moderate correlation with the given indicator as per the correlation analysis in [168], thus it can be provided is all the types of data (input, derived, assumption).
	No evidence	"No evidence" (n.e.) is applied in case there is no strong or moderate correlation related to resulted from the correlation analysis in [168].[2]

[2] Bearing in mind that "No evidence" does not imply no/weak correlation resulted from the cited study since (i) it does not cover all the indicators included in the framework, specifically only few socio-economic ones, (ii) and a weak correlation could have been resulted from a lack of sufficient data. For avoidance of doubt, only evidences supported by strong or moderate correlations are reported to justify a given indicator.

Multiple choices	Several options as detailed in the framework.	"Multiple choices" are given to compile some indicators, in which a single selection should be admitted, and it is to avoid a variety of answers that would barely be processed.
	Not applicable	"Not applicable" (n.a.) is applied in case of there is no need to adopt a multiple-choice indicator.
Type of reference	Type of reference (a): literature analysis	Type of reference (a) refers to the literature analysis which supported the identification of a given indicator.
	Type of reference (b): correlation analysis	Type of reference (b) refers to the correlation analysis' results, as given by [168], which supported the identification of a given indicator.
	Type of reference (c): energy need assessment (ENA)	Type of reference (c) refers to results given by the application of the ENA methodology in [97], and which supported the identification of a given indicator.
	Type of reference (d): case studies	Type of reference (d) refers to case studies, in addition to those analysed in [168], which provide evidences supporting the identification of a given indicator.
Notes	Open notes	Notes includes a variety of information that integrate references and/or better explain what the indicator is referred to.

Table 29 - The framework of indicators' structure

Summary of outside data						
		Sectors				
Item	**Options**	A. Electricity Market Dimensions	B. Technical Aspects	C. Socio-Economic Aspects	D. Habitat Aspects	E. Ownership and Operation Features
Nature of data	Intrinsic	100%	33%	100%	100%	0%
	Extrinsic	0%	67%	0%	0%	100%
Means of data acquisition	Desk	78%	100%	68%	50%	100%
	Field	22%	0%	32%	50%	0%
Type of data	Input	28%	0%	82%	100%	0%
	Derived	72%	33%	18%	0%	0%
	Assumption	0%	67%	0%	0%	100%

Table 30 - Summary of outside data.

FRAMEWORK OF INDICATORS FOR CHARACTERIZATION OF THE COMMUNITY'S ENERGY NEEDS IN GREENFIELD RURAL ELECTRIFICATION PROJECTS *(Please note that the full version of the framework is an Annex to this document)*						
Outside (project's side)						
Code	**Sector / Subsector**	**Code**	**Indicator**	**Nature of data**	**Means of data acquisition**	**Type of data**
A	**ELECTRICITY MARKET DIMENSIONS**					
A.1	Market size	A.1.1	Total households	Intrinsic	Desk	Input
A.2	Penetration rate at year 0	A.2.1	Number of estimated HHs connected / total HHs at year 0	Intrinsic	Desk	Derived
		A.2.2	Number of estimated businesses connected / total businesses at year 0	Intrinsic	Desk	Derived
A.3	Tier for household electricity consumption	A.3.1	Average daily energy per HH	Intrinsic	Desk	Derived
		A.3.2	Average daily peak power per HH	Intrinsic	Desk	Derived
A.4	Type of connections	A.4.1	% of households	Intrinsic	Field	Derived
		A.4.2	% of small business activities (commercial and artisans)	Intrinsic	Field	Input
		A.4.3	% of achor loads	Intrinsic	Field	Input
		A.4.4	% of public services	Intrinsic	Field	Input
A.5	Penetration rate trend	A.5.1	Percentage variation of HHs penetration rate at the 2nd year of operation	Intrinsic	Desk	Derived
		A.5.2	Percentage variation of business penetration rate at the 2nd year of operation	Intrinsic	Desk	Derived
		A.5.3	Percentage variation of HHs penetration rate at the 5th year of operation	Intrinsic	Desk	Derived
		A.5.4	Percentage variation of business penetration rate at the 5th year of operation	Intrinsic	Desk	Derived
A.6	Consumption trend	A.6.1	Percentage variation of Average daily energy per HH at the 2nd year of operation	Intrinsic	Desk	Derived
		A.6.2	Percentage variation of Average daily peak power per HH at the 2nd year of operation	Intrinsic	Desk	Derived
		A.6.3	Percentage variation of Average daily energy per HH at the 5th year of operation	Intrinsic	Desk	Derived

		A.6.4	Percentage variation of Average daily peak power per HH at the 5th year of operation	Intrinsic	Desk	Derived
A.7	Share of productive use of electricity (PUE)	A.7.1	Average daily energy for PUE/total net energy consumed	Intrinsic	Desk	Input
B.	**TECHNICAL ASPECTS**					
B.1	Share of energy generated from RE sources	B.1.1	Yearly energy from RE sources / total yearly energy generated	Extrinsic	Desk	Assumption
B.2	Peak demand	B.2.1	Coincidence factor	Intrinsic	Desk	Derived
B.3	Daily operating hours	B.3.1	Hours of operation per day	Extrinsic	Desk	Assumption
C.	**SOCIO-ECONOMIC ASPECTS**					
C.1	Gender balance in business activities	C.1.1	% of small business activities run by women	Intrinsic	Field	Input
		C.1.2	% of achor loads run by women	Intrinsic	Field	Input
C.2	Business vocation	C.2.1	Total business activities / total HHs	Intrinsic	Desk	Derived
C.3	Economic activities	C.3.1	Main economic activity	Intrinsic	Field	Input
C.4	Education level	C.4.1	% of people with no level completed	Intrinsic	Desk	Input
		C.4.2	% of people with primary level completed	Intrinsic	Desk	Input
		C.4.3	% of people with secondary level completed	Intrinsic	Desk	Input
		C.4.4	% of people with upper levels, at least started	Intrinsic	Desk	Input
C.5	Economic capacity	C.5.1	HHs Average Monthly Income	Intrinsic	Desk	Input
		C.5.2	Small business activities Average Monthly Income	Intrinsic	Desk	Input
		C.5.3	Anchor loads Average Monthly Income	Intrinsic	Desk	Input
C.6	Share of expenditure on electricity substitutes	C.6.1	HHs average monthly expenditure for electricity substitutes / average monthly income	Intrinsic	Desk	Derived
		C.6.2	Small business average monthly expenditure for electricity substitutes / average monthly income	Intrinsic	Desk	Derived
		C.6.3	Anchor load average monthly expenditure for electricity substitutes / average monthly income	Intrinsic	Desk	Derived
C.7	Seasonality of business activities	C.7.1	Number of high income months	Intrinsic	Field	Input
		C.7.2	High / low monthly income ratio	Intrinsic	Field	Input

C.8	Seasonality of resident population	C.8.1	Average number of months living in the village in a year	Intrinsic	Field	Input
C.9	Food security	C.9.1	Food Insecurity Experience Scale (FIES)	Intrinsic	Desk	Input
C.10	Access to finance institutions	C.10.1	% of HHs with account in a finance institutions	Intrinsic	Field	Input
C.11	Expenditure on electricity substitutes	C.11.1	HHs average monthly expenditure for electricity substitutes	Intrinsic	Desk	Input
		C.11.2	Small Business average monthly expenditure for electricity substitutes	Intrinsic	Desk	Input
		C.11.3	Anchor load average monthly expenditure for electricity substitutes	Intrinsic	Desk	Input
D.	**HABITAT ASPECTS**					
D.1	Climatic conditions	D.1.1	Climatic zone	Intrinsic	Desk	Input
		D.1.2	Number of extreme events in the last 10 years	Intrinsic	Desk	Input
D.2	Location	D.2.1	Country	Intrinsic	Desk	Input
		D.2.2	Proximity to key location (km)	Intrinsic	Field	Input
D.3	Settlement	D.3.1	Settlement type	Intrinsic	Desk	Input
		D.3.2	Most common type of latrine	Intrinsic	Field	Input
		D.3.3	Most common type of roof	Intrinsic	Field	Input
		D.3.4	% of buinding with glass windows	Intrinsic	Field	Input
E.	**OWNERSHIP AND OPERATION FEATURES**					
E.1	Ownership type	E.1.1	Ownership type	Extrinsic	Desk	Assumption
E.2	Operating method	E.2.1	Operating method	Extrinsic	Desk	Assumption
E.3	Electricity tariff	E.3.1	Tariff structure	Extrinsic	Desk	Assumption
		E.3.2	Tariff price	Extrinsic	Desk	Assumption
E.4	Services provided	E.4.1	Class of services provided beyond the electricity supply	Extrinsic	Desk	Assumption
E.5	Complementary activities	E.5.1	Level of the complementary activity programme in the start-up phase	Extrinsic	Desk	Assumption
E.6	Marketing campaign	E.6.1	Marketing campaign in the start-up phase	Extrinsic	Desk	Assumption
E.7	DSM strategies	E.7.1	Efficient appliances and lights	Extrinsic	Desk	Assumption
		E.7.2	Commercial load scheduling	Extrinsic	Desk	Assumption
		E.7.3	Restricting residential use	Extrinsic	Desk	Assumption
		E.7.4	Price incentives	Extrinsic	Desk	Assumption

		E.7.5	Community involvement, consumer education, and village committees	Extrinsic	Desk	Assumption
E.8	Productive use of electricity (PUE)	E.8.1	Level of PUE compatibility & integration	Extrinsic	Desk	Assumption

Table 31 - Framework of indicators for characterization of the community's energy needs

6.6 Discussion

The rationale behind the selection of indicators is to identify all the aspects that not only characterize a community in the socio-economic and environmental terms but also directly or indirectly affect the energy needs of a target community in a greenfield project.

In this discussion it should bear in mind that, as declared in the research objective, this framework tool is formulated on the assumption that it is expected to provide the user with outputs to design a mini-grid project which is economically sustainable, without taking into consideration external sources of finance, going beyond the scope of this work and being actually simulated to adjust the load profiles given by ENA in the real application.

On this premise, the main evidence, which leverages results from previous works of our research group [103] [168], is that the proposed framework includes indicators related to the mini-grid business model. It means that the community's energy needs and the related load profile and WTP are strongly dependent from extrinsic factors pertaining to the project strategy and not the community itself.

Despite the correlation analysis in [168] revealed some interdependency between financial features and PUE, electricity tariff and expenditures as well as business model applied, there are no indicator related to the set/expected financial performance of the mini-grid project since, at this stage of the work, ongoing cross-checks revealed that such effects are absorbed by the indicators on electricity tariff. It is supposed that the electricity tariff increases/decreases with the variation of the correlated indicators. For instance, the higher is the electricity tariff the lower is the penetration rate at year 0 and the penetration rate trend over the time, thus the load profile characterizing the community will change accordingly. The specific cause-effect correlation with each correlated indicator is described in the framework and it represents a first step toward a related algorithm, as for all the other indicators with identified correlations.

Another relevant matter is that the framework is designed to leverage evidences and lessons learnt from operating projects for the benefit of upcoming projects and to predict effects of extrinsic factors or habit aspects into the mini-grid operation. An example about prediction of business model-related effect is the following: the correlation analysis revealed that the lowest household electricity tariffs are applied in projects with community ownership, followed by projects with public, hybrid and private ownership, in this order. It means that, in the project's early stage or in micro-small projects not foreseeing to carry out an in-depth ENA (as mentioned in the research objective), in case of private ownership it is reasonable to set the electricity tariff on the upper level to secure the economic sustainability and thus, the penetration rate and the load profile characterizing the community will change accordingly. Another example, still remaining on the ownership model, it is correlated to the level of PUE compatibility & integration and services provided: projects having "full compatibility with integration of PUE in the business"(see section 3.4.6), in the majority of cases are owned by community entities. It means that, in the project's early stage or in micro-small projects not foreseeing to carry out an in-depth ENA, in case of private ownership it is risky to a full compatibility with integration of PUE in the business to assume set the electricity tariff on the upper level to secure the economic sustainability and thus, the penetration rate and the load profile characterizing the community will change accordingly.

In conclusion, this framework is intended as a first hypothesis toward the development of a tool to be adopted by both academics and practitioners in understanding and fostering the large-scale development of off-grid systems. Therefore, besides the data availability limitations for some indicators and the inevitable biases implicit in a proxy assessment, as it is stated in the research objective, the proposed framework required to be tested and validated in the real environment. However, bearing in mind that this framework tool is design for "greenfield" rural electrification projects, it should be underlined that the lack of comprehensive baseline, including socio-economic data, in the majority of mini-grid projects hampered a rapid validation of this framework tool: if comprehensive baselines would have been available, the tool could have been tested by comparing its outputs with real data of operating mini-grids. See Next Steps in section 7.2 for the identified pathway toward a tool's validation.

7

Conclusions

7.1 Summary and conclusions

Mini-grids are considered one of the technical solutions to seize the gap of universal access to energy. With 220 billion dollars estimated to be invested in mini-grids to reach universal access by 2030, such effort would require a strong involvement of private developers and suppliers, in combination with public funding programs [8].

Involving private capital to reach a wider impact of the international action requires to demonstrate the viability of mini-grid business models and their long-term technical and financial sustainability.

The main obstacles are usually identified in the financial, technological and institutional areas, accounting for high initial costs and difficulty in access to finance due to the perceived high-risks of investments, low and unpredictable demand patterns, reduced ability to pay and low tariffs and weak policies, among others [9]. To address these challenges, there is a need of (i) data-driven study on business models for decentralized RE solutions to identify success factors and viable approaches to pursue the viability and replicability of rural electrification projects as well as of (ii) effective methodologies in both the development and operating phases to optimize systems, de-risk investments and assure long-term sustainability.

This doctoral thesis aimed at supporting the off-grid energy sector to deploy viable and scalable renewable energy (RE) systems through methodologies and models for the mini-grid optimization in developing countries.

On the basis of a preliminary work for an in-depth understanding of the context, the core of the research project is focused on (i) a critical assessment of the techno-economic aspects of RE mini-grids and (ii) identification of innovative methodologies and business models for the system optimization and the deployment of RE mini-grids at scale.

The research methodology was structured around (i) field experience in case studies, both in the feasibility studies and executions, and (ii) desk research working on literature overview, stakeholder consultation as well as data collection and analysis of mini-grids in operation. Thus, this research project actually benefits of direct experience in the practitioners' environment and bring it into the academic environment to leverage lesson learnt, food for thought and data by using a scientific approach.

- Understanding of the rural electrification challenge for the system optimization and the deployment of RE mini-grids at scale

The first phase of the research project was focused on **understanding of the rural electrification challenge** for the system optimization and the deployment of RE mini-grids at scale in order to identify aspects which actually affect the adoption of the mini-grid solution. A comprehensive desk research was conducted on the off-grid market and the best solutions for electrification in developing country, with a focus SSA. It revealed that, in terms of the least-cost solution that provides the prescribed tier of supply, there are three options to be considered: grid extension, stand-alone individual solutions and mini-grid systems. The latter have been left behind, even if they can offer a collective solution at a relatively lower cost and they tend to facilitate basic needs as well as PUE thereby promoting local economic development. This is probably because the mini-grid has to face a number of challenges making the business environment risky, such as unknown consumer characteristics and unfamiliar business activities, non-supportive regulatory and policy frameworks, limited access to low cost finance and inadequacies in local skills and capacities. Beyond these aspects, opportunities arising from the productive use of electricity (PUE) and the water-energy-food (WEF) nexus approach were explored within a broader framework of socio-economic development and project sustainability.

This desk research was carried out within the framework of Field Studies for Micro Grid Optimization (FS4MGO) in collaboration with RES4Africa Foundation, with specific reference to the study of mini-grid business models and the WEF nexus approach. Within a broader study including 21 projects, a case study in Tanzania was in-depth analysed by OpenEconomics. In such work, I dealt with providing investment cost, operating and economic costs, and the project's scalability setup.

The **impact assessment of the Tanzanian case study** analyses the structure of a WEF integrated model, based on the idea of transformative change through simultaneous access to general purpose (energy and water) and specific (modern agricultural techniques) technology. The results of the study are helpful to suggest transformative patterns of project design and a broader approach based on regional planning. Specifically, the analysis addresses the transformative impact that could be generated from locally based, but potentially transformative projects through the combination of three specific factors:

- an enabling component based on ensuring access to sustainable energy and water through general purpose technologies,
- an adoption component based on productivity enhancing techniques of agriculture and food production, and

- a transformative component based on the replication, scaling up and diffusion of proposed solutions over a wider region.

However, our evaluation suggests that the success of the project depends on:

- the interdependence built in the project structure,
- the complementarity of water, energy and food components, and
- the mechanisms of adoption and diffusion that would support the replication and the scaling up of the initial, local based project.

As the cost benefit analysis (CBA) reveals, even if the individual project is justified by significant benefits to the population and production sectors directly affected, its huge impact is achieved in the scaleup context, where investing in replicating the project model engenders a chain of diffusion of both general purpose and specific technologies and enhance cascading benefits in terms of value added, production and income distribution, allowing, at the same time, to yield significant contributions to SDGs.

On these premises, the second phase of the research project was focused on the development of specific analysis, methods and methodologies.

- Aggregate and correlation analysis of business model indicators (R1)

Leveraging the business model study carried out in the first phase, an **aggregate and correlation analysis of business model indicators based on 21 RE mini-grids (R1)** was developed. This work aims to critically analyze in retrospective manner what is the state of the art of the mini-grid sector in SSA so far, starting from older projects commissioned in the mid-eighties (the Tanzanian project mentioned above) up to recent develop of new projects.

To pursue this objective, the study was approached from a business model perspective. A set of 48 indicators has been identified to characterize firstly at an aggregate level the 21 mini-grid sample available, and then to search for emerging patterns and possible correlations among the indicators themselves, revealing 66 strong correlations, 85 moderate correlations and 185 weak correlations among the 1,152 potential correlations.

Indicators and results were organized around "burning issues" in the mini-grid sector: (1) Context data, (2) Power generation systems, (3) Business model and PUE, (4) Financial features, (5) Electricity market dimensions and (6) Electricity tariff and expenditures.

Among the most interesting data, the aggregate analysis reveals that:

- Even if the majority of case studies include a diesel component (57%), the share of RE in the energy generation mix is quite high with an average value of 86%.

- In terms of operating method, 43% of cases are operated through a build-own-outsource, 33% of cases are operated through a build-own-operate, and 24% of cases are operated through a build-short operate-transfer.

- On the electricity market dimensions: the average target market is composed of 3,589 households; the total market penetration rate is 24% on average at the 1st year of operation and it rapidly increases up to the 5th year, reaching 44% on average.

- The household yearly consumptions at the 1st year of operation fall in Tier 2, and almost all the project remain in the same Tier in the last year of operation as well; in terms of energy, the average value at the 1st year of operation is 174 kWh/year, and increasing lower than 20% is recorded at the last year of operation, with an average value of 204 kWh/year.

- The business average yearly consumptions at the 1st year of operation are 658 kWh/year, and a slight decreasing lower than 3% is recorded at the last year of operation, with an average value of 639 kWh/year.

- On the expenditure for electricity: the household's expenditure is 96.9 Euro/year on average and the business's expenditure is notably higher with a value of 273.2 Euro/year on average.

- On the electricity tariffs, the average electricity tariff for households is 0.8 Euro/kWh, and the average electricity tariff for businesses is 0.5 Euro/kWh.

Please note that average values provided above should be red together with quartiles' values which reveals notable differences.

Regarding the correlation analysis, beyond several evidences that actually confirm expected results and previous publications, some highlights are particularly interesting about the diesel component, projects operating in steady loss, tariffs applied, project ownership and services provided beyond the sole electricity supply as well as financial performance.

Results show that project design did not take into account the financial sustainability in the large majority of case studies, probably because they were almost fully funded either from grants or public funds (all the projects with public ownership, except one, operate in steady loss). On one hand, it reveals that the approach was not oriented to finance sustainable mini-grid in the past and business-oriented initiatives still required to be demonstrated and monitored over the operating life. On the other hand, projects applying an integrated approach beyond the sole electricity supply (33% of total case studies), through a business model providing other energy-related products/services or WEF nexus-related services beyond the sole electricity supply, showed encouraging financial performance being almost all included in the top-11 IRR ranking.

Furthermore, there are not relevant correlations between the share of energy from RE and OPEX or even between the amount of storage and diesel component installed. Such results show that engineering design is not actually driven by a system optimization approach in the most of case studies but by other financial or operating issues instead.

In conclusion, this work paved the ground for the characterization of the community's energy needs, since it compares and assesses mini-grid projects by means of descriptive and performance indicators.

- Innovative business models for RE mini-grid projects (R2)

The comprehensive techno-economic analysis carried out was integrated with analysis of political and regulatory frameworks as well as access to financing mechanisms in order to allow for the **identification of innovative business models for RE mini-grid projects (R2)**. In order to seize opportunity of investing in rural electrification sector, it is necessary to analyse mature business models as well as explore emerging ones. The study has highlighted how integrated projects, if properly designed, can contribute both to business viability and local development which, in turn, further support the sustainability of the project, in a sort of virtuous cycle.

On the basis of the analysis of case studies' results, the most promising models have emerged by using a multi-layer approach has taken into account the following key features: (i) services provided, (ii) operating methods, (iii) ownership, (iv) ways to apply a WEF nexus in the project, (v) community categorization in terms of local economy, type of PUE and ability to pay, (vi) type of mini-grid operator(s), (vii) the required regulatory framework and (viii) the correlation between investment size-profitability-impact.

It is important to underline that such 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 (BMs) have been selected with a view to provide viable options:

1. BM1 "Electricity supply & appliances provision": a private operator owns and operate small RE power units providing DC electricity and small appliances to customer clusters.
2. BM2 "Electricity supply & agri-food production": an 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.
3. BM3 "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 appliances and retail.
4. BM4 "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 Italian National Research Council (CNR), in partnership with RES4Africa among others, has submitted the proposal "WE4I: water-energy-food based business for green mini-grids" designed around the BM4 to the Horizon 2020 Green Deal Call LC-GD-2-3-2020-Accelerating the green transition and energy access partnership with Africa [198].

Together with the identification of the most promising business models, an action roadmap to sustain the development of mini-grids was outlined.

The analysis of technical, regulatory and financial challenges and opportunities highlighted that a broader perspective including different actors and sectors in an integrated manner is able to pursue *business for impact*. Thus, governments, private sector actors, international financing institutions and development agencies are called to collaborate to: (i) ensure clear and effective policies and regulations, (ii) provide access to the right finance, and (iii) prove business models. The in-depth analysis of these three dimensions reveals that the current vision is partial, or at least too sectorial.

A comprehensive overview of highlights and recommendations for enabling the environment is provided in section 4.2 around the following five topics.

The key **takeaways on (1) technical and technological issues** put the spotlights on:

- adequate ENA and a multi-year planning of the mini-grid;
- relevance of DSM and remote management systems;
- hybrid diesel-RE systems to reduce investment costs and address the intermittency of some types of RE (however diesel generator should only provide a minor contribution in the energy generation mix);
- WEF infrastructures, which should be co-located and adopt well-proven technologies, to be integrated in the DSM.

The key **takeaways on (2) integration of PUE and WEF nexus** put the spotlights on:

- innovative partnerships between agri-food players and energy players;
- PUE and other WEF-related services as source of additional revenue streams for the energy operator;
- integration of the water component in a wider WEF programmes (water alone is a "risky" sector while produces huge indirect benefits)
- SROI as a systematic approach to monetize social, environmental and economic impacts when evaluating investments in the decentralised RE sector.

The key **takeaways on (3) environmental and socio-economic impact** put the spotlights on:

- Awareness on impact, trade-offs and synergies between WEF components;
- linking energy supply to the enhancement of local livelihoods as key for both financial and local development;
- relevance of complementary activities (business incubation programmes, awareness campaigns, capacity building, microcredit support, knowledge management

programmes) to enhances the project sustainability (engaging local communities, promoting community inclusion and ownership as well as supporting the electricity demand pattern);

- Gender considerations should permeate decisions throughout the project cycle;
- ESIA as essential tool to secure both local permits and project bankability.

The key **takeaways on (4) policies and regulations** put the spotlights on:

- Addressing the major challenge for governments: to strike a balance between ensuring affordable and equitable access to energy to rural people, and ensuring profitability and low risk investments;
- Adoption of integrated electrification plan for all the supply modes (grid extension, mini-grid and individual systems), a sound regulatory framework, and an effective institutional organization chart to avoid overlapping of responsibilities between government agencies;
- enabling regulatory framework to accelerate rural electrification and private sector investments to (i) facilitate the projects' bankability, (ii) ensure a comprehensive and stable framework with a segmented approach (size and type of energy source and supply modes), (iii) consider the impact of both the iron law and the viability gap in the allocation of funding and (iv) offer fair electricity price to the most impoverished population in isolated off-grid rural areas through cross-subsidized tariffs.
- Smooth the process for obtaining licences and authorizations and provide clear, transparent and operative regulations.
- Address the "risk" of grid expansion for mini-grid developers by means of (i) accurate, available and updated master energy plans, and (ii) foresee compensation or interconnection mechanisms in case the grid arrives earlier than planned.

The key **takeaways on (5) access to finance** put the spotlights on:

- There is no one-size-fits all financial mechanism for mini-grid development;
- lack of suitable financing options from the national commercial banking system, and high transaction costs for project finance, thus public finance support in the form of grants or subsidies is needed;
- Grants should be combined with mechanisms to leverage commercial financing and to buy down the risk with first loss guarantees and, in any case, be limited in order to avoid later energy market distortions, and thus only be applied in pilot projects and early stage market phases;
- Not limiting the business plan to energy supply, but rather including PUE and in particular food production, has proven to significantly improve the financial viability of mini-grid in rural areas.
- Provision of energy appliances, for instance through a leasing mechanism, promotes energy consumption and therefore positively affects both the cash flows for the mini-grid operator and local productive activities;

- electricity tariff should be tailored to the purchasing power of the energy user, but public finance (e.g. feed-in-tariff) should be needed to make up for the financial shortfall and enable the project viability.

- Methodology for the energy need assessment (R3)

With the aim to support the viability gap of mini-grid business models by de-risking investments, increasing the project sustainability as well as addressing the need to clearly define, test and validate procedures to be applied at scale in order to provide reliable inputs for the system design, a **methodology for the energy need assessment (R3)** was developed. It was conceived to effectively design and deploy mini-grids for rural electrification for high reliable in-depth baselines in greenfield projects, which includes data collection methods, data analysis model, estimation of the WTP for electricity and load profiling (current and forecast). This work paved the ground for the characterization of the community's energy needs.

Hence, the proposed methodology can be used and adapted case-by-case in order to provide an effective applied solution to general recommendations and information from existing micro-grid literature and the lack of proven guidelines for project developers with a view to boost toward a common overall objective of mini-grid's optimization methods and tools. In order to address the requirements of mini-grid sector, the proposed 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.

The evidence of the methodology's reliability is given by comparing a key output of the ENA with the actual value adopted in case study used for the validation: 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 consumption and expenditures and the assessment of current and potential anchor loads (the assessment returns a flat tariff of 2,940 RWF/month to reach the higher penetration rate of potential market and the actual flat tariff negotiated between the mini-grid developer, local communities and authorities was about the same, 3,000 RWF/month).

Considering that the ENA is particularly important from both business perspective, allowing to reduce the investment risk, and technical perspective, allowing to develop reliable load profiling and optimize the energy management systems, the accuracy of inputs used as well as assumptions selected directly affect the technical and financial feasibility studies. Results of the ENA represent such inputs and provide most of the assumptions used in business modelling and mini-grid design. Thus, this study is aimed at contributing to bridging the gap between the development of modelling tools and the field challenges with a focus on uncertainties of remote communities.

The methodology comes from an extensive testing phase I have been dealing with since 2012 and it was applied and improved time and time again along 7 data collection campaigns carried out in 36 villages in Honduras, Uganda and Kenya in the period before this research project (2012-2017). It was finally validated during this research and applied in further 4 data collection campaigns in 24 villages in Rwanda, Mozambique and Democratic Republic of Congo.

- Framework for characterization of the community's energy needs (R4)

This final part of the research project was developed on the basis of results arising along the entire research process and in particular from those given by the development of the methodology for the ENA (R3) and the aggregate and correlation analysis of business model indicators (R1).

With the aim to give a proxy of in-depth baselines to provide the preliminary phase of business development (and/or small size projects not requiring in-depth baselines) with reliable inputs for business planning and systems design, a **framework for characterization of the community's energy needs in greenfield rural electrification project (R4)** was developed.

This work aims to overcome the limitations inherent to case-specific studies and to scope far-reaching findings that can unlock the scaling-up of mini-grid initiatives by means of a framework for characterization of the community's energy needs in greenfield rural electrification project. It is intended as a first hypothesis of a framework tool, which is designed to provide a proxy of an in-depth ENA by considering technical, environmental, socio-economic and business model-related parameters in an integrated manner.

Thus, the framework tool is conceived to be adopted in two fields of application. The primary one is to support the preliminary phase of mini-grid business development and/or small size projects not requiring an in-depth baseline in order to provide reliable inputs for sustainable business planning and systems design and, specifically, the WTP for electricity as well as the shape and amplitude of load profiling (current and forecast). The secondary one is optimizing the rural electrification planning tools to establish more evidence-grounded criteria for extrapolating proxy information.

The proposed framework is structured to clearly provide with the key information to understand how it should work, how it should be applied and how it is supported by the research process in its formulation. It is composed of 68 indicators, which are clustered in 5 thematic sectors (A. Electricity Market Dimensions, B. Technical Aspects, C. Socio-Economic Aspects, D. Habitat Aspects, E. Ownership and Operation Features) and are detailed with as set of information (nature of data, means of data acquisition, type of data, derivations and correlations with other indicators, multiple choices and type of references).

The main evidences to be underlined are that (i) the proposed framework includes indicators related to the mini-grid business model, supposing that extrinsic factors pertaining to the project strategy, and not the community itself, notably affects the community's load profiling and WTP; and that (ii) the framework, by leveraging evidences and lessons learnt from operating projects, predicts effects of extrinsic factors or habit aspects into the mini-grid operation.

In conclusion, this doctoral thesis resulted from the adoption of an original cross-cutting approach throughout the multi-dimensional nature of access to energy. It started from the practitioners' point of view to bring the scientific research beyond the state of the art and provide results to sustain the mini-grid deployment at scale in developing countries.

7.2 Next steps

The research outputs lay the foundation for next studies and for improvement of methodologies, methods and tools already developed to increase their effectiveness and reliability.

Specifically, **the methodology for the ENA (R3) could be improved** by observing the field application of the validated version over the time as well as by comparing the results of the assessments with the evolution of load curves over the operational phase electrification projects. The purpose is to understand which factors affect the households' connection trend (in other word, the market penetration rate) and their electricity consumption over the operational phase of a rural electrification project. Then, the accuracy of forecast load curves will be evaluated on the basis of actual monitoring data collected and examined in order to optimize the prediction calculation process. Furthermore, the methodology, which is conceived for greenfield projects, could be adapted to brownfield projects in order to optimize operational mini-grids, upgrade the electricity tariff plan and/or explore room for improvement of services. Such application requires a general review of tools and methods as well as testing and validation phases in operational environment, which are currently in progress.

Secondly, an **advanced correlation analysis of techno-economic indicators, selected among the strong correlations given in R1**, could be applied to a selection of case studies. An analytical process should be carried out to study selected variables (and their correlations), which directly or indirectly affect the mini-grid business models (e.g. DSM, electricity tariff, energy storage capacity, IRR). It would aim to study correlations between technical, socio-economic and financial indicators, including a sensitise analysis as well, to both optimize systems' engineering and inform practitioners with relevant evidences for the mini-grid business development.

Thirdly, innovative **business models identified for RE mini-grid projects (R2) should be piloted in real environment** and/or similar projects in operation should be observed and investigated. Hopefully, the Horizon2020 project based on the BM4-WEF multi-service supply (evaluated over the eligible threshold but not funded) could see the light.

Lastly, **the framework of indicators for characterization of the community's energy needs in greenfield rural electrification projects (R4) should become a tool**. In particular, the algorithms governing derivations and correlations between indicators should be developed and integrated in an adequate programming platform. About its testing phase, besides the data availability limitations for some indicators and the inevitable biases implicit in a proxy assessment, the proposed framework required to be tested and validated in the real environment. However, bearing in mind that this framework tool is design for greenfield rural electrification projects, the lack of comprehensive baseline, including socio-economic data, in the majority of mini-grid projects hampered a rapid validation of this framework tool. Thus, an extensive work of data gathering among mini-grid with an available comprehensive baseline and/or tests on greenfield project to be observed over the time is required for the validation. In brief, a pathway to finalize such tool should go through (i) development of algorithms between indicators, (ii) selection of at least three operating projects with available baseline and operating data to simulate an assessment at greenfield stage and verify results at brownfield stage, (iii) upgrade the tool according to such preliminary testing phase, (iv) repeat the test on an adequate quantity of projects (to be defined) with the same requirements or on greenfield projects to be observed over the time, (v) upgrade the tool according to such final testing phase and validation it.

A1

Annex 1: Results of the aggregate analysis

Code	Indicator	Main Results			Additional Results		
		Descriptor	Quantity	%	Descriptor	Quantity	%
1	Country	Kenya	4	19%			
		Tanzania	7	33%			
		Zambia	2	10%			
		Cape Verde	1	5%			
		Ghana	5	24%			
		South Africa	2	10%			
		Not Available	0	0%			
		Quantity of cases	21				
2	Location type	rural	19	90%			
		peri-urban	2	10%			
		Not Available	0	0%			
		Quantity of cases	21				
3	System type	off-grid	20	95%			
		grid connected (only for sale of excess generation)	1	5%			
		Not Available	0	0%			
		Quantity of cases	21				
4	Start date	Arithmetic Mean	2012	-	Start date before 2011	4	19%
		1° Quart.	2011	-	Start date from 2011 to 2015	6	29%
		2° Quart.	2016	-	Start date from 2016	11	52%
		3° Quart.	2016	-			
		Minimum	1987	-			
		Maximum	2018	-			
		Not Available	0	-			
		Quantity of cases	21				
5	Current status	Operational	21	100%			
		Not Available	0	0%			
		Quantity of cases	21				
6	Actual years of operation (up to 2019)	Arithmetic Mean	8	-			
		1° Quart.	4	-			
		2° Quart.	4	-			
		3° Quart.	9	-			
		Minimum	2	-			
		Maximum	33	-			
		Not Available	0	-			
		Quantity of cases	21				
7	Climatic zone	A: equatorial	12	57%	Af: fully umid	2	10%
		B: arid	3	14%	As: summer dry	1	5%
		C: warm temperate	6	29%	Aw: winter dry	9	43%
		Not Available	0	0%	BSh: steppe - hot arid	2	10%
					Bwh: winter dry - hot arid	1	5%
					Cwa: winter dry - hot summer	2	10%
					Cwc: winter dry - cool summer	4	19%
					Not Available	0	0%
		Quantity of cases	21				

Code	Indicator	Main Results			Additional Results		
		Descriptor	Quantity	%	Descriptor	Quantity	%
8	Settlement type	Scattered	5	24%			
		Moderate	11	52%			
		Intensive	5	24%			
		Not Available	0	0%			
		Quantity of cases	21				
9	Solar PV power installed (kWp)	Arithmetic Mean	42	-			
		1° Quart.	5	-			
		2° Quart.	30	-			
		3° Quart.	48	-			
		Minimum	5	-			
		Maximum	89	-			
		Quantity of cases	16	-			
		Not Available	0	-			
10	Wind power installed (kW)	Arithmetic Mean	275	-			
		1° Quart.	0	-			
		2° Quart.	0	-			
		3° Quart.	0	-			
		Minimum	60	-			
		Maximum	490	-			
		Quantity of cases	2	-			
		Not Available	0	-			
11	Hydro power installed (kW)	Arithmetic Mean	275	-			
		1° Quart.	0	-			
		2° Quart.	0	-			
		3° Quart.	0	-			
		Minimum	120	-			
		Maximum	430	-			
		Quantity of cases	4	-			
		Not Available	0	-			
12	Diesel generation installed (kW)	Arithmetic Mean	314	-			
		1° Quart.	0	-			
		2° Quart.	16	-			
		3° Quart.	26	-			
		Minimum	10	-			
		Maximum	2440	-			
		Quantity of cases	12	-			
		Not Available	0	-			
13	Storage capacity (kWh)	Arithmetic Mean	278	-			
		1° Quart.	0	-			
		2° Quart.	154	-			
		3° Quart.	340	-			
		Minimum	134	-			
		Maximum	537,6	-			
		Quantity of cases	14	-			
		Not Available	0	-			
14	Yearly Energy Produced [kWh]	Arithmetic Mean	590.373	-			
		1° Quart.	35.025	-			
		2° Quart.	70.64	-			
		3° Quart.	557.136	-			
		Minimum	8.756	-			
		Maximum	4.704.848	-			
		Quantity of cases	21	-			
		Not Available	0	-			
15	Share of energy from RE	Arithmetic Mean	86%	-			
		1° Quart.	99%	-			
		2° Quart.	99%	-			
		3° Quart.	100%	-			
		Minimum	3%	-			

Code	Indicator	Main Results			Additional Results		
		Descriptor	Quantity	%	Descriptor	Quantity	%
		Maximum	100%	-			
		Quantity of cases	21	-			
		Not Available	0	-			
16	Services provided	Electricity supply	14	67%			
		Electricity supply & other WEF nexus-related services	4	19%			
		Electricity supply & other energy-related products/services	3	14%			
		Not Available	0	0%			
		Quantity of cases	21				
17	Type of PUE service	Type I: Restricted compatibility with PUE	4	19%			
		Type II: Full compatibility with PUE	13	62%			
		Type III. Full compatibility with integration of PUE in the business	4	19%			
		Not Available	0	0%			
		Quantity of cases	21				
18	Low Quality of service	Yes (low quality)	5	24%			
		No	9	43%			
		Not Available	7	33%			
		Quantity of cases	14				
19	Marketing campaign	Yes	6	29%			
		No	15	71%			
		Not Available	0	0%			
		Quantity of cases	21				
20	IRR	Arithmetic Mean	-45%	-			
		1° Quart.	-100%	-			
		2° Quart.	-24%	-			
		3° Quart.	-2%	-			
		Minimum	-100,0%	-			
		Maximum	29%	-			
		Quantity of cases	21	-			
		Not Available	0				
21	Ownership	Private	6	28%			
		Public	9	43%			
		Hybrid (PPP)	2	10%			
		Community	4	19%			
		Not Available	0	0%			
		Quantity of cases	21				
22	Developer's assumption for the financial plan	For profit	6	29%			
		to cover O&M costs only	15	71%			
		Not Available	0	0%			
		Quantity of cases	21				
23	Mini-grid in steady loss	Yes (loss)	9	43%			
		No	12	57%			
		Not Available	0	0%			
		Quantity of cases	21				
24	Payment systems	PAY-AS-YOU-GO	10	48%			
		PAY-AS-YOU-GO (prepaid token)	1	5%			
		monthly payment	9	43%			
		DAILY-WEEKLY-MONTHLY payment	1	5%			
		Not Available	0	0%			
		Quantity of cases	21				
25	Operational	Local Main. &Management	11	52%			

Code	Indicator	Main Results			Additional Results		
		Descriptor	Quantity	%	Descriptor	Quantity	%
	structure	Local Main. + Remote Management	10	48%			
		Not Available	0	0%			
		Quantity of cases	21				
26	Complementary activities	Yes	17	81%			
		No	4	19%			
		Not Available	0	0%			
		Quantity of cases	21				
27	Share of revenues from Other Services than electricity	Arithmetic Mean	7%	-			
		1° Quart.	0%	-			
		2° Quart.	0%	-			
		3° Quart.	1%	-			
		Minimum	1%	-			
		Maximum	73%	-			
		Quantity of cases	21	-			
		Not Available	0	-			
28	Operating Method for Electricity Supply	A. Build, own, operate	7	33%			
		B. Build, own, outsource	9	43%			
		C. Build, own, lease	0	0%			
		D. Build, sell	0	0%			
		E. Build, short-operate, transfer	5	24%			
		F. Build, own, operate, transfer	0	0%			
		Not Available	0	0%			
29	Business Model Classification	A.1	3	14%	Operating Method for Other Services than Electricity		
		A.7	4	19%	1. Build, own, operate	3	14%
		B.7	9	43%	2. Build, own, outsource	0	
		E.5	4	19%	3. Build, own, lease	0	
		E.7	1	5%	4. Build, sell	0	
					5. Build, short-operate, transfer	4	19%
					6. Build, own, operate, transfer	0	
					7. None	14	67%
30	Market size - total HHs	Arithmetic Mean	3.589				
		1° Quart.	515				
		2° Quart.	2.655				
		3° Quart.	3.931				
		Minimum	82				
		Maximum	20				
		Quantity of cases	15				
		Not Available	6				

Code	Indicator	Descriptor	Year									
			1	2	3	4	5	6	7	8	9	10
31	Market Penetration rate - TOTAL	Arithmetic mean	25%	32%	38%	42%	44%	45%	45%	45%	45%	45%
		1° Quart.	4%	6%	7%	7%	8%	9%	9%	10%	10%	10%
		2° Quart.	14%	34%	42%	48%	51%	52%	53%	54%	55%	54%
		3° Quart.	30%	51%	54%	63%	65%	68%	67%	68%	68%	68%
		Minimum	0.1%	0.2%	0.3%	0.3%	0.3%	0.3%	0.4%	0.4%	0.4%	0.4%
		Maximum	85%	83%	100%	99%	99%	98%	98%	97%	97%	97%
		Quantity of cases with available data	14	14	14	14	14	14	14	14	14	14
32	Connection rate trend -	Arithmetic mean	-	38%	24%	11%	15%	3%	1%	2%	1%	2%
		1° Quart.	-	8%	23%	0%	1%	0%	0%	0%	0%	0%

Code	Indicator	Main Results Descriptor	Quantity			%	Additional Results Descriptor		Quantity	%		
	Households	2° Quart.	-	41%	27%	0%	5%	0%	1%	0%	1%	1%
		3° Quart.	-	65%	40%	11%	13%	2%	1%	1%	1%	1%
		Minimum	-	-22.2%	-28.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
		Maximum	-	98%	53%	50%	64%	16%	2%	13%	2%	7%
		Quantity of cases with available data	-	6	6	6	6	6	6	6	6	6
33	Connection rate trend - Others (Businesses, Public services)	Arithmetic mean	-	43%	22%	8%	5%	4%	0%	5%	1%	-2%
		1° Quart.	-	0%	5%	0%	0%	0%	0%	0%	0%	0%
		2° Quart.	-	24%	23%	0%	0%	0%	0%	0%	0%	0%
		3° Quart.	-	87%	32%	0%	11%	2%	0%	1%	1%	1%
		Minimum	-	0.0%	0.0%	0.0%	-7.1%	0.0%	0.0%	0.0%	0.0%	-18.6%
		Maximum	-	109%	52%	49%	20%	23%	2%	31%	2%	4%
		Quantity of cases with available data	-	6	6	6	6	6	6	6	6	6

Code	Indicator	Main Results Descriptor	Quantity	%	Additional Results Descriptor	Quantity	%
34	Share of HH consuptions - First Year	Arithmetic Mean	71%				
		1° Quart.	73%				
		2° Quart.	80%				
		3° Quart.	85%				
		Minimum	18,2%				
		Maximum	100%				
		Quantity of cases	13				
		Not Available	8				
35	Share of HH consumptions - Last Year	Arithmetic Mean	78%				
		1° Quart.	78%				
		2° Quart.	82%				
		3° Quart.	85%				
		Minimum	29,1%				
		Maximum	100%				
		Quantity of cases	13				
		Not Available	8				
36	HH yearly consumptions - First Year [kWh]				Tier - First Year		
		Arithmetic Mean	174			2	
		1° Quart.	114			2	
		2° Quart.	169			2	
		3° Quart.	233			2	
		Minimum	48			1	
		Maximum	333			2	
		Quantity of cases	13			13	
		Not Available	8			8	
37	HH yearly consumptions - Last Year [kWh]				Tier - Last Year		
		Arithmetic Mean	204			2	
		1° Quart.	158			2	
		2° Quart.	182			2	
		3° Quart.	244			2	
		Minimum	48			1	
		Maximum	435			3	
		Quantity of cases	13			13	
		Not Available	8			8	
38	BUS yearly consumptions - First Year [kWh]	Arithmetic Mean	658				
		1° Quart.	414				
		2° Quart.	466				
		3° Quart.	662				
		Minimum	402				
		Maximum	2033				
		Quantity of cases	11				

Code	Indicator	Main Results			Additional Results		
		Descriptor	Quantity	%	Descriptor	Quantity	%
		Not Available	10				
39	BUS yearly consumptions - Last Year [kWh]	Arithmetic Mean	639				
		1° Quart.	406				
		2° Quart.	466				
		3° Quart.	548				
		Minimum	360				
		Maximum	2387				
		Quantity of cases	11				
		Not Available	10				
40	Yearly Energy Produced/ HH [kWh]	Arithmetic Mean	386				
		1° Quart.	235				
		2° Quart.	361				
		3° Quart.	524				
		Minimum	75				
		Maximum	683				
		Quantity of cases	13				
		Not Available	8				
41	OPEX per unit [EURO/kWh/year]	Arithmetic Mean	0,361				
		1° Quart.	0,110				
		2° Quart.	0,315				
		3° Quart.	0,410				
		Minimum	0,013				
		Maximum	2,610				
		Quantity of cases	21				
		Not Available	0				
42	HHs expenditure for electricity [EURO/year]	Arithmetic Mean	96,9				
		1° Quart.	45,2				
		2° Quart.	75,9				
		3° Quart.	150,0				
		Minimum	17,7				
		Maximum	172,1				
		Quantity of cases	13				
		Not Available	8				
43	HH average tariff [EURO/kWh]	Arithmetic Mean	0,8				
		1° Quart.	0,3				
		2° Quart.	0,3				
		3° Quart.	1,1				
		Minimum	0,1				
		Maximum	3,1				
		Quantity of cases	13				
		Not Available	8				
44	BUS expenditure for electricity [EURO/year]	Arithmetic Mean	273,2				
		1° Quart.	150,2				
		2° Quart.	204,9				
		3° Quart.	258,6				
		Minimum	32,8				
		Maximum	997,6				
		Quantity of cases	11				
		Not Available	10				
45	BUS average tariff [EURO/kWh]	Arithmetic Mean	0,5				
		1° Quart.	0,3				
		2° Quart.	0,5				
		3° Quart.	0,5				
		Minimum	0,1				
		Maximum	1,1				
		Quantity of cases	11				
		Not Available	10				
46	Share of BUS	Arithmetic Mean	12%				

Code	Indicator	Main Results			Additional Results		
		Descriptor	Quantity	%	Descriptor	Quantity	%
	customers – First year	1° Quart.	3%				
		2° Quart.	9%				
		3° Quart.	22%				
		Minimum	0%				
		Maximum	29%				
		Quantity of cases	13				
		Not Available	8				
47	Share of BUS customers – Last year	Arithmetic Mean	11%				
		1° Quart.	3%				
		2° Quart.	9%				
		3° Quart.	17%				
		Minimum	0%				
		Maximum	29%				
		Quantity of cases	13				
		Not Available	8				
48	Grant component	Arithmetic Mean	74%				
		1° Quart.	75%				
		2° Quart.	90%				
		3° Quart.	90%				
		Minimum	0%				
		Maximum	100%				
		Quantity of cases	21				

A2

Annex 2: Calculation of the average daily consumption from the electricity substitutes per customer

Households	% of Current Users	Max Power (W)	Lighting from (time)	Lighting to (time)	Lighting (hours/ day)	Electrical Devices from (time)	Electrical Devices to (time)	Electrical Devices (hours/ day)	Number of Bulbs (n°)	Number of Units/ Day (Liters, Batteries, etc)	Capacity Per Unit (Wh)	Mobile Phone Charging (charges/ day)	Mobile Phones (% of Total Customer Group)	Radios(% of Total Customer Group)	Other Devices (n° of Devices/ Customer)	Power Assumed for Lighting (W/bulb)	Power for Mobile Phone (W)	Power for Radio (W)	Power Assumed for Other Electrical Devices (W)	Energy for Lighting (Wh)	Energy for Electrical Devices (Wh)	Total Daily Energy/ Customer (Wh)	Total Daily Energy/ Customer Group (Wh)
Solar Home Systems	50.0%	50	18.0	26.5	8.5	12.5	22.0	9.5	2.2	-	-	0.4	100%	75%	0.50	8	6	10	50	146	311	457	915
PV panels (without battery)	0.8%	35	17.9	22.9	5.0	13.3	20.0	6.7	3.0	-	-	0.3	57%	27%		8	6	10	-	118	20	137	1067
PV panels with battery	1.4%	35	17.9	22.9	5.0	13.3	20.0	6.7	3.0	-	-	0.3	57%	27%	0.62	8	6	10	35	118	166	284	3669
Solar lanterns	16.3%	12	17.9	22.9	5.0	13.3	20.0	6.7	3.0	-	-	0.3	57%	27%	-	8	6	10	12	118	20	137	21,335
Rechargeable torches	8.7%	-	17.9	22.9	5.0	13.3	20.0	6.7	3.0	0.1	12.2	0.3	57%	27%	-	-	6	10	-	1	20	21	1699
Torches with battery	27.3%	-	17.9	22.9	5.0	13.3	20.0	6.7	3.0	0.1	12.15	0.3	57%	27%	-	-	6	10	-	1	20	21	5318
Candles (only considering energy for lighting)	4.7%	4	17.9	22.9	5.0	13.3	20.0	6.7	-	2.0	-	0.3	57%	27%	-	-	6	10	4	40	20	60	2670
MIX 2: SHS + PV Panels	0.4%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	236	318	554	2.148
MIX 2: SHS + Solar lanterns	0.4%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	236	318	554	2.148
MIX 2: SHS + Torches with battery	3.7%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	119	318	437	15.246
MIX 2: SHS + Candles	0.4%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	158	318	476	1.845
MIX 3: PV Panels + Solar lanterns	0.4%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	236	39	275	1.067
MIX 6: Solar lanterns + Rechargeable torches	0.8%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	236	39	275	2.133
MIX 6: Solar lanterns + Torches with battery	0.8%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	119	39	158	1.226
MIX 8: Torches with battery + Kerosene lamps	3.7%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	20	21	717
MIX 8: Torches with battery + Candles	7.9%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	41	39	80	6.006
No source of electricity	0.5%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
Not answering	2.5%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
check												100.0%											
Average daily consumption from ELECTRICITY SUBSTITUTES per customer (Wh)																							156

Annex 3: Calculation of the average monthly expenditure from electricity substitutes per customer

Households	Total Number of Current Users	Unit	Unit Cost (RWF)	Monthly Consumption -30 Days Considered- (n° of units)	Asset Costs Splitted Over 36 Months* (RWF)	Total Monthly Expenditure/ Customer (RWF)	Total Monthly Expenditure/ Customer Group (RWF)
Solar Home Systems	184	average monthly fee*	10.970	1	0	10.970	2.019.116
PV panels (without battery)	8	lump sum		1	1.944	1.944	15.086
PV panels with battery	13	lump sum		1	4.131	4.131	53.412
Solar lanterns	155	lump sum		1	472	472	73.276
Rechargeable torches	83	per charge	200	2,2		440	36.414
Torches with battery	259	per disposable batteries	200	2,2		440	113.983
Candles (only considering energy for lighting)	45	pieces	50	60.0		3.000	134.483
MIX 2: SHS + PV Panels	4	-	-	-	-	12.915	50.101
MIX 2: SHS + Solar lanterns	4	-	-	-	-	11.443	44.389
MIX 2: SHS + Torches with battery	35	-	-	-	-	11.410	398.379
MIX 2: SHS + Candles	4	-	-	-	-	13.970	54.195
MIX 3: PV Panels + Solar lanterns	4	-	-	-	-	2.417	9.375
MIX 6: Solar lanterns + Rechargeable torches	8	-	-	-	-	944	7.328
MIX 6: Solar lanterns + Torches with battery	8	-	-	-	-	912	7.078
MIX 8: Torches with battery + Kerosene lamps	35	-	-	-	-	440	15.362
MIX 8: Torches with battery + Candles	75	-	-	-	-	3.440	258.000
No source of electricity	4	-	-	-	-	-	-
Not answering	23	-	-	-	-	-	-
check	950						
People Charging Mobile Phone at kiosk	281	charge	100	10.1		1.009	283.109
Average MONTHLY expenditure for ELECTRICITY SUBSTITUTES per customer (RWF)							3856

A4

Annex 4: Full version of the framework of indicators

Framework of indicators for characterization of the community’s energy needs in greenfield rural electrification projects														
Outside (project's side)							Inside (processing and justification side)							
Code	**Sector/ Subsector**	**Code**	**Indicator**	**Nature of data**	**Means of data acquisition**	**Type of data**	**Derived from**	**Correlated with**	**Multiple choices**	**Type of reference (a): literature**	**Type of reference (b): correlation analysis**	**Type of reference (c): ENA**	**Type of reference (d): case studies**	**Notes**
A	**ELECTRICITY MARKET DIMENSIONS**													
A.1	Market size	A.1.1	Total households	Intrinsic	Desk	Input	n.a.	n.e.	n.a.	Lorenzoni, L.; Cherubini, P.; Fioriti, D.; Poli, D.; Micangeli, A.; Giglioli, R. Classification and modeling of load profiles of isolated mini-grids in developing countries: A data-driven approach. Kemmler A., Spreng D., Energy indicators for tracking sustainability in developing countries, Energy Policy 35 (2007) 2466–2480 Mazur, C., Hoegerle, Y., Brucoli, M., van Dam, K., Guo, M., Markides, C. N., & Shah, N. (2019). A holistic resilience framework development for rural power systems in emerging economies. Applied Energy, 235(October 2018), 219–232. https://doi.org/10.1016/j.apenergy.2018.10.129			All the mini-grid case studies detailed in the Methodology.	In Lorenzoni et a. Number of connections is cited as relevant quantitative data. In Kemmler et al. Households are considered instead of number of people. In Mazur (2019) the connected households are considered among the social resilience indicators
A.2	Penetration rate at year 0	A.2.1	Number of estimated HHs connected / total HHs at year 0	Intrinsic	Desk	Derived	A.1, A.3, C.6., D.2, D.3	n.e.	n.a.				Ikondo mini-grid (Tanzania). Kitobo mini-grid (Uganda). Rutenderi mini-grid (Rwanda). Gatoki mini-grid (Rwanda). Bukasa mini-grid (Uganda). El Dictamo mini-grid (Honduras).	
		A.2.2	Number of estimated businesses connected / total businesses at year 0	Intrinsic	Desk	Derived	A.1, C.6., D.2, D.3	n.e.	n.a.					Businesses include small bus + anchor loads.
A.3	Tier for household electricity consumption	A.3.1	Average daily energy per HH	Intrinsic	Desk	Derived	C.6, C.8, C.9, C.10, D.2, D.3	A.6, E.3, E.8	n.a.	Katre, A., & Tozzi, A. (2018). Assessing the Sustainability of Decentralized RE Systems: A Comprehensive Framework with Analytical Methods. Sustainability, 10(4), 1058. https://doi.org/10.3390/su10041058 Gómez-Hernández, D. F., Domenech, B., Moreira, J., Farrera, N., López-González, A., & Ferrer-Martí, L. (2019). Comparative evaluation of rural electrification project plans: A case study in Mexico. Energy Policy, 129(July 2018), 23–33. https://doi.org/10.1016/j.enpol.2019.02.004	A.6: Correlation [6-37] suggests that household yearly consumptions (kWh/household) increase over the time, even if it mainly happens within Tiers 2 and 3. E.3: Projects applying PAYG systems record higher households’ energy consumptions than those projects applying monthly payments [24-36]. E.3: Considering that electricity tariff affects the financial perfomance, projects with higher IRR record lower household yearly consumptions [20-36] and the correlation is confirmed over the operating life [20-37]. E.8: Lower compatibility of the system with PUE results in both lower household yearly consumptions [17-36] and business yearly consumptions [17-38].	ENA campaigns in Mozambique, Rwanda and Democratic Republic of Congo, for a total of 15 villages and more than 40,000 people assessed, as detailed in the Methodology.	All the mini-grid case studies detailed in the Methodology.	Used by Katre and Tozzi following the MTF method Used by Gomez-Hernandez (2019) by dividing the daily energy that can be produces by the amount of HHs
		A.3.2	Average daily peak power per HH	Intrinsic	Desk	Derived	C.6, C.8, C.9, C.10, D.2, D.3		n.a.					Used by Katre and Tozzi following the MTF method Used by Gomez-Hernandez (2019) by dividing the peak generation power by the number of HHs

A.4	Type of connections	A.4.1	% of households	Intrinsic	Field	Derived	A.1, A.4	D.3, A.7, B.1, E.3	n.a.	Lorenzoni, L.; Cherubini, P.; Fioriti, D.; Poli, D.; Micangeli, A.; Giglioli, R. Classification and modeling of load profiles of isolated mini-grids in developing countries: A data-driven approach.	D.3: Share (%) of household consumptions is higher in moderate and intensive settlements than in scattered ones, both in the first year of operation [8-34] and in the last one [8-35]. A.7: There is a positive correlation between the share of business customers and share of business consumptions [34-46]. It implies that there are no or few anchor loads able to shift business consumptions in rural areas. The correlation is confirmed over the operating life [34-47, 35-47]. B.1: The smaller is the genset size, the higher is the share of business customers, both in the first year of operation [12-46] and in the last one [12-47]. E.3: Business electricity tariff and share of business customers are negatively correlated [45-46] and the correlation is confirmed over the operating life [45-47].	ENA campaigns in Mozambique, Rwanda and Democratic Republic of Congo, for a total of 15 villages and more than 40,000 people assessed, as detailed in the Methodology.	Ikondo mini-grid (Tanzania). Kitobo mini-grid (Uganda). Rutenderi mini-grid (Rwanda). Gatoki mini-grid (Rwanda). Bukasa mini-grid (Uganda). El Dictamo mini-grid (Honduras).	
		A.4.2	% of small business activities (commercial and artisans)	Intrinsic	Field	Input	n.a.		n.a.					
		A.4.3	% of achor loads	Intrinsic	Field	Input	n.a.		n.a.					Achor loads are defined as PUE or other businesses with appliances requiring power over 5 kW and at least a consumption of 10 kWh/day
		A.4.4	% of public services	Intrinsic	Field	Input	n.a.		n.a.	Lorenzoni, L.; Cherubini, P.; Fioriti, D.; Poli, D.; Micangeli, A.; Giglioli, R. Classification and modeling of load profiles of isolated mini-grids in developing countries: A data-driven approach. Ilskog, E. (2008). Indicators for assessment of rural electrification-An approach for the comparison of apples and pears. Energy Policy, 36(7), 2665–2673. https://doi.org/10.1016/j.enpol.2008.03.023				Streetlighting is counted as 1 public service. Featured in Ilskog (2008) under social/ethical dimension
A.5	Penetration rate trend	A.5.1	Percentage variation of HHs penetration rate at the 2nd year of operation	Intrinsic	Desk	Derived	C.2, C.10, D.3	n.e.	n.a.	Lorenzoni, L.; Cherubini, P.; Fioriti, D.; Poli, D.; Micangeli, A.; Giglioli, R. Classification and modeling of load profiles of isolated mini-grids in developing countries: A data-driven approach.			Ikondo mini-grid (Tanzania). Kitobo mini-grid (Uganda). El Dictamo mini-grid (Honduras).	
		A.5.2	Percentage variation of business penetration rate at the 2nd year of operation	Intrinsic	Desk	Derived	C.2, C.10, D.3	n.e.	n.a.		The share (%) of business customers decreases over the time [6-47] since their absolute value is quite stable whereas the household penetration rate increases.			
		A.5.3	Percentage variation of HHs penetration rate at the 5th year of operation	Intrinsic	Desk	Derived	C.2, C.10, D.3	B.1	n.a.		B.1: The last strong correlation regards projects with lower share of energy from RE, which record low quality of the electricity supply service [15-18] and that it is recorded a lost of customers.		Ikondo mini-grid (Tanzania). El Dictamo mini-grid (Honduras).	
		A.5.4	Percentage variation of business penetration rate at the 5th year of operation	Intrinsic	Desk	Derived	C.2, C.10, D.3	B.1	n.a.		B.1: The last strong correlation regards projects with lower share of energy from RE, which record low quality of the electricity supply service [15-18] and that it is recorded a lost of customers. The share (%) of business customers decreases over the time [6-47] since their absolute value is quite stable whereas the household penetration rate increases.			
A.6	Consumption trend	A.6.1	Percentage variation of Average daily energy per HH at the 2nd year of operation	Intrinsic	Desk	Derived	D.2, C.10	E.3, E.8, A.3	n.a.		E.3: Considering that electricity tariff affects the financial perfomance, projects with higher IRR record lower household yearly consumptions [20-36] and the correlation is confirmed over the operating life [20-37]. E.8: Lower compatibility of the system with PUE results in both lower household yearly consumptions [17-36] and business yearly consumptions [17-38]. A.3: Correlation [6-37] suggests that household yearly consumptions (kWh/household) increase over the time, even if it mainly happens within Tiers 2 and 3.		Ikondo mini-grid (Tanzania). Kitobo mini-grid (Uganda). El Dictamo mini-grid (Honduras).	
		A.6.2	Percentage variation of Average daily peak power per HH at the 2nd year of operation	Intrinsic	Desk	Derived	D.2, C.11		n.a.					
		A.6.3	Percentage variation of Average daily energy per HH at the 5th year of operation	Intrinsic	Desk	Derived	D.2, C.12	E.3, A.3	n.a.		E.3: Considering that electricity tariff affects the financial perfomance, projects with higher IRR record lower household yearly consumptions [20-36] and the correlation is confirmed over the operating life [20-37]. A.3: Correlation [6-37] suggests that household yearly consumptions (kWh/household) increase over the time, even if it mainly happens within Tiers 2 and 3.		Ikondo mini-grid (Tanzania). El Dictamo mini-grid (Honduras).	
		A.6.4	Percentage variation of Average daily peak power per HH at the 5th year of operation	Intrinsic	Desk	Derived	D.2, C.13		n.a.					
A.7	Share of productive use of electricity (PUE)	A.7.1	Average daily energy for PUE/total net energy consumed	Intrinsic	Desk	Input	n.a.	A.4	n.a.	Ilskog, E. (2008). Indicators for assessment of rural electrification-An approach for the comparison of apples and pears. Energy Policy, 36(7), 2665–2673. https://doi.org/10.1016/j.enpol.2008.03.023	A.4 There is a positive correlation between the share of business customers and share of business consumptions [34-46]. It implies that there are no or few anchor loads able to shift business consumptions in rural areas. The correlation is confirmed over the operating life [34-47, 35-47].	ENA campaigns in Mozambique, Rwanda and Democratic Republic of Congo, for a total of 15 villages and more than 40,000 people assessed, as detailed in the Methodology.	Ikondo mini-grid (Tanzania). Kitobo mini-grid (Uganda). Rutenderi mini-grid (Rwanda). Gatoki mini-grid (Rwanda). Bukasa mini-grid (Uganda). El Dictamo mini-grid (Honduras).	ENA: WTP for electricity depends on (i) average monthly income (ii) share of expenditure on electricity (iii) education (iv) productive use of electricity. Cited by Ilskog (2008) as the share of electricity consumed by businesses

B.	**TECHNICAL ASPECTS**													
B.1	Share of energy generated from RE sources	B.1.1	Yearly energy from RE sources / total yearly energy generated	Extrinsic	Desk	Assumption	n.a.	E.4, E.8, E.1, A.5, E.3, A.4	n.a.	Ilskog, E. (2008). Indicators for assessment of rural electrification-An approach for the comparison of apples and pears. Energy Policy, 36(7), 2665–2673. https://doi.org/10.1016/j.enpol.2008.03.023	E.4: Considering that RE sources are strictly linked to storage systems, all the cases providing services beyond the sole electricity supply have installed storage systems or count on hydroelectric power components [13-16] and, accordigly, projects with lower share of energy from RE apply a business model which provides "electricity supply only" [15-16]. E.8: Still remaining on the storage indicator, there is a strong correlation for cases providing full compatibility with integration of PUE in the business (Type III of PUE service) [13-18]. E.1: Projects with the lower share of energy from RE have a public ownership, whereas all the projects with private or community ownership have high share of energy from RE [15-21]. A.5: The last strong correlation regards projects with lower share of energy from RE, which record low quality of the electricity supply service [15-18] and that it is recorded a lost of customers. E.3: Considering that electricity tariff affects the financial perfomance, projects operating in steady loss are mini-grids with a prevalent diesel generation component [12-23] and the top-11 IRR ranked projects have a share of energy from RE of 99-100% [15-20] and those with lower share operate in steady loss [15-23]. A.4: The smaller is the genset size, the higher is the share of business customers, both in the first year of operation [12-46] and in the last one [12-47].		All the mini-grid case studies detailed in the Methodology.	Featured in Ilskog (2008) under Environmental development dimension
B.2	Peak demand	B.2.1	Coincidence factor	Intrinsic	Desk	Derived	A.1	n.e.	n.a.	Lorenzoni, L.; Cherubini, P.; Fioriti, D.; Poli, D.; Micangeli, A.; Giglioli, R. Classification and modeling of load profiles of isolated mini-grids in developing countries: A data-driven approach. V. Cataliotti, Electrical systems (Vol.1): Generality components. 2005.			Ikondo mini-grid (Tanzania). Kitobo mini-grid (Uganda). Rutenderi mini-grid (Rwanda). Gatoki mini-grid (Rwanda). Bukasa mini-grid (Uganda). El Dictamo mini-grid (Honduras).	Coincidence factor ia defined as the probability that lights/appliances are switched on at the same time.
B.3	Daily operating hours	B.3.1	Hours of operation per day	Extrinsic	Desk	Assumption	n.a.	n.e.	<4 4<x<8 8<x<12 >12	Ilskog, E. (2008). Indicators for assessment of rural electrification-An approach for the comparison of apples and pears. Energy Policy, 36(7), 2665–2673. https://doi.org/10.1016/j.enpol.2008.03.023 Yadoo, A., & Cruickshank, H. (2012). The role for low carbon electrification technologies in poverty reduction and climate change strategies: A focus on RE mini-grids with case studies in Nepal, Peru and Kenya. Energy Policy, 42, 591–602. https://doi.org/10.1016/j.enpol.2011.12.029			All the mini-grid case studies detailed in the Methodology.	Cited by Isklog as Daily operation services and Availability of services Cited by Yadoo in the technical dimension (Service is reliable, disruptions are minimal)
C.	**SOCIO-ECONOMIC ASPECTS**													
C.1	Gender balance in business activities	C.1.1	% of small business activities run by women	Intrinsic	Field	Input	n.a.	n.e.	n.a.			ENA campaigns in Mozambique, Rwanda and Democratic Republic of Congo, for a total of 15 villages and more than 40,000 people assessed, as detailed in the Methodology.	Kitobo mini-grid (Uganda). Rutenderi mini-grid (Rwanda). Gatoki mini-grid (Rwanda). Ilumina mini-grid (Mozambique). Idjwi mini-grid (Democratic Republic of Congo).	Small business activities are intended as commercial and artisan activities (no PUE).
		C.1.2	% of achor loads run by women	Intrinsic	Field	Input	n.a.	n.e.	n.a.					
C.2	Business vocation	C.2.1	Total business activities / total HHs	Intrinsic	Desk	Derived	A.1, A.4	n.e.	n.a.			ENA campaigns in Mozambique, Rwanda and Democratic Republic of Congo, for a total of 15 villages and more than 40,000 people assessed, as detailed in the Methodology.	All the mini-grid case studies detailed in the Methodology.	Total businesse activities are composed of small businesses and achor loads.

C.3	Economic activities	C.3.1	Main economic activity	Intrinsic	Field	Input	n.a.	n.e.	agricolture fishing livestock other	Twerefou D.K. Willingness to Pay for Improved Electricity Supply in Ghana. Obeng, G. Y., Evers, H.-D., Akuffo, F. O., Braimah, I., & Brew-Hammond, A. (2008). Solar PV electrification and rural energy-poverty in Ghana. Energy for Sustainable Development, 12(1), 43–54. https://doi.org/10.1016/S0973-0826(08)60418-4 Neves, D., Silva, C. A., & Connors, S. (2014). Design and implementation of hybrid RE systems on micro-communities: A review on case studies. Renewable and Sustainable Energy Reviews, 31, 935–946. https://doi.org/10.1016/j.rser.2013.12.047		ENA campaigns in Mozambique, Rwanda and Democratic Republic of Congo, for a total of 15 villages and more than 40,000 people assessed, as detailed in the Methodology.	All the mini-grid case studies detailed in the Methodology.	ENA: WTP for electricity depends on (i) average monthly income (ii) share of expenditure on electricity (iii) education (iv) productive use of electricity. Cited by Obeng (2008) under demographic characteristics Cited by Neves (2014) under community characterization
C.4	Education level	C.4.1	% of people with no level completed	Intrinsic	Desk	Input	n.a.	n.e.	n.a.	Twerefou D.K. Willingness to Pay for Improved Electricity Supply in Ghana.		ENA campaigns in Mozambique, Rwanda and Democratic Republic of Congo, for a total of 15 villages and more than 40,000 people assessed, as detailed in the Methodology.	Kitobo mini-grid (Uganda). Rutenderi mini-grid (Rwanda). Gatoki mini-grid (Rwanda). Ilumina mini-grid (Mozambique). Idjwi mini-grid (Democratic Republic of Congo).	ENA: WTP for electricity depends on (i) average monthly income (ii) share of expenditure on electricity (iii) education (iv) productive use of electricity.
		C.4.2	% of people with primary level completed	Intrinsic	Desk	Input	n.a.	n.e.	n.a.	Twerefou D.K. Willingness to Pay for Improved Electricity Supply in Ghana. Ilskog, E. (2008). Indicators for assessment of rural electrification-An approach for the comparison of apples and pears. Energy Policy, 36(7), 2665–2673. https://doi.org/10.1016/j.enpol.2008.03.023				ENA: WTP for electricity depends on (i) average monthly income (ii) share of expenditure on electricity (iii) education (iv) productive use of electricity. Explicitly mentioned by Ilskog (2008) under social/ethical development dimension
		C.4.3	% of people with secondary level completed	Intrinsic	Desk	Input	n.a.	n.e.	n.a.	Twerefou D.K. Willingness to Pay for Improved Electricity Supply in Ghana.				ENA: WTP for electricity depends on (i) average monthly income (ii) share of expenditure on electricity (iii) education (iv) productive use of electricity.
		C.4.4	% of people with upper levels, at least started	Intrinsic	Desk	Input	n.a.	n.e.	n.a.					ENA: WTP for electricity depends on (i) average monthly income (ii) share of expenditure on electricity (iii) education (iv) productive use of electricity.
C.5	Economic capacity	C.5.1	HHs Average Monthly Income	Intrinsic	Desk	Input	n.a.	n.e.	n.a.	Lorenzoni, L.; Cherubini, P.; Fioriti, D.; Poli, D.; Micangeli, A.; Giglioli, R. Classification and modeling of load profiles of isolated mini-grids in developing countries: A data-driven approach. V. Cataliotti, Electrical systems (Vol.1): Generality components. 2005.		ENA campaigns in Mozambique, Rwanda and Democratic Republic of Congo, for a total of 15 villages and more than 40,000 people assessed, as detailed in the Methodology.	Ikondo mini-grid (Tanzania). Kitobo mini-grid (Uganda). Rutenderi mini-grid (Rwanda). Gatoki mini-grid (Rwanda). Ilumina mini-grid (Mozambique). Idjwi mini-grid (Democratic Republic of Congo).	ENA: WTP for electricity depends on (i) average monthly income (ii) share of expenditure on electricity (iii) education (iv) productive use of electricity.
		C.5.2	Small business activities Average Monthly Income	Intrinsic	Desk	Input	n.a.	n.e.	n.a.					Small business activities are intended as commercial and artisan activities (no PUE). ENA: WTP for electricity depends on (i) average monthly income (ii) share of expenditure on electricity (iii) education (iv) productive use of electricity.
		C.5.3	Anchor loads Average Monthly Income	Intrinsic	Desk	Input	n.a.	n.e.	n.a.					ENA: WTP for electricity depends on (i) average monthly income (ii) share of expenditure on electricity (iii) education (iv) productive use of electricity.

C.6	Share of expenditure on electricity substitutes	C.6.1	HHs average monthly expenditure for electricity substitutes / average monthly income	Intrinsic	Desk	Derived	C.5, C.11	n.e.	n.a.	Banerjee S. et al. Access, affordability, and alternatives: modern infrastructure services in Africa. World Bank, 2008. Obeng, G. Y., Evers, H.-D., Akuffo, F. O., Braimah, I., & Brew-Hammond, A. (2008). Solar PV electrification and rural energy-poverty in Ghana. Energy for Sustainable Development, 12(1), 43–54. https://doi.org/10.1016/S0973-0826(08)60418-4 Mazur, C., Hoegerle, Y., Brucoli, M., van Dam, K., Guo, M., Markides, C. N., & Shah, N. (2019). A holistic resilience framework development for rural power systems in emerging economies. Applied Energy, 235(October 2018), 219–232. https://doi.org/10.1016/j.apenergy.2018.10.129		ENA campaigns in Mozambique, Rwanda and Democratic Republic of Congo, for a total of 15 villages and more than 40,000 people assessed, as detailed in the Methodology.	Ikondo mini-grid (Tanzania). Kitobo mini-grid (Uganda). Rutenderi mini-grid (Rwanda). Gatoki mini-grid (Rwanda). Ilumina mini-grid (Mozambique). Idjwi mini-grid (Democratic Republic of Congo).	ENA: WTP for electricity depends on (i) average monthly income (ii) share of expenditure on electricity (iii) education (iv) productive use of electricity. Cited by Obeng (2008) under economic indicators Cited by Mazur (2019) as an economic resilience indicator
		C.6.2	Small business average monthly expenditure for electricity substitutes / average monthly income	Intrinsic	Desk	Derived	C.5, C.12, E.3	n.e.	n.a.	Banerjee S. et al. Access, affordability, and alternatives: modern infrastructure services in Africa. World Bank, 2008.				ENA: WTP for electricity depends on (i) average monthly income (ii) share of expenditure on electricity (iii) education (iv) productive use of electricity.
		C.6.3	Anchor load average monthly expenditure for electricity substitutes / average monthly income	Intrinsic	Desk	Derived	C.5, C.13, E.3	n.e.	n.a.					In any case, adjusted values should falls from a minimum of 5% to a maximum of 10%. ENA: WTP for electricity depends on (i) average monthly income (ii) share of expenditure on electricity (iii) education (iv) productive use of electricity.
C.7	Seasonality of business activities	C.7.1	Number of high income months	Intrinsic	Field	Input	n.a.	n.e.	n.a.			ENA campaigns in Mozambique, Rwanda and Democratic Republic of Congo, for a total of 15 villages and more than 40,000 people assessed, as detailed in the Methodology.	Ikondo mini-grid (Tanzania). Kitobo mini-grid (Uganda). Rutenderi mini-grid (Rwanda). Gatoki mini-grid (Rwanda). Ilumina mini-grid (Mozambique). Idjwi mini-grid (Democratic Republic of Congo).	
		C.7.2	High / low monthly income ratio	Intrinsic	Field	Input	n.a.	n.e.	n.a.					
C.8	Seasonality of resident population	C.8.1	Average number of months living in the village in a year	Intrinsic	Field	Input	n.a.	n.e.	n.a.					
C.9	Food security	C.9.1	Food Insecurity Experience Scale (FIES)	Intrinsic	Desk	Input	n.a.	n.e.	n.a.	FAO, The Food Insecurity Experience Scale. Access date 13 june 2021. http://www.fao.org/in-action/voices-of-the-hungry/fies/en/			Kitobo mini-grid (Uganda). Idjwi mini-grid (Democratic Republic of Congo).	
C.10	Access to finance institutions	C.10.1	% of HHs with account in a finance institutions	Intrinsic	Field	Input	n.a.	n.e.	n.a.	Ilskog, E. (2008). Indicators for assessment of rural electrification-An approach for the comparison of apples and pears. Energy Policy, 36(7), 2665–2673. https://doi.org/10.1016/j.enpol.2008.03.023		ENA campaigns in Mozambique, Rwanda and Democratic Republic of Congo, for a total of 15 villages and more than 40,000 people assessed, as detailed in the Methodology.	All the mini-grid case studies detailed in the Methodology.	Featured in Ilskog (2008) under Social/Ethical development dimension, as the Micro-credit possibilities available for electricity services connection
C.11	Expenditure on electricity substitutes	C.11.1	HHs average monthly expenditure for electricity substitutes	Intrinsic	Desk	Input	n.a.	D.3	n.a.		D.3: Strong correlation: both household and business expenditure for electricity increase with the intensity of settlement [8-42, 8-44]	ENA campaigns in Mozambique, Rwanda and Democratic Republic of Congo, for a total of 15 villages and more than 40,000 people assessed, as detailed in the Methodology.	Ikondo mini-grid (Tanzania). Kitobo mini-grid (Uganda). Rutenderi mini-grid (Rwanda). Gatoki mini-grid (Rwanda). Ilumina mini-grid (Mozambique). Idjwi mini-grid (Democratic Republic of Congo).	
		C.11.2	Small Business average monthly expenditure for electricity substitutes	Intrinsic	Desk	Input	n.a.		n.a.					
		C.11.3	Anchor load average monthly expenditure for electricity substitutes	Intrinsic	Desk	Input	n.a.		n.a.					

D.	**HABITAT ASPECTS**													
D.1	Climatic conditions	D.1.1	Climatic zone	Intrinsic	Desk	Input	n.a.		tropical arid temperate	Lorenzoni, L.; Cherubini, P.; Fioriti, D.; Poli, D.; Micangeli, A.; Giglioli, R. Classification and modeling of load profiles of isolated mini-grids in developing countries: A data-driven approach.			All the mini-grid case studies detailed in the Methodology.	
		D.1.2	Number of extreme events in the last 10 years	Intrinsic	Desk	Input	n.a.		n.a.	CarbonBrief. Attributing extreme weather to climate change. Access date 13 june 2021. https://www.carbonbrief.org/mapped-how-climate-change-affects-extreme-weather-around-the-world				Extreme events are given per year and geographic position within the country. The matter should be subjected to further study to optimize this indicator.
D.2	Location	D.2.1	Country	Intrinsic	Desk	Input	n.a.		n.a.	Neves, D., Silva, C. A., & Connors, S. (2014). Design and implementation of hybrid RE systems on micro-communities: A review on case studies. *Renewable and Sustainable Energy Reviews*, *31*, 935–946. https://doi.org/10.1016/j.rser.2013.12.047		ENA campaigns in Mozambique, Rwanda and Democratic Republic of Congo, for a total of 15 villages and more than 40,000 people assessed, as detailed in the Methodology.	All the mini-grid case studies detailed in the Methodology.	Featured in the community characterization framework by Neves (2014)
		D.2.2	Proximity to key location (km)	Intrinsic	Field	Input	n.a.		n.a.	RES4Africa Foundation, RE-thinking Access to Energy Business Models. Ways to Walk the Water-Energy-Food Nexus Talk in Sub-Saharan Africa. Rome: Gangemi Editore, 2019.				
D.3	Settlement	D.3.1	Settlement type	Intrinsic	Desk	Input	n.a.	C.11, E.3, A.4	scattered moderate intensive		C.11: Context data are in strong correlations only with indicators on electricity tariff and expenditures: both household and business expenditure for electricity increase with the intensity of settlement [8-42, 8-44]. E.3: Electricity tariffs increase with the intensity of settlement, with strong correlation for business tariff [8-45] and moderate correlation for household tariff [8-43]. A.4: Share (%) of household consumptions is higher in moderate and intensive settlements than in scattered ones, both in the first year of operation [8-34] and in the last one [8-35].		All the mini-grid case studies detailed in the Methodology.	
		D.3.2	Most common type of latrine	Intrinsic	Field	Input	n.a.		n.a.			ENA campaigns in Mozambique, Rwanda and Democratic Republic of Congo, for a total of 15 villages and more than 40,000 people assessed, as detailed in the Methodology.	Kitobo mini-grid (Uganda). Rutenderi mini-grid (Rwanda). Gatoki mini-grid (Rwanda). Ilumina mini-grid (Mozambique). Idjwi mini-grid (Democratic Republic of Congo).	
		D.3.3	Most common type of roof	Intrinsic	Field	Input	n.a.		n.a.					
		D.3.4	% of buinding with glass windows	Intrinsic	Field	Input	n.a.		n.a.					
E.	**OWNERSHIP AND OPERATION FEATURES**													
E.1	Ownership type	E.1.1	Ownership type	Extrinsic	Desk	Assumption	n.a.	B.1, E.3, E.8	public private community-based hybrid public-private other	Lorenzoni, L.; Cherubini, P.; Fioriti, D.; Poli, D.; Micangeli, A.; Giglioli, R. Classification and modeling of load profiles of isolated mini-grids in developing countries: A data-driven approach.	B.1: Projects with the lower share of energy from RE have a public ownership, whereas all the projects with private or community ownership have high share of energy from RE [15-21]. E.3: The lowest household electricity tariffs are applied in projects with community ownership, followed by projects with public, hybrid and private ownership, in this order [21-43]. On the other side, the lowest business electricity tariffs are applied in projects with community and hybrid ownership, followed by projects with public and private ownership, in this order [21-45]. E.8: Correlation between the level of PUE compatibility & integration and the BM classifications based on criteria of ownership [17-21].		All the mini-grid case studies detailed in the Methodology.	

E.2	Operating method	E.2.1	Operating method	Extrinsic	Desk	Assumption	n.a.	E.3	A. build, own, operate B. build, own, outsource C. build, own, lease D. build, sell E. build, short-operate, transfer F. build, own, operate, transfer		E.3: Both for household tariff [28-43] and business tariff [28-45], projects operating with build-own-operate business model apply higher tariffs than other projects, while projects operating with build-short-operate-transfer business model apply lower tariffs than other projects.		All the mini-grid case studies detailed in the Methodology.	
E.3	Electricity tariff	E.3.1	Tariff structure	Extrinsic	Desk	Assumption	n.a.	A.3	flat tariff consumption tariff	Gómez-Hernández, D. F., Domenech, B., Moreira, J., Farrera, N., López-González, A., & Ferrer-Martí, L. (2019). Comparative evaluation of rural electrification project plans: A case study in Mexico. Energy Policy, 129(July 2018), 23–33. https://doi.org/10.1016/j.enpol.2019.02.004	A.3: projects applying PAYG systems record higher households' energy consumptions than those projects applying monthly payments [24-36].			Considered by Gomez-hernandez (2019) as part of the economic management indicators
		E.3.2	Tariff price	Extrinsic	Desk	Assumption	n.a.	C.11, D.3, B.1, E.4, E.2, E.1, E.8, A.6, A.3, A.4	Lower than national price for HHs/small bus/anchor load As the national price for HHs/small bus/anchor load Higher than national price for HHs/small bus/anchor load Free	Lorenzoni, L.; Cherubini, P.; Fioriti, D.; Poli, D.; Micangeli, A.; Giglioli, R. Classification and modeling of load profiles of isolated mini-grids in developing countries: A data-driven approach.	C.11: Strong correlation revealed that business expenditure for electricity and electricity tariff are clearly and positively correlated [44-45]. D.3: Electricity tariffs increase with the intensity of settlement, with strong correlation for business tariff [8-45] and moderate correlation for household tariff [8-43]. B.1: Considering that electricity tariff affects the financial perfomance, projects operating in steady loss are mini-grids with a prevalent diesel generation component [12-23] and the top-11 IRR ranked projects have a share of energy from RE of 99-100% [15-20] and those with lower share operate in steady loss [15-23]. E.4-E.8: Considering that electricity tariff affects the financial perfomance, mini-grids in steady loss provide "electricity supply service" only [16-23] and the IRR is positively correlated to the WEF nexus approach [16-20], which often involves PUE. E.8 Lower compatibility of the system with PUE (types I and II) results in higher household tariff [17-43]; full compatibility with PUE (type II) without integration in business results in a higher business tariff [17-45]. E.2: Both for household tariff [28-43] and business tariff [28-45], projects operating with build-own-operate business model apply higher tariffs than other projects, while projects operating with build-short-operate-transfer business model apply lower tariffs than other projects. E.1: The lowest household electricity tariffs are applied in projects with community ownership, followed by projects with public, hybrid and private ownership, in this order [21-43]. On the other side, the lowest business electricity tariffs are applied in projects with community and hybrid ownership, followed by projects with public and private ownership, in this order [21-45]. A.3-A.6: Considering that electricity tariff affects the financial perfomance, projects with higher IRR record lower household yearly consumptions [20-36] and the correlation is confirmed over the operating life [20-37]. A.4: Business electricity tariff and share of business customers are negatively correlated [45-46] and the correlation is confirmed over the operating life [45-47].	ENA campaigns in Mozambique, Rwanda and Democratic Republic of Congo, for a total of 15 villages and more than 40,000 people assessed, as detailed in the Methodology.	All the mini-grid case studies detailed in the Methodology.	
E.4	Services provided	E.4.1	Class of services provided beyond the electricity supply	Extrinsic	Desk	Assumption	n.a.	B.1, E.3, E.8	Electricity supply only Electricity supply & other energy-related products/services Electricity supply & other WEF nexus-related services		B.1: Considering that RE sources are strictly linked to storage systems, all the cases providing services beyond the sole electricity supply have installed storage systems or count on hydroelectric power components [13-16] and, accordigly, projects with lower share of energy from RE apply a business model which provides "electricity supply only" [15-16]. E.3-E.8: Considering that electricity tariff affects the financial perfomance, mini-grids in steady loss provide "electricity supply service" only [16-23] and the IRR is positively correlated to the WEF nexus approach [16-20], , which often involves PUE.		All the mini-grid case studies detailed in the Methodology.	

E.5	Complementary activities	E.5.1	Level of the complementary activity programme in the start-up phase	Extrinsic	Desk	Assumption	n.a.		None Light (awareness and/or marketing campaigns) Medium (capacity building, vocational trainings) Strong (business incubation, job-shadowing, microfinance mechanisms)	RES4Africa Foundation, RE-thinking Access to Energy Business Models. Ways to Walk the Water-Energy-Food Nexus Talk in Sub-Saharan Africa. Rome: Gangemi Editore, 2019.			All the mini-grid case studies detailed in the Methodology.	
E.6	Marketing campaign	E.6.1	Marketing campaign in the start-up phase	Extrinsic	Desk	Assumption	n.a.		Yes No	RES4Africa Foundation, RE-thinking Access to Energy Business Models. Ways to Walk the Water-Energy-Food Nexus Talk in Sub-Saharan Africa. Rome: Gangemi Editore, 2019.			All the mini-grid case studies detailed in the Methodology.	
E.7	DS) strategies	E.7.1	Efficient appliances and lights	Extrinsic	Desk	Assumption	n.a.		Yes No	Harper M. Review of Strategies and Technologies for Demand-Side Management on Isolated Mini-Grids. Lawrence Barkeley National Laboratory: Berkeley, CA, 2013. Saengprajak, A. Efficiency of DSM Measures in Small Village Electrification Systems. Kassel University Press: Germany, 2007. Mehra, V. at al. Estimating the value of demand-side management in low-cost, solar micro-grids. Energy. 2018, 163, 74-87. Augusto, C. et al. Evaluation of potential of DSMstrategies in isolated microgrid. In Proceedings of the 6th Int. Conf. Clean Electr. Power Renew. Energy Resour. Impact, (ICCEP 2017), 19 June 2017, pp. 359-361.			All the mini-grid case studies detailed in the Methodology.	
		E.7.2	Commercial load scheduling	Extrinsic	Desk	Assumption	n.a.		Yes No					
		E.7.3	Restricting residential use	Extrinsic	Desk	Assumption	n.a.		Yes No					
		E.7.4	Price incentives	Extrinsic	Desk	Assumption	n.a.		Yes No					
		E.7.5	Community involvement, consumer education, and village committees	Extrinsic	Desk	Assumption	n.a.		Yes No					
E.8	Productive use of electricity (PUE)	E.8.1	Level of PUE compatibility & integration	Extrinsic	Desk	Assumption	n.a.	E.1, B.1, E.3, E.4, A.3, A.6	i) Restricted compatibility with PUE ii) Full compatibility with PUE iii) Full compatibility with integration of PUE in the business		E.1: Correlation between the level of PUE compatibility & integration and the BM classifications based on criteria of ownership [17-21]. B.1: Still remaining on the storage indicator, there is a strong correlation for cases providing full compatibility with integration of PUE in the business (Type III of PUE service) [13-18]. and the IRR is positively correlated to the WEF nexus approach [16-20]. E.3-E.4: Considering that electricity tariff affects the financial perfomance, mini-grids in steady loss provide "electricity supply service" only [16-23] and the IRR is positively correlated to the WEF nexus approach [16-20], which often involves PUE. E.3: Lower compatibility of the system with PUE (types I and II) results in higher household tariff [17-43]; full compatibility with PUE (type II) without integration in business results in a higher business tariff [17-45]. A.3-A.6: Lower compatibility of the system with PUE results in both lower household yearly consumptions [17-36] and business yearly consumptions [17-38].		All the mini-grid case studies detailed in the Methodology.	(i) Restricted compatibility with PUE: the use of electricity to feed limited equipment and appliances in terms of technical specifications or time of use, which are often not compatible with productive uses in rural areas. E.g. DC supply which implies specific DC devices for PUE and/or low thresholds per customer in terms of power peak and electricity consumption. ii) Full compatibility with PUE: the use of electricity to feed equipment and appliances for productive uses carried out by off-takers, allowing AC and DC supply, power peaks of machineries commonly used by business off-takers in rural areas and time of use for PUE. iii) Full compatibility with integration of PUE in the business: the use of electricity for productive uses as part of a single integrated business case. It powers PUE carried out by off-takers, as defined in II, as well as by mini-grid developer, which adds revenue streams to the sole provision of electricity.

Bibliography

[1] U. N. S.-G. (UNSG), 'Progress towards the Sustainable Devlopment Goals', *United Nations Econ. Soc. Counc.*, no. July, p. 28, 2016, doi: 10.1017/S0020818300011322.

[2] UN High-level Political Forum, *Accelerating SDG7 Achievement. Policy Briefs in support of the first SDG7 review at the UN high-level politcal forum 2018*. United Nations, 2018.

[3] IEA, IRENA, UNSD, World Bank, and WHO, *Tracking SDG7: The Energy Progress Report 2020*. Washington DC: World Bank, 2020.

[4] Practical Action, 'Beyond a new normal. The energy access landscape after Covid-19', 2020. https://www.sun-connect-news.org/articles/business/details/the-energy-access-landscape-after-covid-19/ (accessed Jun. 01, 2021).

[5] 'Sustainable Energy for All', 2013. https://www.seforall.org/about-us (accessed Aug. 01, 2018).

[6] International Energy Agency, *Africa Energy Outlook 2019*. Paris, 2019.

[7] M. Franz, N. Peterschmidt, M. Rohrer, and G. Kondev, 'Mini-grid Policy Toolkit: Policy and Business Frameworks for Successful Mini-grid Roll-outs', 2014.

[8] ESMAP, *Mini Grids for Half a Billion People: Market Outlook and Handbook for Decision Makers. Executive Summary*. Washington, DC: Energy Sector Management Assistance Program (ESMAP) Technical Report 014/19. World Bank, 2019.

[9] N. J. Williams, P. Jaramillo, J. Taneja, and T. S. Ustun, 'Enabling private sector investment in microgrid-based rural electrification in developing countries: A review', *Renew. Sustain. Energy Rev.*, vol. 52, pp. 1268–1281, 2015, doi: 10.1016/j.rser.2015.07.153.

[10] African Development Bank Group, Sustainable Energy For All - Africa Hub, and Sustainable Energy Fund for Africa, 'Green Mini-Grids in Sub-Saharan Africa: Analysis of Barriers to Growth and the Potential Role of the African Development Bank in Supporting the Sector', *GMG MDP Doc. Ser. n°1*, no. December, 2016.

[11] Africa Minigrid Developers Association (AMDA) and Economic Consulting Associates (ECA), 'Africa Minigrid Benchmarking Report', Nairobi, 2020.

[12] M. Moner-Girona, M. Solano-Peralta, M. Lazopoulou, E. K. Ackom, X. Vallve, and S. Szabó, 'Electrification of Sub-Saharan Africa through PV/hybrid mini-grids: Reducing the gap between current business models and on-site experience', *Renew. Sustain. Energy Rev.*, vol. 91, no. July 2017, pp. 1148–1161, 2018, doi: 10.1016/j.rser.2018.04.018.

[13] International Energy Agency (IEA), 'Energy Access Outlook 2017: From poverty to

prosperity', 2017. doi: 10.1787/9789264285569-en.

[14] World Bank, 'Access to Electricity'. https://data.worldbank.org/indicator/eg.elc.accs.zs (accessed May 01, 2019).

[15] IEA, 'Access to Electricity'. https://www.iea.org/sdg/electricity (accessed May 01, 2019).

[16] W. IEA, IRENA, UNSD, World Bank Group, 'Tracking SDG7: The Energy Progress Report', Washington, DC, 2018.

[17] IEA, 'World Energy Outlook 2018: Highlights', *Int. Energy Agency*, vol. 1, pp. 1–661, 2018, [Online]. Available: https://www.oecd-ilibrary.org/energy/world-energy-outlook-2018/executive-summary_weo-2018-2-en.

[18] 'SAUBHAGYA'. https://saubhagya.gov.in (accessed May 01, 2019).

[19] UNCTD, *Economic Development in Africa Report 2012*. 2012.

[20] Leke A.; Chironga M.; Desvaux G., 'McKinsey Quarterly: Africa's overlooked business revolution.', 2018.

[21] Sustainable Energy For All, 'Energizing Finance: Understanding the landscape.', Vienna, Austria, 2018.

[22] Climatescope, '3Q 2018 Off-Grid And Mini-Grid Market Outlook.', 2018. https://medium.com/climatescope/3q-2018-off-grid-and-mini-grid-market-outlook-70ed47656c31 (accessed May 01, 2019).

[23] Abel Oyuke, P. H. Penar, and B. Howard, 'Off-grid or "off-on": lack of access, unreliable electricity supply still plague majority of Africans', *Afrobarom. Dispatch*, no. 75, pp. 1–26, 2016, [Online]. Available: http://afrobarometer.org/sites/default/files/publications/Dispatches/ab_r6_dispatchno75_electricity_in_africa_eng1.pdf.

[24] World Bank, 'An analysis of issues shaping Africa's economic future', *Africa's Pulse*, vol. 15, no. April, 2017, pp. 1–52, 2017.

[25] Infinergia Consulting, 'Mini-grid for village electrification: Industry and African & Asian markets.', Grenoble, France, 2018.

[26] R. Kempener, O. Lavagne, D. Saygin, J. Skeer, S. Vinci, and D. Gielen, 'Off-Grid Renewable Energy Systems: Status and Methodological Issues', 2015. [Online]. Available: http://www.irena.org/DocumentDownloads/Publications/IRENA_Off-grid_Renewable_Systems_WP_2015.pdf.

[27] IRENA, *Innovation Outlook Mini-Grids*. 2016.

[28] Bloomberg NEF, 'Powering Last-Mile Connectivity', 2018. https://about.bnef.com/blog/powering-last-mile-connectivity (accessed May 01, 2019).

[29] GIZ, 'What size shall it be ?', 2016.

[30] S. Ghosh Banerjee, K. Malik, A. Tipping, J. Besnard, and J. Nash, 'Double Dividend:

Power and Agriculture Nexus in Sub-Saharan Africa', 2017. [Online]. Available: http://www.sun-connect-news.org/fileadmin/DATEIEN/Dateien/New/114112-WP-P150323-Power-and-Agriculture-Web-PUBLIC.compressed.pdf.

[31] World Bank, 'Off-grid Solar Market Trends Report 2018', 2018. [Online]. Available: www.ifc.org.

[32] GOGLA, 'Standardized Impact Metrics for the Off-Grid Solar Energy Sector Table of Contents', 2019.

[33] Futurepump, 'Productive use of off-grid solar: appliances and solar water pumps as drivers of growth', no. 2018, p. 8, 2019.

[34] OnSSET, 'Open Source Spatial Electrification Tool'. http://www.onsset.org (accessed May 01, 2019).

[35] UNSDG, 'Open Source Spatial Electrification Toolkit (OnSSET)'. https://undg.org/sdg_toolkit/open-source-spatial-electrification-tool-onsset (accessed May 01, 2019).

[36] R. Amatya *et al.*, 'Computer-aided electrification planning in developing countries: The Reference Electrification Model (REM)', *Univers. Energy Access Lab*, pp. 1–111, 2018, [Online]. Available: https://www.iit.comillas.edu/publicacion/mostrar_publicacion_working_paper.php.en?id=347%0AAuthors.

[37] W. B. E.- KTH, 'Electrification Pathways For Nigeria, Tanzania and Zambia.' http://electrification.energydata.info (accessed May 01, 2019).

[38] S. J. Lee, 'Adaptive Electricity Access Planning. Massachusetts Institute of Technology.2018', 2018.

[39] F. Fuso Nerini *et al.*, 'Mapping synergies and trade-offs between energy and the Sustainable Development Goals', *Nat. Energy*, vol. 3, no. 1, pp. 10–15, 2018, doi: 10.1038/s41560-017-0036-5.

[40] M. Bhatia and N. Angelou, 'Capturing the Multi-Dimensionality of Energy Access', *Livewire Knowl. Note Ser.*, pp. 1–8, 2014, [Online]. Available: http://documents.worldbank.org/curated/en/937711468320944879/pdf/88699-REVISED-LW16-Fin-Logo-OKR.pdf.

[41] M. Bhatia and N. Angelou, 'Beyond Connections Energy Access Redefined. World Bank. Energy Sector Management Assistance Program (ESMAP)', *World Bank*, pp. 1–224, 2015.

[42] SEforALL., 'Global Tracking Framework 2013'. Washington, DC, 2013.

[43] G. Padam, D. Rysankova, E. Portale, B. Bonsuk Koo, and G. Fleurantin, 'Beyond Connections Ethiopia', *Energy Access Diagnostic Rep. Based Multi-Tier Framew.*, 2018.

[44] World Bank, 'Access to Electricity'. https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS?locations=ET (accessed May 01, 2019).

[45] A. Bos, K.; Chaplin, D.; Mamun, 'Benefits and Challenges of Expanding Grid Electricity in Africa: A Review of Rigorous Evidence on Household Impacts in Developing Countries.', *Energy Sust. Dev.*, vol. 44, pp. 64–77, 2018.

[46] L. Lenz, A. Munyehirwe, J. Peters, and M. Sievert, 'Does Large-Scale Infrastructure Investment Alleviate Poverty? Impacts of Rwanda's Electricity Access Roll-Out Program', *World Dev.*, vol. 89, pp. 88–110, 2017, doi: 10.1016/j.worlddev.2016.08.003.

[47] D. Chaplin *et al.*, 'Grid electricity expansion in tanzania by MCC: Findings from a rigorous impact evaluation', *Rep. Submitt. to Millenn. Chall. Corp. Washington, DC Math. Policy Res.*, no. 202, 2017.

[48] P. Cook, 'Infrastructure, rural electrification and development', *Energy Sustain. Dev.*, vol. 15, no. 3, pp. 304–313, 2011, doi: 10.1016/j.esd.2011.07.008.

[49] P. A. Trotter, 'Rural electrification, electrification inequality and democratic institutions in sub-Saharan Africa', *Energy Sustain. Dev.*, vol. 34, no. October, pp. 111–129, 2016, doi: 10.1016/j.esd.2016.07.008.

[50] OpenEconomics and RES4Africa Foundation, 'Applying the water-energy-food nexus approach to catalyse transformational change in africa', 2019.

[51] F. Almeshqab and T. S. Ustun, 'Lessons learned from rural electrification initiatives in developing countries: Insights for technical, social, financial and public policy aspects.', *Ren. Sustain. Energy Rev.*, vol. 102, pp. 35–53, 2019.

[52] V. Panapanaan, T. Bruce, T. Virkki-Hatakka, and L. Linnanen, 'Analysis of Shared and Sustainable Value Creation of Companies Providing Energy Solutions at the Base of the Pyramid (BoP).', *Bus Strateg Environ.*, vol. 25(5), pp. 293–309, 2016.

[53] T. Winther, M. N. Matinga, K. Ulsrud, and K. Standal, 'Women's empowerment through electricity access: scoping study and proposal for a framework of analysis', *J. Dev. Eff.*, vol. 9, no. 3, pp. 389–417, 2017, doi: 10.1080/19439342.2017.1343368.

[54] C. Edition, 'MINI-GRIDS & GENDER EQUALITY : INCLUSIVE DESIGN , BETTER DEVELOPMENT OUTCOMES. KEY ISSUES , AND POTENTIAL ACTIONS.', no. February, 2017.

[55] 'Productive Use of Energy – PRODUSE A Manual for Electrification Practitioners'.

[56] 'No Title'. https://www.unido.org/our-focus/safeguarding-environment/energy-access-productive-uses (accessed May 19, 2021).

[57] World Health Organization and UNICEF, *Progress on DrinkingWater, Sanitation and Hygiene 2017 Update and SDG Baselines*, no. February. 2017.

[58] L. Nhamo, B. Ndlela, C. Nhemachena, T. Mabhaudhi, S. Mpandeli, and G. Matchaya, 'The water-energy-food nexus: Climate risks and opportunities in Southern Africa', *Water (Switzerland)*, vol. 10, no. 5, pp. 1–18, 2018, doi: 10.3390/w10050567.

[59] K. V. Patrick Curran, Andrew Dougill, Joanna Pardoe, 'Policy brief Policy coherence for sustainable development in sub-Saharan Africa', 2018.

[60] G. Rasul and B. Sharma, 'The nexus approach to water–energy–food security: an

option for adaptation to climate change', *Clim. Policy*, vol. 16, no. 6, pp. 682–702, 2016, doi: 10.1080/14693062.2015.1029865.

[61] U. Lele, M. Klousia-Marquis, and S. Goswami, 'Good Governance for Food, Water and Energy Security', *Aquat. Procedia*, vol. 1, pp. 44–63, 2013, doi: 10.1016/j.aqpro.2013.07.005.

[62] P. A. Trotter, M. C. McManus, and R. Maconachie, 'Electricity planning and implementation in sub-Saharan Africa: A systematic review', *Renew. Sustain. Energy Rev.*, vol. 74, no. December 2016, pp. 1189–1209, 2017, doi: 10.1016/j.rser.2017.03.001.

[63] 'United Nations SDGs'. https://in.one.un.org/sdg-wheel/ (accessed Apr. 01, 2019).

[64] IRENA, *Decentralised Solutions in the Agri-Food Chain*. 2016.

[65] International Council for Science, 'A Guide To SDG Interactions : From Science', pp. 1–239, 2017.

[66] World Bank, 'Access to Energy is at the Heart Of Development.', 2018. https://www.worldbank.org/en/news/feature/2018/04/18/access-energy-sustainable-development-goal-7 (accessed May 01, 2019).

[67] Business and Sustainable Development Commission, 'Better business Better world', 2015.

[68] IEA, 'Energy And The Sustainable Development Goals.', 2017. https://www.iea.org/access2017/ (accessed Mar. 29, 2019).

[69] RES4Africa Foundation, 'Africa's Future Counts.', Rome, Italy, 2019.

[70] A. Santilli, 'Renewable energies, sustainability, and human development a multifaced relation.', 2018.

[71] Energy Sector Management Assistance Program, 'Fighting Poverty through Decentralized Renewable Energy - Energy SME Conference', *Fight. Poverty through Decentralized Renew. Energy*, 2009, [Online]. Available: https://openknowledge.worldbank.org/bitstream/handle/10986/17522/774320WP0ESMAP00PUBLIC00PROCEEDINGS.pdf?sequence=1&isAllowed=y.

[72] D. Coote, 'The benefits of decentralised energy. Business Spectator.', *2011*. https://www.theaustralian.com.au/business/business-spectator/news-story/the-benefits-of-decentralised-energy/cb371b416e3930f3d8ee7683ea2f3fe1 (accessed Apr. 01, 2019).

[73] H. Gustafsson, Ö.; Kruså, M.; Zencak, Z.; Sheesley, R. J.; Granat, L.; Engström, E.; Praveen, P. S.; Rao, P. S. P.; Leck, C.; Rodhe, 'Brown clouds over South Asia: Biomass or fossil fuel combustion?', *Science.*, vol. 323, pp. 495–498, 2019.

[74] J. Fox-Skelly, 'There are diseases hidden in ice, and they are waking up.', 2017. http://www.bbc.com/earth/story/20170504-there-are-diseases-hidden-in-ice-and-they-are-waking-up (accessed Mar. 26, 2019).

[75] C. Vezzoli *et al.*, *Designing Sustainable Energy for All*. 2018.

[76] International Energy Agency, 'Africa Energy Outlook. A focus on the energy prospects in sub-Saharan Africa', *World Energy Outlook Spec. Report, Int. Energy Agency Publ.*, pp. 1–237, 2014.

[77] IPCC, 'Special Report On Renewable Energy And Climate Change Mitigation.', Cambridge, United Kingdom and New York, NY, USA, 2011.

[78] W. B. ESMP, 'Reducing The Cost Of Grid Extension For Rural Electrification.', Washington, DC, 2000.

[79] A. Kirubi, C.; Jacobson, A.; Kammen, D.M.; Mills, 'Community-based electric micro-grids can contribute to rural development: Evidence from Kenya.', *World Dev.*, vol. 37(7), pp. 1208–1221, 2008.

[80] M. Sheahan and C. B. Barrett, 'Food loss and waste in Sub-Saharan Africa: A critical review', *Food Policy*, vol. 70, pp. 1–12, 2017, doi: 10.1016/j.foodpol.2017.03.012.

[81] S. Booth, X. Li, I. Baring-Gould, D. Kollanyi, A. Bharadwaj, and P. Weston, 'Productive Use of Energy in African Micro-Grids : Technical and Business Considerations', *Usaid, Nrel*, no. August, 2018, [Online]. Available: www.nrel.gov/publications.%0Ahttps://www.nrel.gov/docs/fy18osti/71663.pdf.

[82] M. Toman and J. Peters, 'Rural electrification: How much does Sub-Sharan Africa need the grid?', 2017. https://blogs.worldbank.org/developmenttalk/rural-electrification-how-much-does-sub-saharan-africa-need-grid (accessed May 01, 2019).

[83] Irena, *Solar Pv in Africa: Costs and market*, no. September. 2016.

[84] EnGreen, 'Going Beyond the Sole Energy Delivery to Attract Blended Finance in Off-Grid RE Projects', 2020. https://www.ruralelec.org/newsletter/are-newsletter-april-2020-financing-de-risking-mechanisms (accessed Jan. 01, 2021).

[85] R. Sims, A. Flammini, M. Puri, and S. Bracco, *Opportunities for agri-food chains to become energy-smart*, vol. 43, no. 2. 2016.

[86] L. Mayer-Tasch, M. Mukherjee, and K. Reiche, 'Productive Use of Energy – PRODUSE Measuring Impacts of Electrification on Small and Micro-Enterprises', *Report*, p. 156, 2013, [Online]. Available: http://www.produse.org/imglib/downloads/PRODUSE_study/PRODUSE Study_Full Text.pdf.

[87] GSMA, 'The Mobile Economy. Sub-Saharan Africa 2018.', London, UK, 2018.

[88] M. Nique and K. Opala, 'The SynergieS beTween Mobile, energy and waTer acceSS: africa', *Gsma.Com*, no. march, 2014, [Online]. Available: http://www.gsma.com/mobilefordevelopment/new-report-on-sizing-the-opportunity-of-mobile-to-support-energy-water-access.

[89] GSMA, 'State of the Industry Report on Mobile Money', *Gsma*, pp. 1–75, 2021, [Online]. Available: www.gsma.com/mobilemoney.

[90] K. Harrison and T. Adams, 'Evidence Review : How affordable is off-grid energy access in Africa?', no. March, pp. 1–45, 2017.

[91] A. Tenenbaum, B.; Greacen, C.; Siyambalapitiya, T.; Knuckles, 'From the Bottom Up', Washington, DC, 2014.

[92] A. Saengprajak, *Efficiency of Demand Side Management Measures in Small Village Electrification Systems (Google eBook)*. 2006.

[93] M. Harper, 'Review of Strategies and Technologies for Demand-Side Management on Isolated Mini-Grids', *Lawrence Berkeley Natl. Lab.*, vol. 3, no. March, pp. 1–26, 2013.

[94] R. J. Mehra, V.; Amatya, R.; Ram, 'Estimating the value of demand-side management in low-cost, solar micro-grids.', *Energy*, vol. 163, pp. 74–87, 2018.

[95] M. C. Augusto, C.; Almeida, R. H.; Mandelli, S.; Brito, 'Evaluation of potential of demand side management strategies in isolated microgrid.', in *Proceedings of the 6th Int. Conf. Clean Electr. Power Renew. Energy Resour. Impact, (ICCEP 2017)*, 2017, pp. 359–361.

[96] C. Briganti, M.; Vallvé, X.; Alves, L.; Pujol, D.; Cabral, J.; Lopes, 'Implementation of a PV rural micro grid in the island of Santo Antão (Cape Verde) with an individual energy allowance scheme for demand control.', in *Proceedings of the 27th European Photovoltaic Solar Energy Conference and Exhibition (EU PVSEC 2012)*, 2012, pp. 3874–3879.

[97] V. Gambino, R. D. Citto, P. Cherubini, C. Tacconelli, A. Micangeli, and R. Giglioli, 'Methodology for the energy need assessment to effectively design and deploy mini-grids for rural electrification', *Energies*, vol. 12, no. 3, 2019, doi: 10.3390/en12030574.

[98] P. A. I. . M. A. . S. M., 'Unleashing sustainable human capital through innovative capacity building & vocational training: The Micro Grid Academy to Unlock Micro-Grid's Potential in East Africa. RES4MED&Africa: Rome, Italy, 2018.', in *Unlocking Value From Sustainable Renewable Energy.*, RES4MED&Africa, Ed. Rome, Italy: RES4MED&Africa, 2018.

[99] Laura Hammond(SOAS University of London), 'Global Hunger Index:Freed Migration and Hunger', *Glob. Hunger Index*, p. 66, 2018.

[100] USAID, 'TANZANIA: NUTRITION PROFILE'. https://www.usaid.gov/global-health/health-areas/nutrition/countries/tanzania-nutrition-profile (accessed Jun. 01, 2019).

[101] C. F. Scandizzo, P.L., 'A CGE Model for Tanzania.', 2015.

[102] M. De Vroey, 'The Marshallian market and the Walrasian economy. Two incompatible bedfellows', *Scott. J. Polit. Econ.*, vol. 46, no. 3, pp. 319–338, 1999, doi: 10.1111/1467-9485.00135.

[103] RES4Africa Foundation, *RE-thinking Access to Energy Business Models. Ways to Walk the Water-Energy-Food Nexus Talk in Sub-Saharan Africa*. Rome: Gangemi Editore, 2019.

[104] 'WACC Expert'. .

[105] IFC, 'Operational and Financial Performance of Mini-Grid Descos', no. January, 2017, [Online]. Available: http://sun-connect-news.org/fileadmin/DATEIEN/Dateien/New/IFC_Minigrids_Benchmarking_Repor

t_Single_Pages_January_2017.pdf.

[106] Energy Sector Management Assistance Program (ESMAP), 'Mini-grid design Manual', 2000.

[107] M. Kottek and F. Rubel, 'World Maps of Köppen-Geiger climate classification', 2019. .

[108] M. Bhatia and N. Angelou, 'Beyond Connections: Energy Access Redefined', *World Bank*, pp. 1–244, 2015.

[109] D. Manetsgruber, B. Wagemann, B. Kondev, and K. Dziergwa, *Risk Management for Mini-Grids: A new approach to guide mini-grid deployment*. Alliance for Rural Electrification (ARE), 2015.

[110] EU Commission, 'Scaling-up Energy Investments in Africa for Inclusive and Sustainable Growth Report of the Africa-Europe High-Level Platform for Sustainable Energy Investments in Africa', pp. 1–88, 2018.

[111] M. Kojima and C. Trimble, 'Making Power Affordable for Africa and Viable for Its Utilities', *Mak. Power Afford. Africa Viable Its Util.*, 2016, doi: 10.1596/25091.

[112] C. Alvial-Palavicino, N. Garrido-Echeverría, G. Jiménez-Estévez, L. Reyes, and R. Palma-Behnke, 'A methodology for community engagement in the introduction of renewable based smart microgrid', *Energy Sustain. Dev.*, vol. 15, no. 3, pp. 314–323, 2011, doi: 10.1016/j.esd.2011.06.007.

[113] I. Baudish and A. Bruce, 'Maximising Sustainability and Trasformative Potential Via Community Engagement in Mini Grid Deployment Models', in *31st European Photovoltaic Solar Energy Conference and Exhibition*, 2015, pp. 2718–2725, doi: 10.4229/EUPVSEC20152015-6EO.3.5.

[114] IRENA, *Policies and Regulations for Private Sector Renewable Energy Mini-grids*. 2016.

[115] International Energy Agency (IEA), *World Energy Outlook 2014*. 2014.

[116] C. Blodgett, P. Dauenhauer, H. Louie, and L. Kickham, 'Energy for Sustainable Development Accuracy of energy-use surveys in predicting rural mini-grid user consumption', *Energy Sustain. Dev.*, vol. 41, pp. 88–105, 2017, doi: 10.1016/j.esd.2017.08.002.

[117] N. J. Williams, P. Jaramillo, J. Taneja, and T. S. Ustun, 'Enabling private sector investment in microgrid-based rural electrification in developing countries: A review', *Renew. Sustain. Energy Rev.*, vol. 52, pp. 1268–1281, 2015, doi: 10.1016/j.rser.2015.07.153.

[118] D. Schnitzer, D. S. Lounsbury, J. P. Carvallo, R. Deshmukh, J. Apt, and D. M. Kammen, 'Microgrids for Rural Electrification : A critical review of best practices based on seven case studies', 2014.

[119] D. Fioriti *et al.*, 'Stochastic sizing of isolated rural mini-grids , including effects of fuel procurement and operational strategies', *Electr. Power Syst. Res.*, vol. 160, pp. 419–428, 2018, doi: 10.1016/j.epsr.2018.03.020.

[120] T. Lambert, P. Gilman, and P. Lilienthal, 'Micropower System Modeling with Homer',

Integr. Altern. Sources Energy, pp. 379–418, 2006, doi: 10.1002/0471755621.ch15.

[121] A. Micangeli, R. Del Citto, F. Checchi, D. Viganò, S. Nouboundieu, and G. Cestari, 'Rural Electrification in Central America and East Africa , two case Rural Electrification in Central America and East Africa, two case studies of sustainable microgrids', *Iberoam. J. Dev. Stud.*, 2018, doi: 10.26754/ojs_ried/ijds.254.

[122] A. Micangeli *et al.*, 'Energy production analysis and optimization of mini-grid in remote areas: The case study of Habaswein, Kenya', *Energies*, vol. 10, no. 12, 2017, doi: 10.3390/en10122041.

[123] D. Fioriti, R. Giglioli, D. Poli, G. Lutzemberger, A. Vanni, and P. Salza, 'Optimal sizing of a hybrid mini-grid considering the fuel procurement and a rolling horizon system operation'.

[124] D. Fioriti, R. Giglioli, and D. Poli, 'Short-term operation of a hybrid minigrid under load and renewable production uncertainty', 2016, doi: 10.1109/GHTC.2016.7857317.

[125] M. L. Kolhe, K. M. I. U. Ranaweera, and A. G. B. S. Gunawardana, 'Techno-economic sizing of off-grid hybrid renewable energy system for rural electrification in Sri Lanka', *Sustain. Energy Technol. Assessments*, vol. 11, pp. 53–64, 2015, doi: 10.1016/j.seta.2015.03.008.

[126] B. H. Louie, P. Dauenhauer, M. Wilson, A. Zomers, and J. Mutale, 'Eternal Light', *IEEE power energy Mag.*, no. august, pp. 70–78, 2014, doi: 10.1109/MPE.2014.2317093.

[127] N. J. Williams, P. Jaramillo, B. Cornell, I. Lyons-Galante, and E. Wynn, 'Load characteristics of East African microgrids', *Proc. - 2017 IEEE PES-IAS PowerAfrica Conf. Harnessing Energy, Inf. Commun. Technol. Afford. Electrif. Africa, PowerAfrica 2017*, pp. 236–241, 2017, doi: 10.1109/PowerAfrica.2017.7991230.

[128] G. Prinsloo, R. Dobson, and A. Brent, 'Scoping exercise to determine load profile archetype reference shapes for solar co-generation models in isolated off-grid rural African villages', *J. Energy South. Africa*, vol. 28, no. 3, pp. 1–33, 2016, doi: 10.17159/2413-3051/2016/v27i3a1375.

[129] H. Louie and P. Dauenhauer, 'Effects of load estimation error on small-scale off-grid photovoltaic system design, cost and reliability', *Energy Sustain. Dev.*, vol. 34, pp. 30–43, 2016, doi: 10.1016/j.esd.2016.08.002.

[130] E. Hartvigsson and E. O. Ahlgren, 'Energy for Sustainable Development Comparison of load pro fi les in a mini-grid : Assessment of performance metrics using measured and interview-based data', *Energy Sustain. Dev.*, vol. 43, pp. 186–195, 2018, doi: 10.1016/j.esd.2018.01.009.

[131] K. Louw, B. Conradie, M. Howells, and M. Dekenah, 'Determinants of electricity demand for newly electrified low-income African households', vol. 36, pp. 2812–2818, 2008, doi: 10.1016/j.enpol.2008.02.032.

[132] H. Camblong *et al.*, 'Micro-grids project, Part 1: Analysis of rural electrification with high content of renewable energy sources in Senegal', *Renew. Energy*, vol. 34, no. 10, pp. 2141–2150, 2009, doi: 10.1016/j.renene.2009.01.015.

[133] J. A. Alzola, I. Vechiu, H. Camblong, M. Santos, M. Sall, and G. Sow, 'Microgrids

project, Part 2: Design of an electrification kit with high content of renewable energy sources in Senegal', *Renew. Energy*, vol. 34, no. 10, pp. 2151–2159, 2009, doi: 10.1016/j.renene.2009.01.013.

[134] P. Sandwell *et al.*, 'Analysis of energy access and impact of modern energy sources in unelectrified villages in Uttar Pradesh', *Energy Sustain. Dev.*, vol. 35, pp. 67–79, 2016, doi: 10.1016/j.esd.2016.09.002.

[135] G. S. Dutt, 'Illumination and sustainable development Part I : Technology and economics', *Energy Sustain. Dev.*, vol. 1, no. 1, pp. 23–35, 1994, doi: 10.1016/S0973-0826(08)60010-1.

[136] S. Mahapatra, H. N. Chanakya, and S. Dasappa, 'Energy for Sustainable Development Evaluation of various energy devices for domestic lighting in India : Technology , economics and CO 2 emissions', *ESD*, vol. 13, no. 4, pp. 271–279, 2009, doi: 10.1016/j.esd.2009.10.005.

[137] P. Lloyd, 'The energy profile of a rural community', *J. Energy South. Africa*, vol. 15, no. 3, 2004, doi: 10.1109/DUE.2014.6827762.

[138] A. Deaton, *The Analysis of Household Surveys. A Microeconometric Approach to Development Policy*. The International Bank for Reconstruction and Development /, 1997.

[139] M. E. Grosh and P. Glewwe, 'Living Standards Measurement Study Working Paper No. 120 - A Guide to Living Standards Measurement Study Surveys and Their Data Sets', 1995.

[140] M. Ainsworth and J. van der Gaag, *Living Standards Measurement Study Working Paper No. 34 - Guidelines for Adapting the LSMS Living Standards Questionnaires to Local Conditions*, no. 34. 1988.

[141] R. Olivier, 'Living Standards Measurement Study Working Paper No. 130 - Model Living Standards Measurement Study Survey Questionnaire for the Countries of the Former Soviet Union', 1997.

[142] M. E. Grosh and J. Muñoz, 'Living Standards Measurement Study Working Paper No. 126 - A Manual for Planning and Implementing the Living Standards Measurement Study Survey', 1996.

[143] D. F. Barnes and K. O'Sullivan, *Energy Policies and Multitopic Household Surveys Guidelines for Questionnaire Design in Living Standards Measurement Studies Energy Policies and Multitopic Household Surveys Guidelines for Questionnaire Design*. 2007.

[144] D-Lab, 'About D-Lab'. https://d-lab.mit.edu/about (accessed Aug. 01, 2018).

[145] D-Lab, 'D-Lab's Off-Grid Energy Group'. https://d-lab.mit.edu/research/energy (accessed Aug. 01, 2018).

[146] E. Verploegen, 'Energy Assessment Toolkit', 2017. http://d-lab.mit.edu/research/energy/energy-needs-assessment-toolkit (accessed Aug. 01, 2018).

[147] D-Lab, 'Off-Grid Energy Roadmap'. http://d-lab.mit.edu/research/energy/energy-

needs-assessment-toolkit (accessed Aug. 01, 2018).

[148] R. Smith and K. Leith, 'D-Lab Scale-Ups User Research Framework', 2015.

[149] A. K. N. Reddy, 'Rural energy consumption patterns — A field study', *Biomass*, vol. 2, no. 4, pp. 255–280, 1982, doi: 10.1016/0144-4565(82)90013-0.

[150] V. Van Acker, S. J. Szablya, H. Louie, J. McLean Sloughter, and A. S. Pirbhai, 'Survey of Energy Use and Costs in Rural Kenya for Community Microgrid Business Model Development', *IEEE Glob. Humanit. Technol. Conf. (GHTC 2014)*, pp. 166–173, 2014, doi: 10.1109/GHTC.2014.6970277.

[151] L. G. Swan and V. I. Ugursal, 'Modeling of end-use energy consumption in the residential sector: A review of modeling techniques', *Renew. Sustain. Energy Rev.*, vol. 13, no. 8, pp. 1819–1835, 2009, doi: 10.1016/j.rser.2008.09.033.

[152] S. Mandelli, M. Merlo, and E. Colombo, 'Novel procedure to formulate load profiles for off-grid rural areas', *Energy Sustain. Dev.*, vol. 31, pp. 130–142, 2016, doi: 10.1016/j.esd.2016.01.005.

[153] T. Yamane, *Statistics: An Introductory Analysis*, 3rd Editio. Harper and Row, New York, 1973.

[154] National Institute of Statistics of Rwanda (NSIR), 'Fourth Population and Housing Census, Rwanda, 2012', 2014.

[155] J. Cust, A. Singh, and K. Neuhoff, 'Rural Electrification in India: Economic and Industrial Aspects of Renewables', no. December, p. 36, 2007, doi: https://dx.doi.org/10.2139/ssrn.2760810.

[156] H. R. Varian, *Microeconomic Analysis, Vol. 3*. New York.

[157] S. Graber, T. Narayanan, J. Alfaro, and D. Palit, 'Solar microgrids in rural India: Consumers' willingness to pay for attributes of electricity', *Energy Sustain. Dev.*, vol. 42, pp. 32–43, 2018, doi: 10.1016/j.esd.2017.10.002.

[158] B. Gill, S. Saluja, and D. Palit, *Electricity Pricing and the Willingness to Pay for Electricity in India: Current Understanding and the Way Forward*. New Delhi: The Energy and Resources Institute, 2017.

[159] HOMER Energy LLC, 'HOMER Energy'. https://www.homerenergy.com/products/pro/index.html (accessed Aug. 01, 2018).

[160] NASA, 'NASA Power'. https://power.larc.nasa.gov/ (accessed Aug. 01, 2018).

[161] T. Kobayakawa and T. C. Kandpal, 'Photovoltaic micro-grid in a remote village in India: Survey based identification of socio-economic and other characteristics affecting connectivity with micro-grid', *Energy Sustain. Dev.*, vol. 18, no. 1, pp. 28–35, 2014, doi: 10.1016/j.esd.2013.11.002.

[162] S. Mandelli, C. Brivio, E. Colombo, and M. Merlo, 'Effect of load profile uncertainty on the optimum sizing of off-grid PV systems for rural electrification', *Sustain. Energy Technol. Assessments*, vol. 18, pp. 34–47, 2016, doi: 10.1016/j.seta.2016.09.010.

[163] P. Boait, V. Advani, and R. Gammon, 'Estimation of demand diversity and daily demand pro fi le for off-grid electri fi cation in developing countries', vol. 29, pp. 135–141, 2015, doi: 10.1016/j.esd.2015.10.009.

[164] A. Islam and R. Hasib, 'Short Term Electricity Demand Forecasting for an Isolated Area using Two Different Approaches', *J. Power Technol.*, vol. 93, no. 4, pp. 185–193, 2013.

[165] T. A. Rashid, 'A Hybrid Kohonen-based Approach forecasting (1). pdf', no. October, 2014.

[166] 'Reliable and Affordable Off-Grid Electricity Services for the Poor', *Reliab. Afford. Off-Grid Electr. Serv. Poor*, 2016, doi: 10.1596/25391.

[167] D. Ross and F. Simonsen, 'How do we finance it? A guide to financing of mini-grid companies and projects', 2017.

[168] V.Gambino, P. Cherubini, A. Micangeli, R. Giglioli, 'Case study analysis of 21 RE mini-grids in sub-Saharan Africa: aggregate and correlation analysis of business model indicators.', *Renew. Sustain. Energy Transit.*, p. In course of publication., 2021.

[169] F. Riva, A. Tognollo, F. Gardumi, and E. Colombo, 'Long-term energy planning and demand forecast in remote areas of developing countries: Classification of case studies and insights from a modelling perspective', *Energy Strateg. Rev.*, vol. 20, pp. 71–89, 2018, doi: 10.1016/j.esr.2018.02.006.

[170] P. Boait, R. Gammon, V. Advani, N. Wade, D. Greenwood, and P. Davison, 'ESCoBox: A Set of Tools for Mini-Grid Sustainability in the Developing World', *Sustainability*, vol. 9, no. 5, p. 738, May 2017, doi: 10.3390/su9050738.

[171] A. Sahlberg, A. Korkovelos, B. K. Oluchi, M. D. Mentis, and C. Arderne, 'OnSSET's documentation', 2020. .

[172] D. Mentis *et al.*, 'The benefits of geospatial planning in energy access - A case study on Ethiopia', *Appl. Geogr.*, vol. 72, pp. 1–13, 2016, doi: 10.1016/j.apgeog.2016.04.009.

[173] D. Mentis *et al.*, 'Lighting the World: the first application of an open source, spatial electrification tool (OnSSET) on Sub-Saharan Africa', *Environ. Res. Lett.*, vol. 12, no. 8, 2017, doi: 10.1088/1748-9326/aa7b29.

[174] A. Korkovelos, B. Khavari, A. Sahlberg, M. Howells, and C. Arderne, 'The role of open access data in geospatial electrification planning and the achievement of SDG7. An onsset-based case study for Malawi', *Energies*, vol. 12, no. 7, 2019, doi: 10.3390/en12071395.

[175] ESMAP and World Bank Group, 'Welcome to the Global Electrification Platform'. https://electrifynow.energydata.info/ (accessed Jul. 01, 2021).

[176] USAID and Power Africa, 'Mozambique Route-to-Market Analysis: Introduction', 2021.

[177] USAID and Power Africa, 'Can Mozambican Households Afford SH? insights from a local survey', 2020.

[178] P. Ciller *et al.*, 'Optimal Electrification Planning Incorporating On- and Off-Grid Technologies: The Reference Electrification Model (REM)', *Proc. IEEE*, vol. 107, no. 9, pp. 1872–1905, Sep. 2019, doi: 10.1109/JPROC.2019.2922543.

[179] P. Ciller, F. de Cuadra, and S. Lumbreras, 'Optimizing Off-Grid Generation in Large-Scale Electrification-Planning Problems: A Direct-Search Approach', *Energies*, vol. 12, no. 24, p. 4634, Dec. 2019, doi: http://dx.doi.org/10.3390/en12244634.

[180] F. Riva, F. Gardumi, A. Tognollo, and E. Colombo, 'Soft-linking energy demand and optimisation models for local long-term electricity planning: An application to rural India', *Energy*, vol. 166, pp. 32–46, 2019, doi: 10.1016/j.energy.2018.10.067.

[181] L. Lorenzoni, P. Cherubini, D. Fioriti, D. Poli, A. Micangeli, and R. Giglioli, 'Classification and modeling of load profiles of isolated mini-grids in developing countries: A data-driven approach', *Energy Sustain. Dev.*, vol. 59, pp. 208–225, Dec. 2020, doi: 10.1016/j.esd.2020.10.001.

[182] M. Torero, 'The Impact of Rural Electrification: Challenges and Ways Forward', *Rev. Econ. Dev.*, vol. 23, no. HS, p. 49, 2015, doi: 10.3917/edd.hs03.0049.

[183] A. Eales, E. Colenbrander, and L. Walley, 'Social Impact of Mini-grids: Monitoring, Evaluation and Learning. Tools and Guidelines for Practitioners and Researchers', 2018.

[184] A. Katre and A. Tozzi, 'Assessing the Sustainability of Decentralized Renewable Energy Systems: A Comprehensive Framework with Analytical Methods', *Sustainability*, vol. 10, no. 4, p. 1058, Apr. 2018, doi: 10.3390/su10041058.

[185] E. Ilskog, 'Rural electrification sustainability indicators:-Manual for field workers', *KTH Univ. Press*, no. January, 2008.

[186] E. Ilskog, 'Indicators for assessment of rural electrification-An approach for the comparison of apples and pears', *Energy Policy*, vol. 36, no. 7, pp. 2665–2673, 2008, doi: 10.1016/j.enpol.2008.03.023.

[187] E. Ilskog and B. Kjellström, 'And then they lived sustainably ever after?-Assessment of rural electrification cases by means of indicators', *Energy Policy*, vol. 36, no. 7, pp. 2674–2684, 2008, doi: 10.1016/j.enpol.2008.03.022.

[188] A. Yadoo and H. Cruickshank, 'The role for low carbon electrification technologies in poverty reduction and climate change strategies: A focus on renewable energy mini-grids with case studies in Nepal, Peru and Kenya', *Energy Policy*, vol. 42, pp. 591–602, Mar. 2012, doi: 10.1016/j.enpol.2011.12.029.

[189] H. Lestari, M. Arentsen, H. Bressers, B. Gunawan, J. Iskandar, and Parikesit, 'Sustainability of Renewable Off-Grid Technology for Rural Electrification: A Comparative Study Using the IAD Framework', *Sustainability*, vol. 10, no. 12, p. 4512, Nov. 2018, doi: 10.3390/su10124512.

[190] G. Y. Obeng, H.-D. Evers, F. O. Akuffo, I. Braimah, and A. Brew-Hammond, 'Solar photovoltaic electrification and rural energy-poverty in Ghana', *Energy Sustain. Dev.*, vol. 12, no. 1, pp. 43–54, Mar. 2008, doi: 10.1016/S0973-0826(08)60418-4.

[191] D. Neves, C. A. Silva, and S. Connors, 'Design and implementation of hybrid

renewable energy systems on micro-communities: A review on case studies', *Renew. Sustain. Energy Rev.*, vol. 31, pp. 935–946, 2014, doi: 10.1016/j.rser.2013.12.047.

[192] A. Katre, A. Tozzi, and S. Bhattacharyya, 'Sustainability of community-owned mini-grids: evidence from India', *Energy. Sustain. Soc.*, vol. 9, no. 1, p. 2, Dec. 2019, doi: 10.1186/s13705-018-0185-9.

[193] P. M. Dauenhauer, D. Frame, A. Eales, S. Strachan, S. Galloway, and H. Buckland, 'Sustainability evaluation of community-based, solar photovoltaic projects in Malawi', *Energy. Sustain. Soc.*, vol. 10, no. 1, p. 12, Dec. 2020, doi: 10.1186/s13705-020-0241-0.

[194] C. Mazur *et al.*, 'A holistic resilience framework development for rural power systems in emerging economies', *Appl. Energy*, vol. 235, no. October 2018, pp. 219–232, 2019, doi: 10.1016/j.apenergy.2018.10.129.

[195] D. F. Gómez-Hernández, B. Domenech, J. Moreira, N. Farrera, A. López-González, and L. Ferrer-Martí, 'Comparative evaluation of rural electrification project plans: A case study in Mexico', *Energy Policy*, vol. 129, no. July 2018, pp. 23–33, Jun. 2019, doi: 10.1016/j.enpol.2019.02.004.

[196] M. Juanpera, B. Domenech, L. Ferrer-Martí, A. Garzón, and R. Pastor, 'Renewable-based electrification for remote locations. Does short-term success endure over time? A case study in Peru', *Renew. Sustain. Energy Rev.*, vol. 146, 2021, doi: 10.1016/j.rser.2021.111177.

[197] C. M. Afgan N.H., *Sustainable Assessment Method for Energy Systems. Indicators, Criteria and Decision Making Procedure*. 2000.

[198] CNR-IIA, 'CNR-IIA and RES4AFRICA together to improve air quality and energy efficiency in Africa', 2021. https://www.cnr.it/en/press-note/n-10166/cnr-iia-and-res4africa-together-to-improve-air-quality-and-energy-efficiency-in-africa (accessed Apr. 09, 2021).