SCUOLA DI INGEGNERIA INDUSTRIALE
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Assessment of the reliability of a hydropower based mini-grid in Mozambique rural area.

TESI DI LAUREA MAGISTRALE IN ENERGY ENGINEERING-INGEGNERIA ENERGETICA

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Abstract

The goal of this work is to address the problems of the existing mini grids in rural electrification of Mozambique related to their planning and sizing through taking Muôha village as a case study. Muôha has an existing mini hydropower plant that operates to serve a certain number of beneficiaries. The issues associated with the existing plant are: 1) The mini-hydro plant was planned with complete ignorance to the dry season the area experiences 2) The mini-hydro was planned without expectation of a load demand evolution 3) The plant is suffering from frequent shutdowns. All these problems are leaving the people living in a duck. To be able to assess the existing grid and identify an optimal solution to the village, 4 modelling approaches will be considered. Prior to that, 3 load demand scenarios will be created using RAMP tool which is a stochastic model to generate multi-energy load profiles. Then the modelling is performed using MicroGridspy, an open source tool that can optimize the technology capacity and minimize the net present cost taking into account the already in place grid (Brownfield investment). The 4 modelling approaches are as the following: 1)The hydropower resource availability don't suffer from any interruption and no diesel genset is possible in the grid. 2)The hydropower resource availability don't suffer from any interruption and the diesel genset is possible in the grid.3)The hydropower resource has 5 months, from June till end of October, of zero output provided due to the dry season that leads to the dry of the river associated to it. 4)same condition as approach 3 but diesel genset is not possible to be present in the grid. The software will give a solution to each model according to the input parameters set. The comparison among the solutions show at a first level that the mini-hydro plant can't stand alone and we are in need of a hybrid mini grid (HP, PV and battery bank, and diesel genset as back up) to be able to satisfy the load demand evolution and excluding the diesel genset would result in a very high cost putting the project in risk. Also, taking into account the current situation of Muôha of 5 months dry season demonstrates that the results of approach 3 is the optimal solution where PV capacity to be installed is of the same dependency as the hydropower in the grid unlike that of Approach 2.

Key words: Rural electrification, Energy access, Hybrid mini grid, Optimization, Mozambique

Abstract in lingua italiana

L'obiettivo di questo lavoro è affrontare i problemi delle mini reti esistenti nell'elettrificazione rurale del Mozambico in relazione alla loro pianificazione e dimensionamento attraverso l'analisi di un caso studio del villaggio di Muôha. Muôha dispone di una mini centrale idroelettrica esistente che opera servendo un certo numero di beneficiari in modo efficiente. I problemi associati all'impianto esistente sono: 1) L'impianto mini-idro è stato progettato ignorando completamente la stagione secca che l'area vive 2) L'impianto mini-idro è stato progettato senza aspettarsi un'evoluzione della domanda di carico 3) L'impianto soffre di frequenti arresti. Tutti questi problemi stanno lasciando le persone che vivono in una papera. Per essere in grado di valutare la rete esistente e identificare una soluzione ottimale per il villaggio, saranno considerati 4 approcci di modellazione. Prima di ciò, verranno creati 3 scenari di domanda di carico utilizzando lo strumento RAMP che è un modello stocastico per generare profili di carico multi-energia. Quindi la modellazione viene eseguita utilizzando MicroGridspy, uno strumento open source in grado di ottimizzare la capacità tecnologica e ridurre al minimo il costo attuale netto tenendo conto della griglia già in atto. I 4 approcci di modellazione sono i seguenti: 1) La disponibilità di risorse idroelettriche non subisce alcuna interruzione e nessun gruppo elettrogeno diesel è possibile nella rete. 2) La disponibilità della risorsa idroelettrica non subisce alcuna interruzione e il gruppo elettrogeno diesel è possibile in rete. 3) La risorsa idroelettrica ha 5 mesi, da giugno a fine ottobre, di produzione zero fornita a causa della stagione secca che porta alla secca del fiume ad esso associato. 4) stessa condizione dell'approccio 3 ma non è possibile che il gruppo elettrogeno diesel sia presente nella rete. Il software darà una soluzione a ciascun modello in base ai parametri di input impostati. Il confronto tra le soluzioni mostra a un primo livello che il mini impianto idroelettrico non può stare da solo e abbiamo bisogno di una mini rete ibrida (HP, fotovoltaico e batteria, e gruppo elettrogeno diesel come back up) per poter soddisfare l'evoluzione della domanda di carico ed escludere il gruppo elettrogeno diesel comporterebbe un costo molto elevato che metterebbe a rischio il progetto. Inoltre, tenendo conto dell'attuale situazione di Muôha di 5 mesi di stagione secca, si dimostra che i risultati dell'approccio 3 sono la soluzione ottimale in cui la capacità fotovoltaica da installare è della stessa dipendenza dell'energia idroelettrica nella rete, a differenza di quella dell'approccio 2.

Abstract in lingua italiana

Parole chiave: elettrificazione rurale, accesso all'energia, mini rete ibrida, ottimizzazione, Mozambico

Contents

Introduction

Mozambique is one of the poorest countries in the world. It is still lacking behind despite the economic development in the recent few years. One of the major issues the population of Mozambique faces is the access to energy and specifically to electrification. Although the country is rich in different energy resources, mainly hydropower, only 40% of the population has access to electricity and just 4% of the rural areas are electrified. The issue which the Mozambique Government is trying to tackle, in order to reach a higher access to the population and to achieve SDG7, is to increase the electrification rate for the rural areas through the mini grids development. FUNAE, the operator in charge of all energy projects developing in the rural areas, is still having a lot of challenges related to the success of these projects. Despite the deployment of many projects in rural villages still these mini grids carry on with lots of doubts and questions. The main question is related to the planning and sizing of these grids whether they are oversized or undersized.

This presented work is going to give a sight for the purpose of demonstrating how the existing mini grids in Mozambique are poorly planned. The target will be a village called Muôha located in the province of Manica, Mozambique. The village already has an existing mini hydropower plant of 100 KW installed by FUNAE in 2015. However, this mini hydropower isn't fulfilling the village demand needs. The thesis work is going to analyze the existing mini plant in Muôha through running 4 modelling scenarios that will be compared together. RAMP tool will be used in order to assess the current load demand of the village as well as creating three load demand scenarios. For the modelling part, an open-source tool will be used named Microgridspy which provides a cost effective solution for a hybrid mini grid (more than one technology together such as hydropower, PV, battery bank and diesel generators) based on input parameters set by the user.

The modelling approaches differ in the input parameters related to two main configurations: 1) The hydropower resource availability is normal without any interruption or shutdowns 2) The hydropower resource has 5 months with zero availability due to the climate condition of the country.

In addition to these configurations, the approaches will be be set according to a possibility of letting the diesel genset to be present in the mini grid optimization or absent.

The comparison is aiming to come up with a conclusion on the best possible solution to our case study to have a reliable and efficient grid with respect to the current situation of the already in placed mini hydropower plant.

The thesis will be composed of 8 chapters.

Chapter 1 give an overview of the energy sector in Mozambique , mainly the most rich energy resources and what is the current situation in the country. Also delivers a historical background for the electricity sector and its main characteristics in Mozambique.

Chapter 2 focuses on the Renewables potential in the country through each available resource and how Mozambique isn't exploiting them in an efficient way. Then it delivers a more understanding for the main operators and players in the energy sector as well as the strategies set by the Government all over the past years to change the present condition. Finally, the off grid electrification strategy in Mozambique will be addressed mentioning its history and future efforts needed.

Chapter 3 provides a comprehensive understanding of the small scale generation systems that are needed to the rural electrification.

Chapter 4 deepens in the problems and challenges associated to increase the electricity access rates to the rural areas of Mozambique.

Chapter 5 is dedicated to understand the tools that the presented work relies on to perform the modelling configurations.

Chapter 6 is the discussion of our case study starting with the characteristics of the village itself . Then giving a more detailed load and energy resource assessment that are going to be implemented in our tools.

Chapter 7 is a detailed explanation of the scope of work that is going to be followed to perform our optimization scenarios according to our considerations.

Chapter 8 is the presentation of the main results obtained after running the models and the discussion of each one alone and all together to come up with a final conclusion to the case studied.

1. Mozambique Energy Sector

1.1 Overview

Mozambique is located in the eastern part of south Africa and comprises a land surface of about 800,000 km2 with a 2500 km long coastline as well as borders with Tanzania, Malawi, Zambia, Zimbabwe, South Africa and Swaziland . It has a total population of 32,163,045 by 2021 with an annual growth of 4% [1].

Figure 1-1: Mozambique map

Mozambique is a highly rich country in non-Renewables as well as in Renewables energy sources. It has the largest power production potential relying on a huge potential available for hydropower, coal, natural gas, wind, and solar. Such an interesting energy mix is unfortunately not well exploited. The power sector is dominated by the hydropower potential estimated of 12,000MW. However, it was realized that recently the energy mix could be diversified with the big discoveries of coal and natural gas.

According to the International Energy Agency (IEA) the total primary energy supply of Mozambique haven't witnessed a dramatic change throughout the recent years. Bio fuels & waste, including the traditional use of the biomass, is still accounting for more than 60% of the energy mix [2] as 80% of the population is still considering the traditional exploitation of biomass to meet their energy demands [3] (See chart 1-1). With the recent gas recoveries the energy mix has a big opportunity to be diversified. Most of the power is currently generated through hydroelectric projects but a change is anticipated to occur where renewables (solar and wind) as well as the natural gas would have a huge impact in the future. Natural gas is expected to provide around 44% of the total energy generation in the next decade noticing that the total gas reserves might be as high as 3.5 trillion cubic feet.

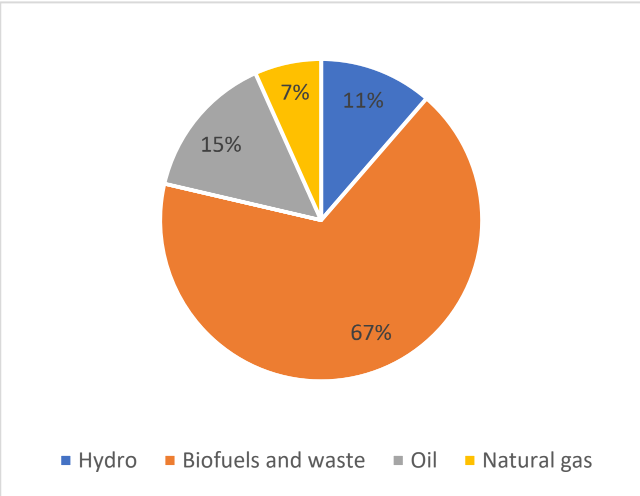


Chart 1-1: TPES of Mozambique – IEA (2019)

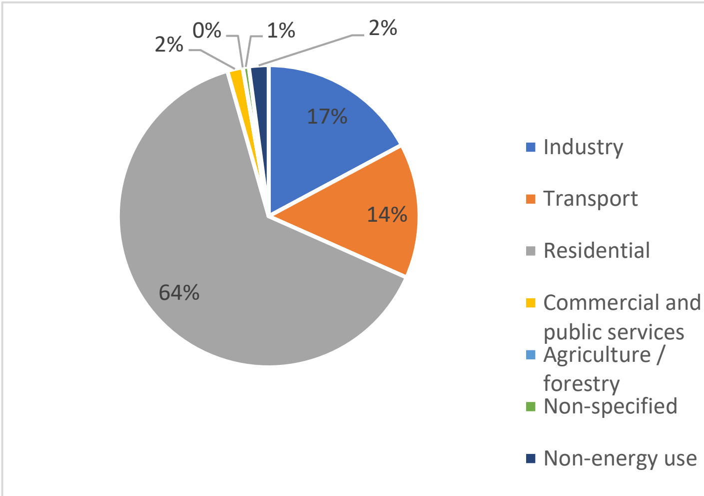


Chart 1-2: Total Energy Consumption, IEA (2019)

Chart 1-2 shows clearly how the residential sector is the main consumer of the energy sector in Mozambique while the industry and transport sectors come after with much less percentages.

An Important issue of the Mozambique energy sector is the orientation towards export and mainly the export of gas and electricity to South Africa & Zimbabwe, and export of the coal to other countries mainly Brazil [4]. With the advantage of exporting, still Mozambique imports the equal amount due to the undeveloped transmission lines infrastructure.

1.2. Electricity Sector

In 2021, only 40% of the population of the Mozambique had access to electricity (36% on-grid and 4% off-grid) a number that requires a lot of efforts and cooperation between the governmental non-governmental institution of the Mozambique and Europe that are aiming to support undeveloped countries.

In 2004, the Mozambique Government announced a master plan aiming at increasing the access to electricity with a ratio of 30% giving attention to the transmission projects, distribution, and few to rural electrification [5].

Indeed, Mozambique efforts for increasing electrification was highly significant by which a 30% raise of access to electrification occurred between 2001 and 2020. However, a 10% increase took place just from 2021 to 2022. The Government has set new targets in the upcoming years to develop the electricity sector by installing additional 2300 MW by 2030 and almost 5 million connections (on-grid and off-grid)[6].

The total installed capacity by 2020 is around 2780 MW by which the vast majority of electricity production comes from the hydropower projects that accounts for 79% of the Mozambique's Electrification (Chart 1-3) and mainly through the Cahora Bass dam which is expected to change in the upcoming decades to have a diversified generation by sources.

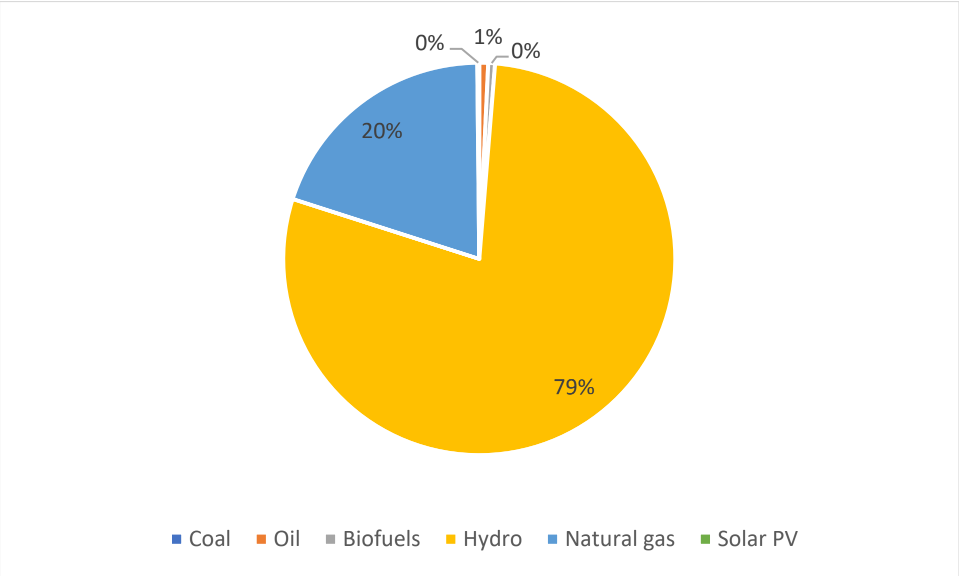


Chart 1-3: Mozambique electricity by sector

Across the country, there is 6 main hydropower plants with different installed capacities but the Cahora Bass Dam supplies the majority as mentioned with a capacity 2075 MW and operated by Hidroeléctrica de Cahora Bassa (HCB) and the other plants are operated by Electricidade de Moçambique EDM. Due to a low electricity demand as well as weak transmission infrastructure and access to energy, the produced electricity is exported to South Africa at most and with lower amounts to Zimbabwe and Botsawna [7][8].

Table: Hydropower installed capacity in Mozambique

Plant	Installed Capacity (MW)	Location	Operator
Cahora Bassa	2075	Tete	Hidroeléctrica de Cahora Bassa
Mavuzi	52	Manica	EDM
Chicamba	44	Manica	EDM
Corumana	16.6	Maputo	EDM
Cuamba	1.09	Niassa	EDM
Lichinga	0.73	Niassa	EDM

Table 1: Mozambique Hydropower plants 1 – 2019

According to IEA the industrial sector in Mozambique is the one that consumes the most leading the residential sector which comes next with around 14% of the total consumption (Chart 1-3). However, the electricity produced by the grid operated by EDM is mostly directed to the Residential users. The data from the IEA claims that in 2019 the Total Electric Consumption was 13.7 Twh roughly equal to the previous 5 years however the electricity production increased with a significant amount in that duration suggesting more exportation of electricity to South Africa.

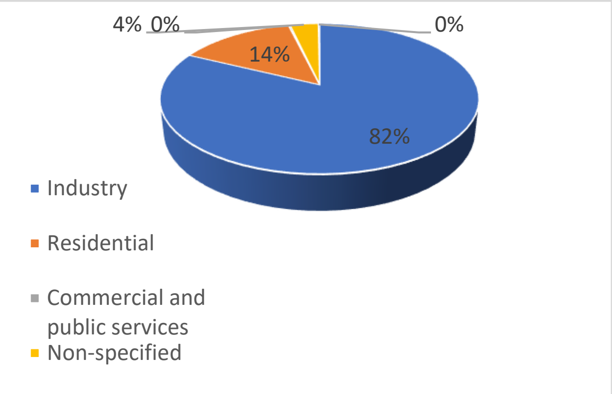


Chart 1-4: Electricity Consumption by Sector (IEA)

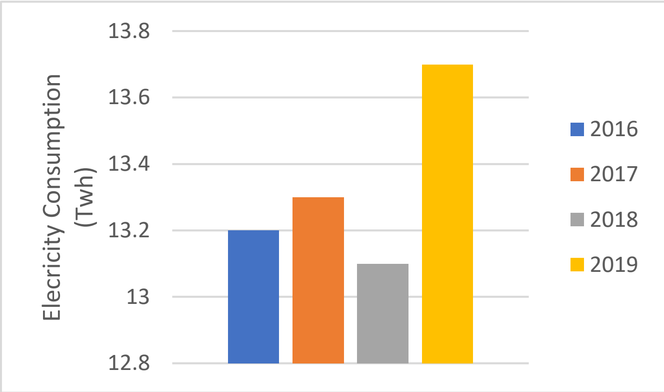


Chart 1-5: Total Electricity Consumption (2016-2019)

1.2.1. Transmission & Distribution

One of the critical issues that makes the electricity sector in Mozambique lack behind is the transmission system in the country that it is very expensive to dispatch power all over the country due to its large size [9] so the system is not able to cover all areas. For instance, power delivered to the Maputo region is delivered through South Africa as HCB exports power first to Eksom(south African electricity public utility) and then resells it back to Mozambique. This leads to essential problems related to the technicalities as well as the energy security.

Nevertheless, long dispatching systems causes power wastes due to line losses. And in the areas where the system does reach still it lacks resilience and reliability due to the missing power grid.

The national grid is mainly operated by Edm although some of the lines are owned by HCB, the operator of the Cahora Bassa hydroelectric plant, and by Mozambique Transmission company (MOTARCO) which is responsible to supply power directly from EKSOM SA.

The EdM transmission system comprises three regions: [10]

- The northern region has a 220 kV transmission system covering about 1,000 km from the Songo substation to Nampula and continuing at 110 kV to the town of Nacala. A separate 220 kV system (operated at 110 kV) extends from Tete, linking with the central region at Chibata.
- The central region has a 110 kV system linking the hydroelectric power stations at Chicamba and Mavuzi with the load centres in the Beira-Manica corridor.
- The southern region comprises a 110 kV network extending from Maputo to XaiXai, Chokwe and Inhambane, together with a 275 km single-circuit line from Maputo to Komatipoort, where it connects with the system operated by South African utility ESKOM.

EDM has mainly two operational concerns related to the finance related to the company as revenue raising is being not possible as well as being able to balance the energy needs of the large-scale energy users with the domestic at peak load. The balancing problem is referred to the aging of the infrastructural assets and often breakouts and shortages [11]. EDM registered by 2019 7498 power interruptions with an average duration of 73 min[12].

Another concern for the sector is having a tariff which is considered among the highest in southern Africa (USD 10.58 cent/kwh), a situation that is affecting the majority of the population as they live on less than 1.9 USD per day. [13].

Generally speaking, the power sector in Mozambique is facing three main challenges that need to be addressed in order to to be able to achieve the universal access by 2030 as set in the Country’s plan.

These challenges are :

i. Providing reliable and efficient electricity supply and it is proved that this is not the current case as for the number of the interruptions mentioned in the above text. In addition, the financial struggles EDM passing through are a big barrier for proper maintenance for the grid.
ii. Dealing with the generation and transmission capacity to be able to handle the demand expansion. It is expected that the demand will continue increasing in

the upcoming years as it witnessed an increase of 9% per annum in the previous 5 years.

iii. To provide access of the electricity to the vast majority of population. 70% of the population lives in rural areas and are still without access to electricity. Access rate is just 32% with 15% goes to the rural areas while 57% is dedicated to the urbans[14].

Mozambique targets 50% of all households to be grid-connected by 2030. Hence, Edm requires to connect 175,000 household every year till 2030. So the notion of off-grid electrification comes into life as it can increase significantly the electricity access rate in the country.

2. Renewables in Mozambique

According to a report done by AMER (Associação Moçambicana de Energias Renováveis) renewables integration target in the national grid is 20%. Energy for All programme, was set by the government to increase the electrification access to electricity by 2024 to around 10 new million people. Still the biggest challenge would be reaching the universal access by 2030 which includes not only the on-grid systems but also the off-grid ones.

The Mozambique Renewable Energy Atlas, published by FUNAE in 2014, states a total renewable potential of 23,026 GW which corresponds to 7,537 MW of priority projects, including 599 MW of solar power, 5,645 MW of hydro power and 1,146 MW of wind power [8]. As mentioned in chapter 1.2 the hydropower potential out of the renewables is the most used where it accounts to 79% of the total installed capacity of the 2780 MW (only 38% available for the national consumption as the majority is dedicated for the export phase).

The contribution of the Renewables is on the pathway of the increase, where Solar & wind counts for 41 MW currently and is expected to grow into 306 MW. Also, IPP (Independent Power Producers) are considered to substantially keep increasing in the next decade and contribute significantly to the 100% access to electrification.

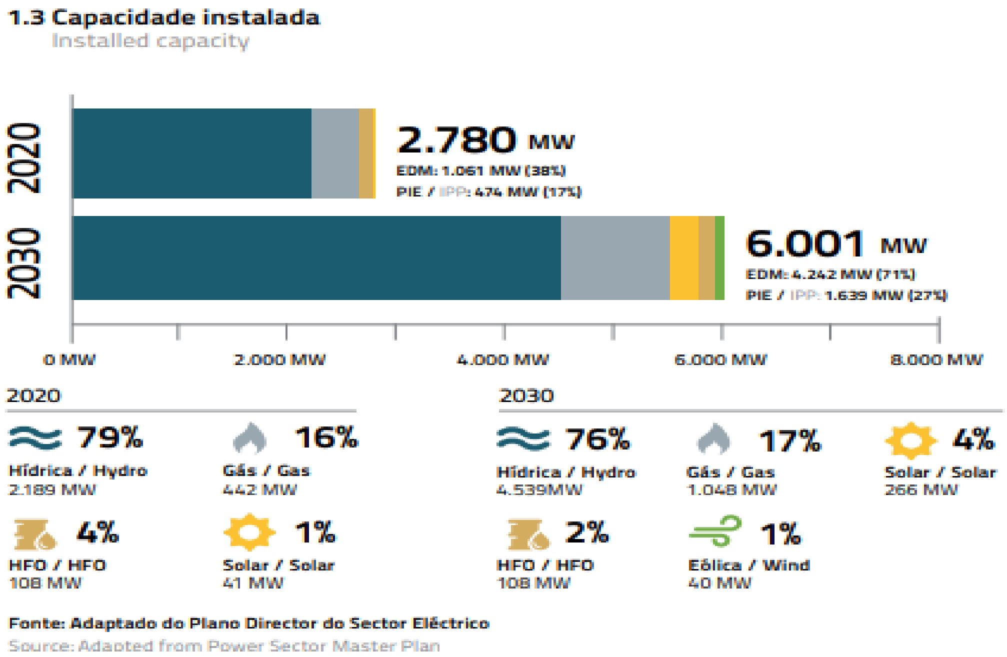


Figure 2-1: Installed capacity in 2020 and the expected progress by 2030

Figure 2-1 clearly shows how the renewables integration and the dependency on the IPP (independent power producers) would change in the upcoming years.

Bio-energy

The country has a potential of 2 GW where only 128 MW will be exploited in the short term.

The biomass resources for electricity generation can be distributed on:

- Forest Biomass: of woody residues
- Sugar industry: Residual bagasse resulting from the sugarcane crushing process is used to produce energy in cogeneration.
- Municipal solid waste: deposition in the landfills of biogas
- Other: vegetable oils extracted for coconut[15].

Projects related to bio energy will definitely create more jobs in the industry of Mozambique. For instance, the Mozambician oil company petromac is projecting production of 226 million of biodiesel a year which will cover the country's total petro-diesel consumption and will offer around 800 jobs.

Solar

As other countries of Sub-Sahran Africa Mozambique has a substantial solar potential that is not being exploited in an efficient way although it could form a huge solution for both utility scale and the residential PV for o and off grid electrification. The global average of solar power is of 5.7 kWh/m2 /day, being the minimum average of 5.2 kWh/m2 /day (Lichinga, province of Niassa) and the maximum 6.0 kWh/m2 /day (Pemba, province of Cabo Delgado). The value of global radiation increases from south to north along the coastal line[16].
The total potential reaches around 23,000 GW. However, according to the current policies and needs of Mozambique as well as the population dispersion all over the country there is approximately 2.7 GW that could be developed easily. Off-grid solar home systems showed effectiveness for rural electrification than extending the on-grid due to the distribution of the solar home potential.

The SHS (Solar Home Systems) market in the past was with big vagueness as the distribution was through FUNAE and here was informal selling of low quality or without guarantee for well installation.
However, since 2017 private operators were introduced to the market selling SHS through certain schemes (PAYGO). They sold around 70,000 which is still really far from the estimated potential of 824,000 [8].

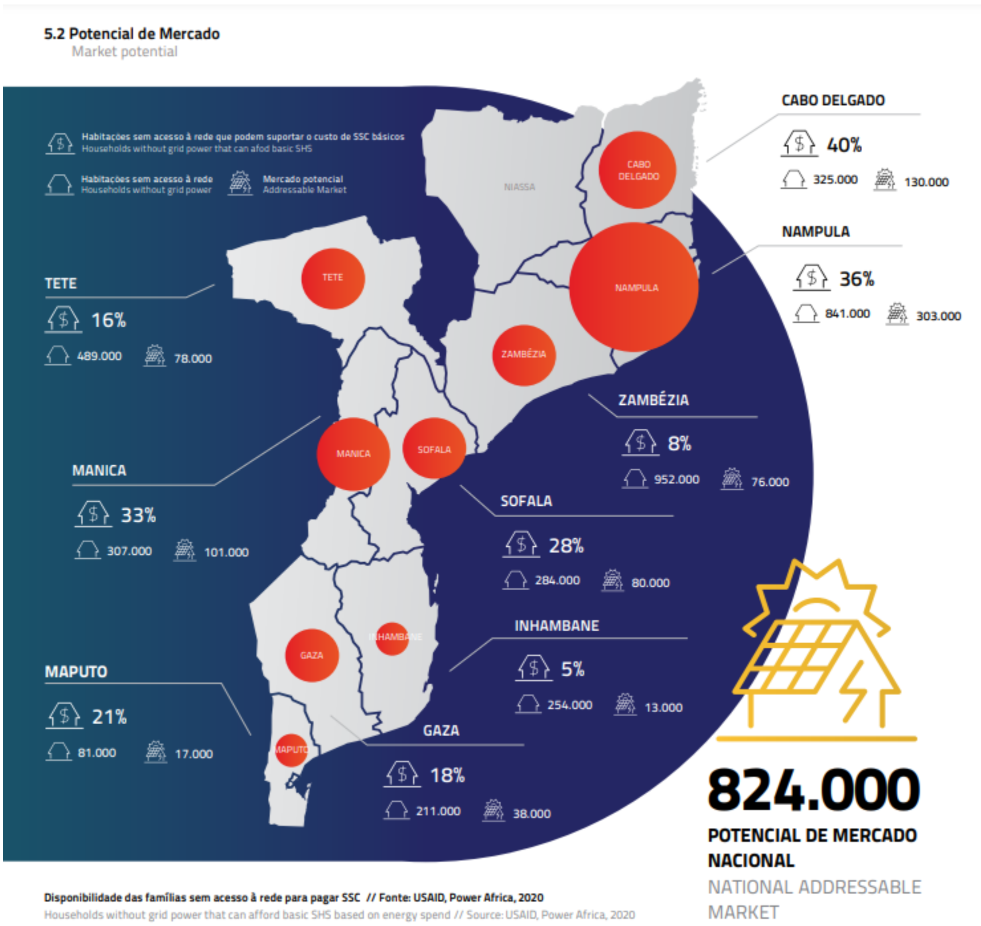


Figure 2-2: Households that can afford SHS systems based on energy spend.

In general, the SHS market as well as building based solar mini grids by the effort of FUNAE is on an increasing trend as it's going in line with the target of increasing access to electrification but more study is required to the plants installed to align with the demand of the rural villages.

Hydropower

Is the highest among the African countries with a potential that varies between 17000MW to 19000 MW. More than 80% of total potential is located in the Zambezi valley, including the existing Cahora Bassa dam with an installed capacity of 2075 MW , as mentioned previously, this dam produces electricity domestically and to South Africa and Zimbabwe. The Dam brings to the country huge revenues as the majority of the power produced is exported but this urges the problem of the low access to electricity by the Mozambiqan population.

Therefore, the building of mini hydropower plants and the exploitation of the 12 other major rivers in Mozambique in this sense could offer a huge opportunity to the rural areas to have access to electricity.

Wind

Wind Power potential capacity in Mozambqiue is about 4.5 GW where 25% is ready for direct exploitation with the national grid. The projects are quite limited and the average wind speed is 7m/s in the regions of Naputo and Gaz [17]

In 2019 IRENA published that electricity capacity and generation due to wind energy was 0 MW. The same data was delivered by another report published in 2018 " Mozambique Final Report" commissioned by Netherlands Enterprise Agency.

IRENA also compared the onshore wind potential of the country with that of the world in seven different classes, with a height of 100 m. The results as shown in the bar chart below.

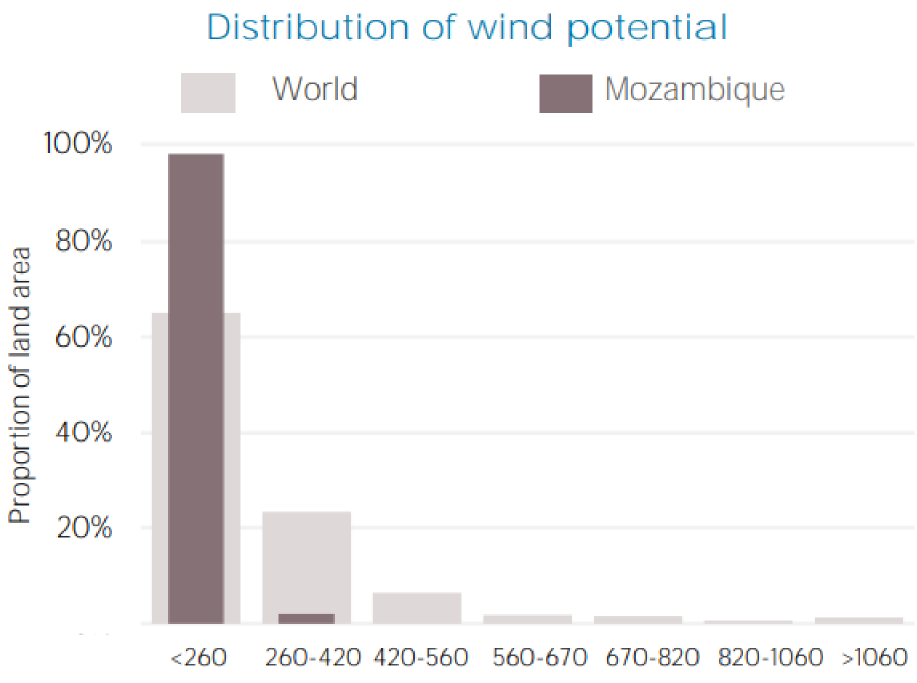


Chart 2-1: wind power density at 100 m height [18]

2.1. Institutional Arrangements

The energy sector in Mozambique is regulated and supervised by the Ministry of Mineral Resources and Energy (MIREME). MIREME formulates Energy Policy and monitors policy implementation. However, there are other key institutions within the government structure whose functions and objectives have a direct impact on the sector and on the implementation of relevant measures concerning its development. For the electricity and energy access sector, the most relevant institutions are the Energy Regulatory Authority (ARENE), the Electricity of Mozambique (EdM) and the Energy Fund (FUNAE).

The Energy Regulatory Authority (ARENE) was established by Law 11/2017, September 8, 2017. ARENE's mission comprises the supervision, regulation, representation, control and sanctioning of all electricity operators (ERI 2020 Mozambique Country Profile Note). ARENE's regulatory functions extend to Economic Regulation (TariffSetting), Technical regulation (Quality of Service), Institutional Capacity, and Energy Efficiency Development. ARENE has a public website that provide public access to key regulatory documents such as license application procedures, laws, tariff methodology, providing a first comprehensive overview of the sector to prospective investors [19].

Two main companies are the main operators for electricity:

Electricidade de Moçambique (EDM), which is the national power utility company responsible for part of the generation, for transmission and distribution, and Hidroeléctrica de Cahora Bassa (HCB), responsible for the management of one of the biggest hydropower systems in Africa, with an installed capacity of 2,075 MW [20].

The Energy Fund (FUNAE) was created to promote the development, generation and use of several forms of energy at low cost to supply rural and urban areas inhabited by low-income households and to ensure a rational and sustainable management of energy resources. The Fund is under MIREME's authority and develops its activity at national level; additionally, its Board of Directors may decide to open or close branches or other forms of representation and appoint other institutions to act on its behalf.

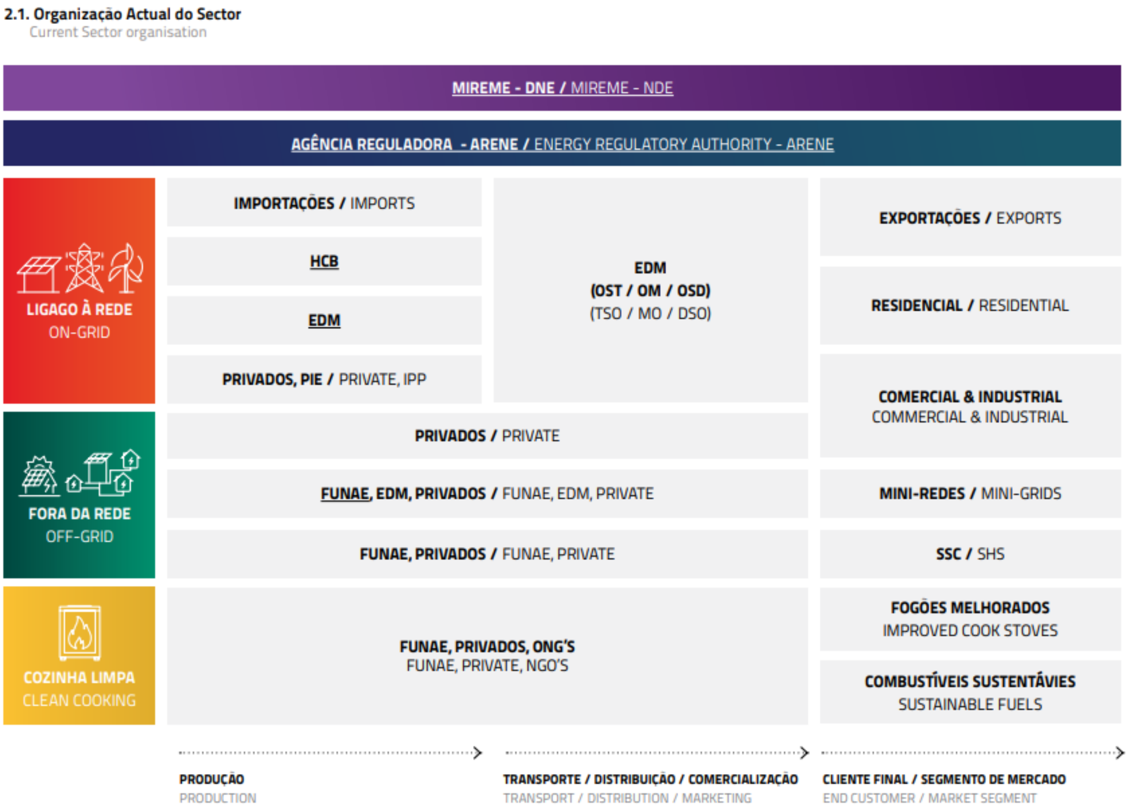


Figure 2-3: Energy sector organization according to a Report prepared by AMER

2.2. Energy Strategies and Policies

Since the 90s and the government of Mozambique is signing laws and cooperate with other countries in order to set some strategies and policies for the energy sector with a focus on increasing the electricity rate to the population. In 2020 the ERI (Electricity Regulatory Index) of Mozambique was 0.382 which is considered really low compared to the average index of Africa (0.485) and the World. Endeavors to mitigate this situations are many and a lot of actions need to be deployed such as developing tarrif methodology, provide simplifying legal framework for small systems, and develop legislation and policies.

In 1997, the first electricity act was announced to cover the generation, transmission, distribution and commercialization of electricity in Mozambique, as well as the import and export of electricity. It allows for private participation in the sector under a concession system, but it does not outline operational requirements for off-grid access projects. Inadequate clarity means that private sector-led mini-grids are made to use the same regulation applicable to the utility-scale energy projects and are thus obliged to charge sub-commercial national tariffs.

Few Energy Strategies were set and discussed throughout all the years until today:

Energy Policy 1998 – council of Ministers: It aims to promote economical viable investments for the development of energy resources (hydropower, coal, natural gas) and to ensure reliable supply of energy at possible low costs.

Renewable Energy Development Policy 2011-2025: Promote the use of new energy sources and Renewables particularly in the rural areas through public and private sector. Increase access to high quality energy services at affordable costs and ensure energy security.

Biofuel Policy and strategy: defining policy guidelines and important measures for the sake of promoting biofuels and the procedures to implement it.

Energy Strategy 2009: The policy aims to achieve the diversification of the use of the energy sources available. Try to adopt new strategies for the tarrif scheme that reflect actual costs taking into consideration the combating to the environmental adverse effects.

Fostering business investment in the exploitation of new technologies and research with the urge on international cooperation and coordination.

The National Energy Strategy (2014 – 2023) which main objectives are to strengthen Mozambique's position as a major regional energy producer, to contribute to social development and poverty reduction, and to boost overall economic growth. The strategy includes: (i) creation of an energy authority; (ii) promoting energy efficiency, including fostering habits of reasonable and responsible energy consumption; (iii) revision of the tariff methodology settlement and creation of feed-in-tariff system and; (iv) fostering rural and peri-urban electrification, including extending grid access, improving energy quality, and increasing administrative capacity to encourage the productive use of energy to raise USD 200 million each year for the next seven years to extend and improve energy access in rural and peri-urban areas, with the goal of obtaining 44% universal access by 2021 and 50% grid-based access by 2023.

EDM – Rural Electrification Plan : The plan aims at achieving all the projects designed to be implemented in the period of 2005- 2019, and to use the cross subside to maintain the rural areas where there is no profit. Increase investments in rural electrification to more than 70 MUSD per year relying on donors and EDM.

2.3. Off-Grid Electrification for Mozambique

In September 2021 the government of Mozambique approved the Regulation for off-grid energy access [21]. This regulation is the outcome of the efforts put by Ministry of Mineral Resources and Energy (MIREME), the Energy Regulatory Authority (ARENE), and the National Energy Fund (FUNAE) which makes Mozambique joins the neighboring countries for having a clear regulatory framework to the off grid operations. The government is aiming to ensure the necessary conditions for the private sector to develop its activities and protect investments in a diverse set of technologies applicable to the off-grid context, such as solar home systems, mini-grids, and improved cooking solutions. The off-grid rural electrification is led by FUNAE which has an experience of two decades in the rural electrification and it accounts for giving access to around 3.7 million people through the supervision of several projects funded by international donors between the period of 2005 – 2014 [22].

FUNAE has installed approximately 70 diesel-based mini-grids operated by local communities, and approximately 1,500 solar home systems (SHS) as of end 2015. It also manages the 50 Vilas Solaires project, which installs 4 kW solar plants with battery backup to electrify rural institutions, microenterprises, and households in 50 villages. It has additionally installed several (approximately 60) solar irrigation systems between 2006 and 2016 [23]. The integration of the private sector in the mini grid systems is still considered scarce and this is basically the adverse of regulations present that can ensure the rights of the private sector which is probably going to change in the current years.

The Mozambique's National Electrification Strategy in 2018 sets the universal access to 100% of electrification to be reached by 2030 and suggests to have a rely of 70% from the on-grid and the other 30% from the off-grid. This indicates that Mozambique will need 4 million off-grid connection by 2030 considering that 8 million households will be present by that time. Unfortunately, if the effort doesn't accelerate and the pace of off-grid connections remain the same Mozambique will not be able to achieve the over ambitious target of total electricity access. To achieve universal access to energy by 2030, the country will need approximatively to connect between 450,000 and 550,000 households each year (for a total cost between 4 and 5 billion USD, approximatively)[8].

Mini grids are an effective solution offered by FUNAE to assist the government of Mozambique to reach the universal access target in addition to have a good impact on the socio-economic development of the communities.

According to the 2nd edition of the **Renewable Energy portfolio – Hydro and Solar** presented by FUNAE in 2019, 31 hydropower projects were identified with a total potential of 100.2 MW; of which two are under construction, one has a feasibility study, five have pre-feasibility studies and 23 have baseline studies. Also identified were 178 solar energy projects, with a total capacity of 8.7 MW, of which feasibility studies were carried out at 38 sites and four are in the execution phase [24].

The main challenge for off-grid remains the lack of institutional and legal framework, the unorganized planning of the projects, and the affordability of the communities households to the tariffs of the SHS and other projects.

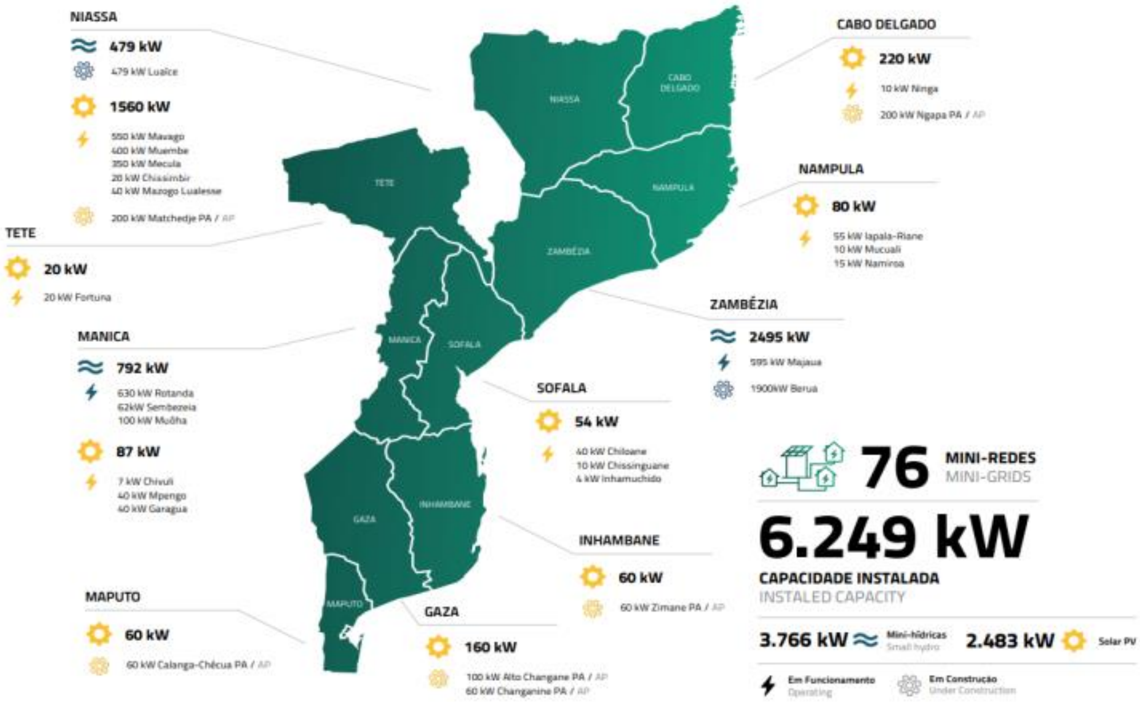


Figure 2-4 : mini-grids projects by FUNAE

3. Small – Scale Generation System

3.1. Definition

Mini girds aim to deliver power over low voltage distribution networks to supply relatively a small number of consumers. It relies on an interconnected local generation sources such as micro-hydro or photovoltaic or biogas gasifiers or wind potential [25].

The naming is not universal or distinguished from other terms and can be interchangeably used, we will be using mainly the term "mini grid". Actually, the usage of such small scale generation systems is not a new approach as in the beginnings of the electricity production period, small generation plants were quite decentralized and supplying DC grid to nearby dense load. This changed with technical advancements to switch into large scale generation plants and huge transmission grids supplying AC power.

According to the EU energy initiative Partnership Dialogue Facility, mini grids are systems involving small scale generations (from 10KW to 10 MW) , and the distribution of electricity to local customers through grid connections that could be isolated from the national grid system. It differentiates the "Micro grids" as generation systems similar to mini grids but are smaller in size and capacity (up to 10 KW) [26].

IRENA defines the mini grids; an integrated system that could be interconnected to the main grid or independent and depends on load and energy sources. It has certain functionalities: power generation; power storage; control, manage and measure (CMM); convert and consume.

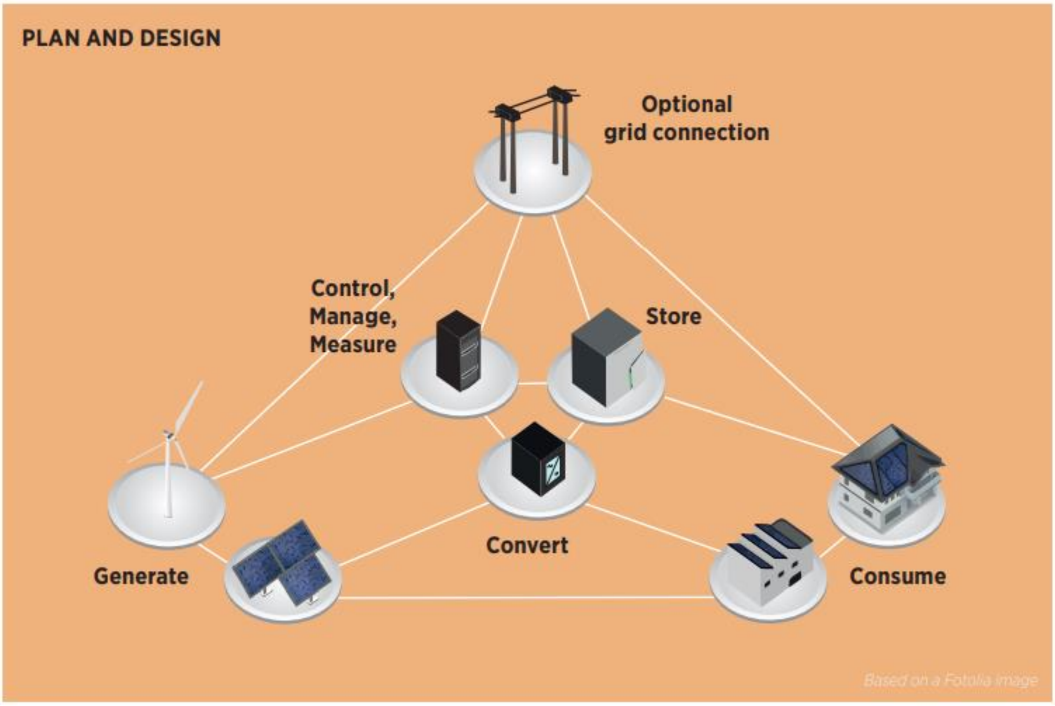


Figure 3-1: Example of Renewable mini-grid. [IRENA]

3.2. Classifications

It was clear that access to electricity has a huge positive impact on improving the life conditions of the communities from social and economical point of view. However, the expansion of electric supply in the world is not equal so we can still find countries mainly in Africa that suffer from low electrification rate, low consumption per capita as well as low quality of the electric supply. The United Nations explicitly demonstrated the importance of modern energy, thus the access to electricity, through SDG 7 of the sustainable development goals-2030 Agenda which states “ensure access to affordable, reliable, sustainable and modern energy to all”. This ambitious goal is pointing out directly to help the developing countries of Africa to be able to increase the electrification rates as 35% of the African population only has access to electricity.

In general, the absence of electrification in the African countries is centered in the rural areas which already are scattered populated, isolated and struggling from good health care systems and access to clean water. This is due fundamentally to the high costs of grid extension in such countries.

With the progressive interest in achieving universal access to energy and the sustainable development goals, the solution of deploying decentralized systems came to rise and specifically micro grids to the aim of rural electrification.

Major factors that contributed to the increase of interest in the use of small scale generation systems can be divided into 5 main categories:

- Economic : related to the avoiding of the transmission and distribution costs. In addition, to the reduction of power plants costs of combined heat and power generation
- Environmental : GHG emissions is the forefront subject of many governments and countries and the raise of the public awareness across nations regarding the electricity sector impacts.
- Political : reduction of the fossil fuels dependency has been recently a huge matter for the big governments as well as increasing primary source diversification.
- Technical: small power technologies proved their efficiency to meet demands with reliable supply and the possibility of metering and controlling the equipment
- Social: promoting green technologies all over the world as well as the positive impact did such mini grids provide for the social conditions of the rural areas communities.

According to a publishment by the *department of Energy at Politecnico Di Milano " Off-grid systems for rural electrification in developing countries: Definitions, classification and a comprehensive literature review"* decentralized systems are systems where conversion and distribution are not interconnected to other units.

They are basically supplying a single consumer or a number of consumers. Using the number method of consumers allow us to differentiate between Stand-alone systems or micro-grids.

- Stand alone systems: usually supply power through a single energy source to a single user (e.g: school, health center, household, kiosk).
- Micro-grids: local energy conversion based on one single source delivered to multiple consumers categories (home based systems, community based systems, and productive based systems) [27].

Hybrid mini-grids are related to distributed energy systems and consist of more than one generation unit of different energy sources connected to a central brain and interact each other through a grid network to supply a number of different consumer types.

3.3. Three generation of Mini grids

The following will be a review on the types of mini grids related to the change and development experienced in technology through out the years.The world bank clearly indicates the different between each generation of mini grids.

1. First Generation of Minigrids:

Historically, most of the current centralized huge systems started as isolated small power plants and mini grids. Hence, the first generation were the base of what we have now from well distributed power supply. They stand behind the early development of the electricity sector and the industrialization of the developed countries. As demand increased, technologies became more advanced, and the regulations get more stabilized. These scattered first generation were either integrated or combined with larger grids to form the centralized huge power plants.

2. Second generation mini grids

Typically, small and isolated systems serving small villages mainly rural areas with low demand and low population densities. When such mini grids were built little consideration was given to be extended later to the main grid of the country, so when the main grid arrives usually they get abandoned. Regarding the technical side of such mini grids, mainly depends on standard technologies which already exist (diesel or hydropower) and the control is referred to basic methods like on site reading and in person bill charge. Across the world almost 19,000 second generation mini grids were identified by ESMAP of the world bank.

3. Third Generation Mini grids

Several important factors make such generation different from the previously mentioned.

Technology development is the main driver behind the commence of the third generation. The improvement we are witnessing in the technology sector has an impact in all over the electricity sector and not certainly on mini grids. But the rapid decrease in the cost of renewable technologies as Solar PV, batteries, and electronics made it easier for this kind of mini grids to be introduced in the sake of electrifying the rural areas.

Nevertheless, the presence of national and international private companies interest in being part of the market as it aligns with their missions an targets, encouraged the building of the third generation. Big companies found it effective to promote themselves and scale up their proprietary technologies. Another factor in this aspect is related to the public-private sector cooperation in the manner of increasing third generation mini grids. Such agreements proved the facilitation of the work for private companies in terms of legislations and subsidies received.

The improvement of the regulatory framework by nations concerning rural electrification and the mini grids permitted the increase in the emerging of the third generation in the sector and specifically in some sub-suhara African countries that still are required to implement better regulations and laws. The thought of the mini grids being available to the extension to the main grid or even directly connected is usually not ignored in the third generation and this what makes them not isolated as the second generation.

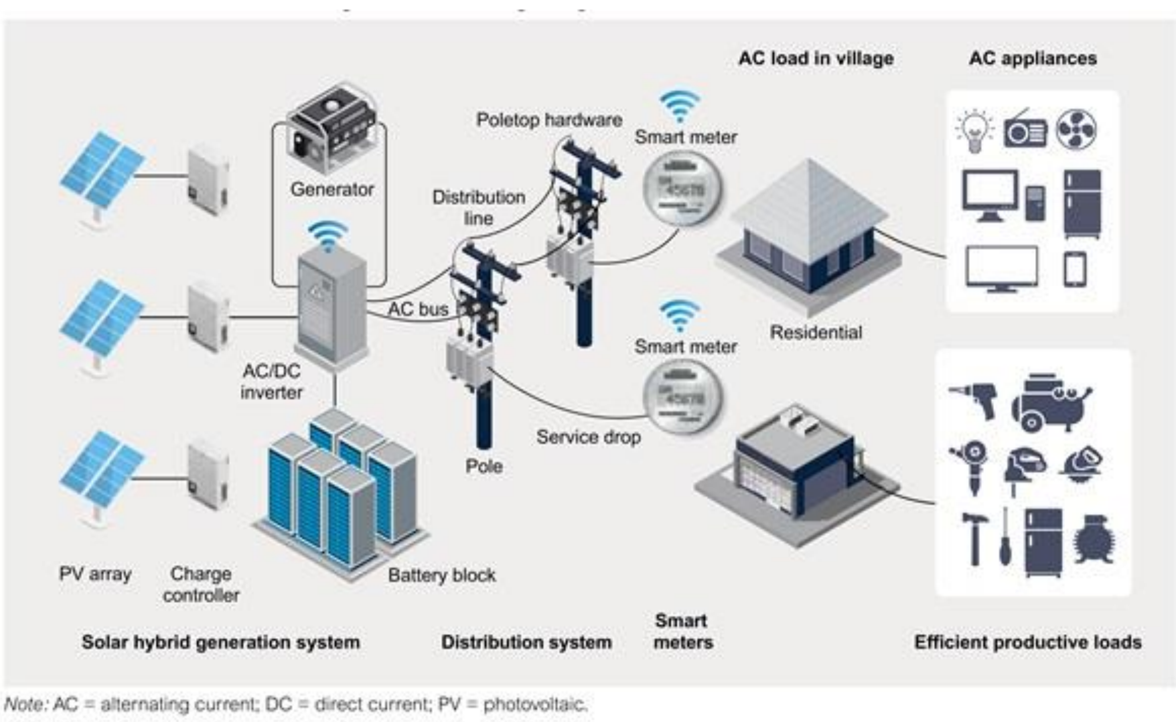


Figure 3-2: third generation mini grid

3.4. Technical Design

Any grid system consists of three main components : production, distribution, and end user.

For the mini grid system of third generation the same is applied but the control management and metering is advanced and well designed.

1. Production:
   Generation of energy could be through several energy resources that interconnect together. And it is not necessary to be a renewable source as we can find beside PV photovoltaic; wind, hydropower sources, diesel generators are also included in many of the African hybrid mini grids. For the mini grids the generation might be from a single source or multiple sources.
   All types of mini grids use inverters as the end user current would be different from the one generated. For example, solar PV usually generate DC current and in this case we are in need of inverters that would change DC to AC as the majority of the appliances require AC.

Production systems include management systems as they serve the mini grid by measuring ,monitoring and controlling electrical loads. Metering and monitoring allows the managers of the mini grid to gather data about the end user consumption and energy activities which impacts operational decisions. It is also suitable for remote controlling way unlike the second generation mini grid. Other component of production system that needs a lot of consideration is storage. Usually, diesel generation systems don't require storage systems as the power are dispatchable. However, tackling renewable resources as solar and wind that are not available through out all the day, a storage batteries are required to store energy and supply the end consumers when the main resources are not available. In this sense all kinds of mini grids require some kind of storage [26].

The appropriate energy technology for the mini grid depend on several factors considered by the project developers from the cost and longevity to the optimization of performance.Throughout history, lead acid batteries are the most commonly used however advanced technologies have addressed to the market the lithium ion batteries. According to a report by IRENA, in 2019 66% of the mini grids installed with storage systems were using lead acid and 32% were relying on lithium based ion. As the cost of the lithium is falling a massive change is expected in the future [28].

The BESS (Battery Energy Storage System) mainly differs according to five characteristics related to: life cycle, temperature efficiency, round-trip efficiency, initial cost and specific energy.

Battery Technology	Status	Cycle Life	Temperature Sensitivity	Round-Trip Efficiency (%)	Initial Cost ($/kWh)	Specific Energy Wh/kg
Deep-cycle lead-acid	Available	**1,650 cycles at 50% DOD, 1050 cycles at 80% DOD**	Cycle life degrades substantially above 25 deg C	**80%**	**$300** per kWh	33–42
Lithium-ion	Available	**1,900–3,000** cycles at 80% DOD	Degrades substantially above 45 deg C	**90%**	**$700** per kWh	**128–256**
Lithium-sulfur	Mostly laboratory	(Data not available)	**Laboratories developing versions safe at 55 deg C**	**90%**	>$1,500 per kWh	500
Zinc-air	Available	Up to **500** cycles	(Data not available)	(Data not available)	**Competitive with lead-acid** batteries	Up to **400**

Figure 3-3: Different technologies parameters for BESS – USAID

Despite the low life cycle for lead acid and their low energy density they were mostly used due to their cost effectiveness. LIB (Lithium ion batteries) are the most favorable nowadays as they are of high energy density and are light weight. The change in prices as mentioned will make LIB dominating the grid market specifically in rural electrification. New innovations, such as replacing graphite with silicon to increase the battery's power capacity, are seeking to make lithium-ion batteries even more competitive for longer-term storage.

2. Distribution System

They transmit the power generated form the minigrid to the end user. It consists mainly of transmission lines, transofrmers, and infrastructures to support the lines. The aim of the transformers is to change the voltage of the electricity either by increasing or decreasing.

3. End user System

Such systems creates for the consumer and the operator an easy pathway to access, use and monitor electricity supplied by the mini grid. It consists of connections from the mini grid as well as the protections related to the electrical appliance used and the purpose of it.

It is very crucial as it provides data for the consumer for his energy consumption and estimate its cost and understanding his usage of the system. At the same level, this allows the operator to control the system and forecast the efficiency of the system in addition to the demand pattern. Furthermore, the operator would able to provide suitable tariffs compared to each energy consumption.

Smart technologies are improving performances sustainability and making complexity of the system less such as smart meters; a two way communication by which the device electronically record the consumption and provide the data to the utility, & remote payments. For example, in Kenya the tariff collection process is automatized by interlinking tariff payments with the widespread telecommunication network, allowing people to pay bills via their mobile phones [M-PESA mobile phone] [29].

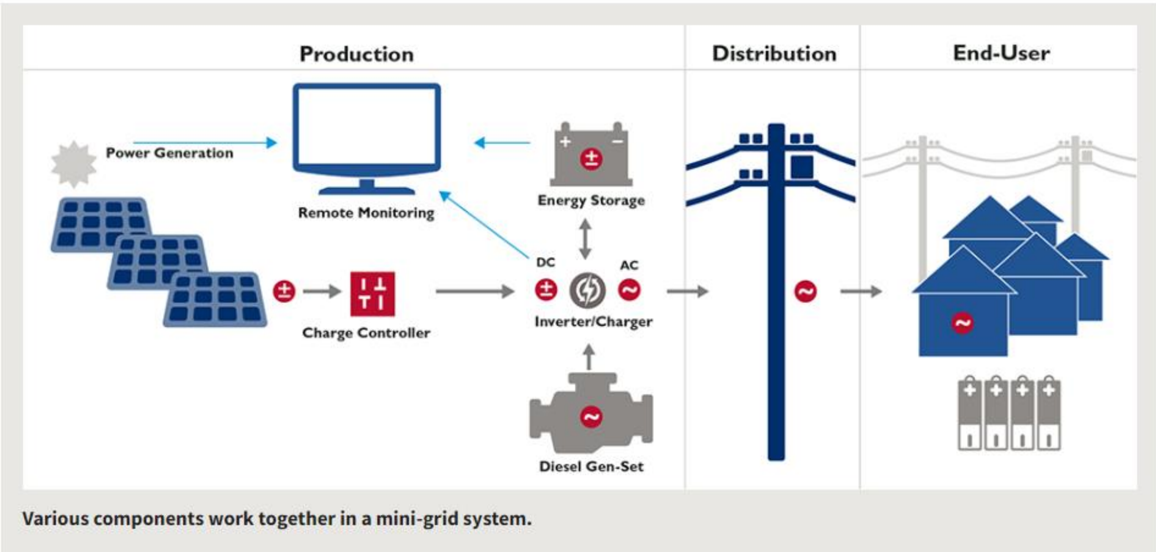


Figure 3-4: Technical components of the mini grid system

4. Rural Electrification in Mozambique

4.1. Rural areas situation

According to the world bank data just 4.5% of the rural electrification population has access to electricity. A number which decreased compared to 2018 and this anticipated to be due to the mis management of some rural electrification projects during this period [30].

As other rural areas in South Africa poverty is still dominating the communities living there. For Mozambique, the vast majority of the population lives on almost 1.25 USD per day. Areas are way far from the electricity infrastructure (main grid) and due to the low scattered population density, the demand for electricity is very low.

Mainly farming is the main source of food, usually with fishing rural communities can contribute to the their households basic requirements without having a huge surplus for sales. This low agricultural productivity is a result of lacking appropriate technologies and supports. Agricultural potential varies among regions of Mozambique as the center and northern provinces experience a better condition. Soil are more fertile and the rainfalls are abundant compared to the south. Southern provinces have poor soil and the climate is drier where natural disasters such as floods may occur. So southern communities along with the coastal ones are consider the poorest among the country.

Women suffer from less education compared to men and thus fewer skills. Hence, women usually work in agricultural activities as growing crops. With minimal health system care, women suffer from during childbirth. Although land law ensures equalized access to lands to women, still they are not aware of their legal rights and they have limited lands to farm and therefore food security.

As mentioned in the previous chapters, access to electricity increase the opportunities to a better social economic conditions. However, to let the investment is financially viable, we have to ensure the sustainability and affordability between the power generation, the power demand and the consumption market of these areas.

Figure 4-1: Mozmabique women working in Land

4.2. Challenges

Mozambique's endeavors to reach universal access of 100% electrification by 2030 increased the efforts of local and international organizations to make this target achievable. However, FUNAE, the main player in bringing electrification to rural areas of Mozambique bumped against several factors that could lead to the their failure.

At the first level, the population growth in Mozambique is growing steadily and is expected to reach 48.2 million in 2042 according to study done in 2017 and around 52 million according to the " world population growth review " [31].

IF (International Future System – a tool to forecast country's population growth) mentions that in 2040 Mozambique will have around 53 million person by which the population growth will be around 2.5% per year. Infact, just in rural areas the population reached approximately 20 million individual in 2022; an increase of 2% from 2020.

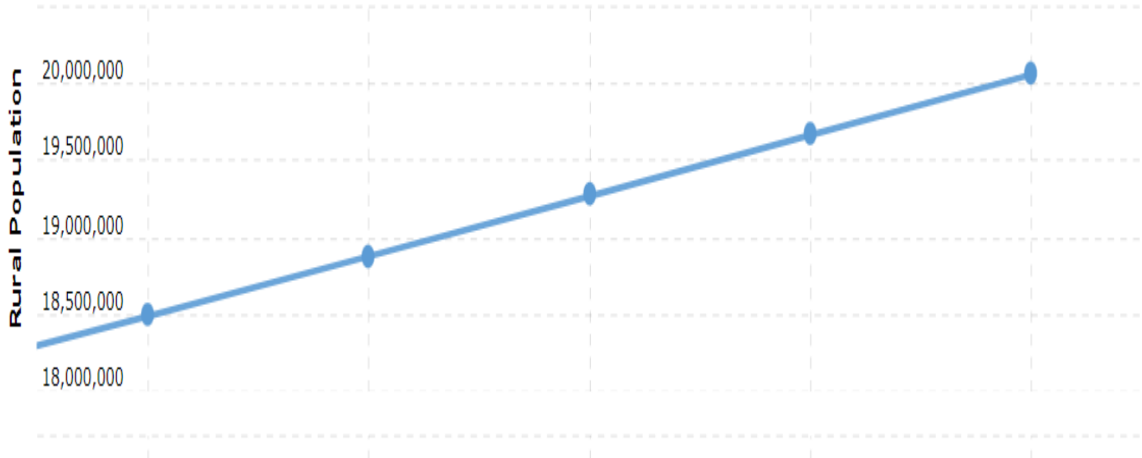


Chart 4-1: rural population growth between 2017 – 2022 [32]

In this sense, electrification would reach 77 % of the population with the current pace put by the government and stakeholders, which means efforts shall be doubled to fulfill the aim of 2030.

Another essential factor challenging the rural electrification sector is the power demand and consumption in such areas. With no doubt, power demand is increasing in parallel to the population growth. Like the majority of rural areas of sub Saharan African countries, communities in rural Mozambique have low productive activities and activities, demand even in their houses is low where even in lighting they depend on kerosene lamps. And as electricity is essential to the human development, the investments in this sector for rural areas shall be on different levels and with large funds.

Moreover, the large investments consider too the land availability and occupation. In rural areas of Mozambique, lands are occupied in a very chaotic way which makes implementing electrification projects hard to achieve knowing that even communities are disorderly scattered. These, increase the challenges for the Mozambique government and institutions to have a territorial planning to provide suitable locations for electrification as investments in the utility infrastructure is far from being achieved.

Human behavior and cultural habits found in Mozambique, and many other poor countries, is a serious issue into transforming rural areas to be electrified. The use of biomass for cooking and heating is widely known and this relies on burning of firewood and charcoal which is also an outcome of deforestation. Such practices are in the depth of such communities as are considered part of their cultural aspects and it's difficult to drive them into changing to sustainable environmentally friendly practices. Furthermore, for FUNAE to implement these projects the communities need to be well educated and trained on changing their life style that is precedently influenced by cultural values and this requires huge and well planned efforts too.

4.3. FUNAE Projects

According to FUNAE, 11 cities, 669 schools, 623 health centres and 77 public buildings were electrified through off-grid PV installations during 2005-2014. The fund also installed approximately 70 diesel-based mini-grids operated by local communities, and approximately 1,500 solar home systems (SHS) as of end 2015. It also manages 50 Vilas Solaires project, which installs 4 kW solar plants with battery backup to electrify rural institutions, micro-enterprises and households in 50 villages. FUNAE installed 60 solar irrigation systems between 2006 and 2016. A recent report by the World Bank notes, however, that the cost of electrification programmes delivered by FUNAE is not covered by electricity tariffs, nor is EDM receiving subsidies from the government for this purpose. So far, EDM and FUNAE have been implementing the electrification investments with limited available resources based on unclear priorities set at the political level and without proper planning following low-cost prioritization[33].

5. Tools Overview

Achieving SDG7 requires a thorough attention to the rural areas and communities. Although hybrid microgrids present benefits such as reliable and secure access to local energy as well as economic boost for the community itself, still the plan and design is a complex issue to ensure that the renewable sources are deployed optimally. Such complexities are mainly referred to the units sizing and system configuration, power dispatch strategy and the uncertainty of future power consumption, and also the network design [34].

In the aid of rural electrification an open source tools were developed to allow us identify the load demand through stochastic optimization and to check how can we deploy our technologies with different objective optimizations related to cost and technological aspects.

5.1 Load Generation – RAMP Tool

Uncertainties about energy demand and profiles depend on different factors and hard to be predicted. Bottom up approaches of modelling load profiles for remote off grid systems basically relies on interview based information which provides less detailed data than time-use diaries and significantly affected by uncertainty. Moreover, energy planning in remote areas requires a highly flexible and customizable modelling approach, in such a way to ensure it applicability to a wide range of contexts [35].

For the generation of high resolution multi energy load profile “RAMP - Remote-Areas Multi-energy systems load Profiles” tool is going to be used through out our study. RAMP is a bottom stochastic approach based on information often required by field surveys about people’s appliances, while timing and duration of usage of each are taken from the literature, and proposes an expanded stochastic approach with an increased degree of stochasticity.

From a conceptual point of view, RAMP is based on three main layers of modelling, which are:

1. User type layer. Where a set of arbitrary User types is defined (e.g. Household, IGAs, public lighting, health and education centres) whose level of discretization depends on the modeler’s needs; for instance, when more precise

information is available, a "Household" User type may be further subdivided by income classes or building type.

2. ii) User layer. Where each User type is subsequently characterized in terms of the number of individual Users associated to that category.
3. iii) Appliance layer. Where each of the Users belonging to a given User type is further characterized in terms of Appliances owned.

User type and Users	
$Usertype_j$	Name of *User type* (e.g. "households")
n	Number of $Users_{ij}$ (for $i = 1:n$) within $Usertype_j$
Appliances	
$Appliance_{jik}$	Name of the *k-th Appliance* associated with the *j-th User type* and the *i-th User*
m_{jik}	Numerosity of $Appliance_{jik}$ (e.g. numerosity of 'indoor light bulbs')
P_{jik} $[W]$	Power absorbed by a single item of $Appliance_{jik}$
$tot_{use_{jik}}$ $[min]$	Total time of use of the $Appliance_{jik}$ in a day
$t_{min_{jik}}$ $[min]$	Minimum time that the $Appliance_{jik}$ is kept on after a switch-on event
$\delta_{t_{min}\,jik}$ [%]	Percentage random variability applied to t_min_{jik}
$use_{frames_{jik}}$	Time frames in which a random switch-on of $Appliance_{jik}$ can occur
$\delta_{frames\,jik}$ [%]	Percentage random variability applied to use_frames_{jik}
Appliances' optional attributes	
$cycle_{jik}$	Duty cycle of $Appliance_{jik}$ (up to 3 per appliance)
$\delta_{cycle\ jik}$ [%]	Percentage random variability applied to the duration of the segments composing $cycle_{jik}$
$cycle_{mod_{jik}}$	Association between time frames and different duty cycles
$frequency_{jik}$	Weekly frequency of use of $Appliance_{jik}$ (<100% for "occasional-use" appliances)
$fixed_{num_{jik}}$	Constraint for all the m_{jik} appliances to always switch-on simultaneously
$\delta_{p,thermal}$ [%]	Percentage random variability applied to P_{jik}, conceived for thermal appliances

Table 5-1: Summary of the inputs required by RAMP [link same]

The three-layer structure allows to independently model the behavior of each jik-th Appliance, so that each individual ji-th User within a given i-th User type will have a unique and independent load profile. The aggregation of all independent user profiles ultimately results in a total load profile, which is uniquely generated at each model run. Multiple runs of the model generate different total load profiles, reproducing the inherent randomness and unpredictability of user's behavior and allowing to obtain a series of different daily profiles. Furthermore, RAMP offers the possibility to define several optional Appliances' attributes, which allow to further enhance the customizability and the stochasticity of the model. Key optional attributes are those allowing to model pre-defined duty cycles and to modulate the behavior of such cycles throughout the day.

The generation of a complete year 365 days load demand is possible with the ability to distinguish between weekday and weekdays appliance usage [36] .

Thanks to colleagues at "Politecnico Di Milano" an upgrade version of RAMP was developed to permit to obtain a long term load evolution due to changes in appliances or new customers connections to the mini grid. Due to stochastic variation of the model parameters, this model allows for the creation of a variety of possible scenarios. The most significant change in RAMP is the addition of a new temporal dimension that accounts for the number of years, with each year equivalent to a complete set of 365 daily profiles with a 1-min resolution. It allows to implement two novel appliance attributes in this approach, namely the year of the appliance's appearance and the appliance's minimum share at the year of appearance. The initial year in which the appliance is supposed to be available as an option for a particular class of users is defined by the first attribute: prior to the year of appearance, no user of the selected class possesses the appliance, but later, a limited number of users may have access to it. The minimum share feature, in particular, is used to specify this number of users as a fraction of the total; from its beginning, the share of users who own the appliance has been increasing at a random rate every year.

5.2 Multi Year Capacity Expansion Tool

Finding an optimal solution to design and plan a micro grid system has always been a concern. Throughout history of modelling the majority of the planning tools were biased toward cost effectiveness of the system compared to other possible solutions. However, in the recent years, many software tools and models have been developed to mitigate the complexities inherent in disregarding the technical design and optimisation of hybrid energy systems; they typically minimise the costs of investment and/or operation and try to maximise the share of renewable sources exploited. [37]

MicroGridSpy, developed by Balderrama [40], is an open-source python-based model conceived for the optimization of hybrid electric mini-grids, including solar PV, wind turbines, diesel genset and batteries[38].
It's an open source model aiming to the problem of sizing and dispatch of energy in the isolated regions, written in python language[39]. The Model is a two-stage stochastic optimization that accounts for two variables, first and second stage. The first

is the resources availability that are optimized by varying the second – stage which are the energy flowing from each component. The mathematical structure consists in a linear programming formulation as well as mixed-integer linear programming (MILP) by which more details are required (for Diesel genset for example) by increasing computational efficiency. MicroGridsPY ask to have inputs for the load demand with hourly resolution, the time series of the variable RES with the same time resolution of the demand, and other parameters of techno-economic and financial nature. Both the inputs and the outputs are very user-friendly since they are written in intuitive excel sheets.

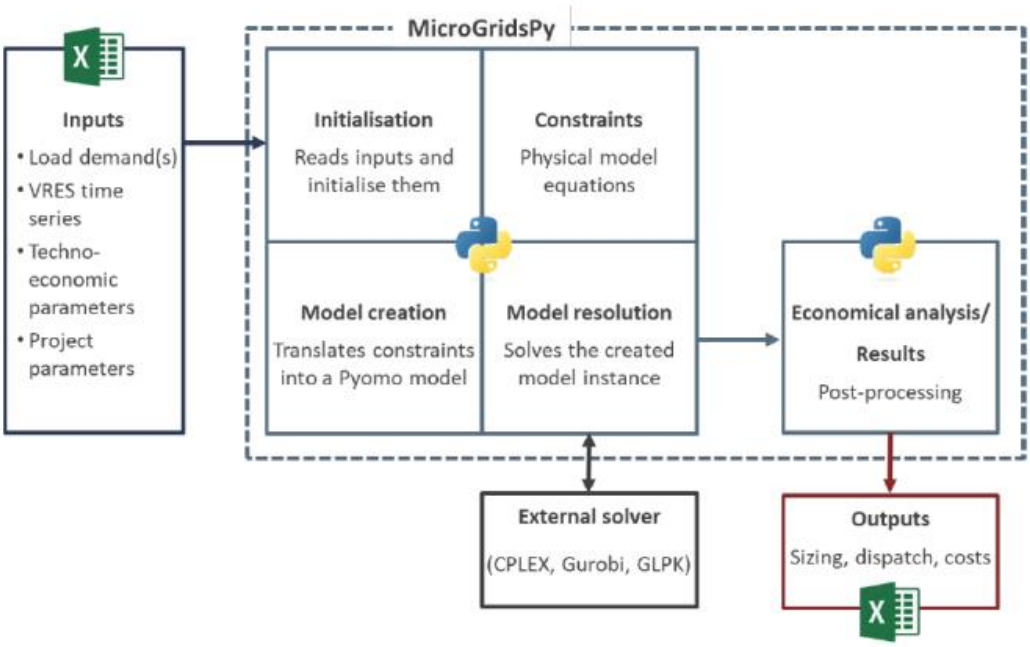


Figure 5-1: MicroGridsPy work flow process.

Since the development of Microgridspy in 2019 by Balderma, different upgraded versions has the chance to show up.

One version succeeded to reach capacity-expansion by allowing the expansion of the installed capacity over the years relying of the demand load evolution and this would be a function of the investment decision steps *u* that is an input defined by the user. In brief, the expansion of the installed system is a response to the demand changes. It's crucial to mention that this upgrade still allows the original two stage stochastic optimization. MYCE is the tool that we are going to reply on for our case discussion.

Usually, the user set the objective function either to be the NPC (Net Present Cost) or the Operation Cost. For example, the objective function would be as the following: $OBJ = NPC = INVtot + \sum_{S=1}^{S} O\&M\ (s)xP(s)$ where s is the scenario defined and P is the arbitrary probability of occurrence for each scenario.

$\sum P(s) = 1$

Thanks to our Colleagues from Politecnico Di Milano, a modified version of the Multi year Capacity Expansion MYCE has been developed. The upgraded features mainly tackle the option of giving the environmental aspect for the project a sight. The objective function would be related to the NPC/O&M as well as the carbon emissions of each project. Furthermore, it was possible to allow for "Brown Field investment" meaning working on optimizing a hybrid system already has some capacity of a technology installed.

The user was given the flexibility to choose on whether choosing the multi-objective function or no as well as considering a Green or Brown field. This can be selected using the main script model where it's possible to switch between Greenfield and Brownfield Investment and between Single-objective and Multi-objective optimization. The two new features can be used simultaneously to optimize a brownfield investment with a higher concern about the environmental sustainability of the project.

Brownfield Investment: A brownfield (also known as "brown-field") investment is when a company or government entity purchases or leases existing production facilities to launch a new production activity. This is one strategy used in foreign direct investment. The alternative to this is a greenfield investment, in which a new plant is constructed. The clear advantage of a brownfield investment strategy is that the facilities are already constructed. The costs and time of starting up may thus be greatly reduced and the plant already up to code.

Multi-Objective function: The majority of the optimization models tend to ignore the environmental and social aspect during electrification giving the optimization a bias for the cost factor for the effectiveness of the project implemented. This new function tends to consider the cost and the environmental issue through providing a Pareto Frontier that give the operator a comprehensive view of the possible alternatives and give him better insight to take a detailed decision. The Pareto frontier is composed by the set of so-called non-dominated points, i.e. solutions in which the performance of one objective function cannot be improved without worsening at least one other objective function.

This new configuration explained will be our designing tool for our case discussion with a focus on Brown field investment and just quick observation to the multi objective by providing the results related to it.

6. Case Discussion

In the following, a rural village in Mozambique would be addressed and discussed in order to find its optimal solution to be electrified according to some attained data and some assumptions. The rural area is a "Brownfield Investment" where a previous mini grid was installed but delivering unreliable system as FUNAE didn't develop a system associated to the load evolution over a period of time in addition to mismanagement while assessing the energy resource availability all over the years.

6.1. Muôha Village

Muôha Village is located in the province of Manica, Sussendenga district and according to a report by FUNAE it has total population of 17936 person and 3445 Households [40].

FUNAE developed in 2015 the mini Muôha hydropower plant with a capacity of 100 KW and a distribution network of connections and public lighting. According to FUNAE the number of beneficiaries are 57 with basic appliances used. 47 households and other activities are limited to a Post Administration, Health Center, School and 7 tents of different uses.

Through the data provided, thanks to FUNAE, to the type of appliances used for each household and the energy consumption of each appliance as well as average of hours of using, the basic load demand of Muôha was generated.

It was clear that the majority demand is a result of the households activities although they tend to use basic appliances as lamp lighting and chargers. The productive activities had the least effect on the demand as they are scarcely present in the village and the public services are related to the health center, school and public lighting are more demanding.

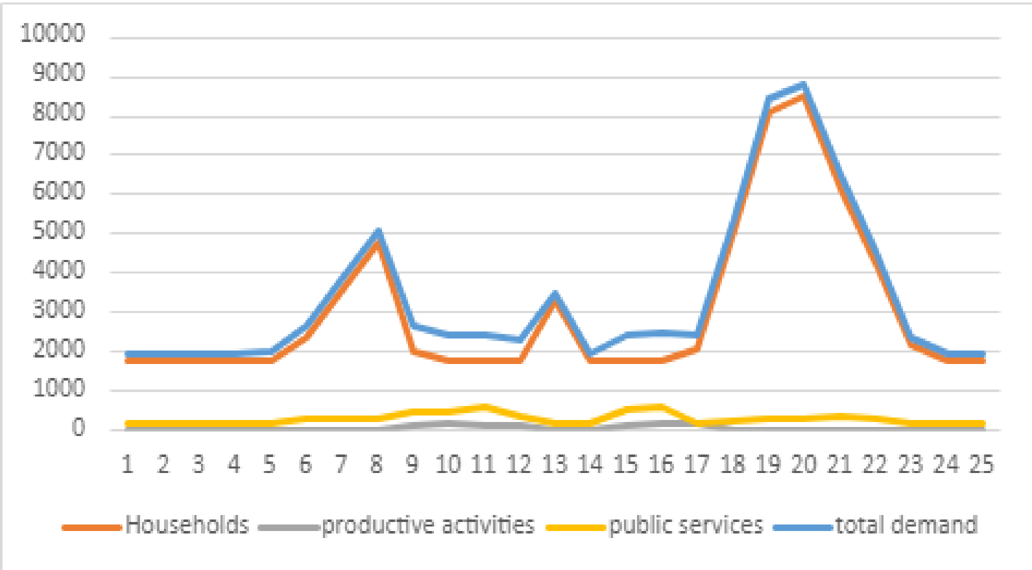


Chart 6-1: Baseload demand of Muoha village for one day divided for households, activities, services, and the total demand

To study the current demand related to our households and the appliances available related to each including as well the other categories of public services and productive activities, a load assessment is conducted using our ramp tool where it gives us a stochastic estimation from our current year according to the input parameters we implemented for the available appliances and it resulted in a peak load of 11KW. Figure 1 shows the load demand of one day per each category (households, productive activities, and public services.)

Considering the basic load demand to be the situation for the next years with the already installed capacity of hydropower results a huge amount of loss power as well as non effective supply that cannot lead to the improvement of the socio-economic conditions of the families.

Thus, for the purpose of our analysis to figure out the most cost effective mini grid needed to Muôha relative to its energy resource availability and the demand expectation of increasing through out the next 20 years, we are going to conduct different scenarios assessments.

6.2. Muôha Load Assessment

Rural electrification projects have to be deployed not only in the aid of satisfying the current demand. However, to the purpose of being able to cover the demand change over a period of time which happens usually due a change of the appliances used [41]. And in the case of African rural areas, year after year with lots of funds and aiding programs more appliances are being introduced to rural areas.

Hence, the complexity here is the uncertainty of the load evolution over a period of time and thus if not properly assessed; deploying of ineffective mini grids is taking place or oversized ones.

For our case discussion of Muôha and in order to be able to figure a proper sizing of a hybrid mini grid with the reference of our energy availability and as well as demand evolution for the following 20 years, three scenarios of different levels of strength will be conducted. Mainly, low level of demand, moderate and high level which not only accounting change of the appliances types and numbers but also an evolution in the number of activities and households present in the rural area.

With the absence of any previous load assessments and the current data available for the appliances and number of beneficiaries it was suggested to start our scenarios based on estimations of how the case would look like with an overnight shift introducing different new appliances and productive activities with respect to the baseload demand which is relatively low for the village.

Thanks to the Multi year Ramp tool we were allowed to perform the scenarios for a duration of 20 years in our case with a stochastic approach over this period of time. Basically, each scenario is differentiated from the other by : number of households increase, number of productive activities and public services in addition to the number of appliances per each category being addressed with an option of setting the year of appearance of new appliances in each scenario throughout the duration.

USER	Scenario 1		Scenario 2		Scenario 3	
	Original number	New number	Original number	New number	Original number	New number
Number of LI households	25	5	25	8	25	14
Number of MI Households	15	4	15	6	15	12
Number of HI income households	7	3	7	5	7	8

Table 6-1: Difference in # of new households per each scenario

USER (Productive activity & Public Services)	Base Demand	Scenario 1	Scenario 2	Scenario 3
	Number present per each category			
Church	0	1	1	1
Health Center	1	1	1	1
School	1	1	1	1
Public Administration	1	1	1	1

Tents	7	10	10	16
Carpenter	0	-	1	1
Mill	0	-	1	1
Barbershop	0	1	1	1
Tailor workshop	0	1	1	1
Bars	0	3	4	5
Police office	0	-	-	1
Eateries	0	1	2	4
Mobile Tower	0	1	1	1
Metallurgy	0	-	1	1
Pharmacy	0	-	1	2
Public lighting	0	8	12	20

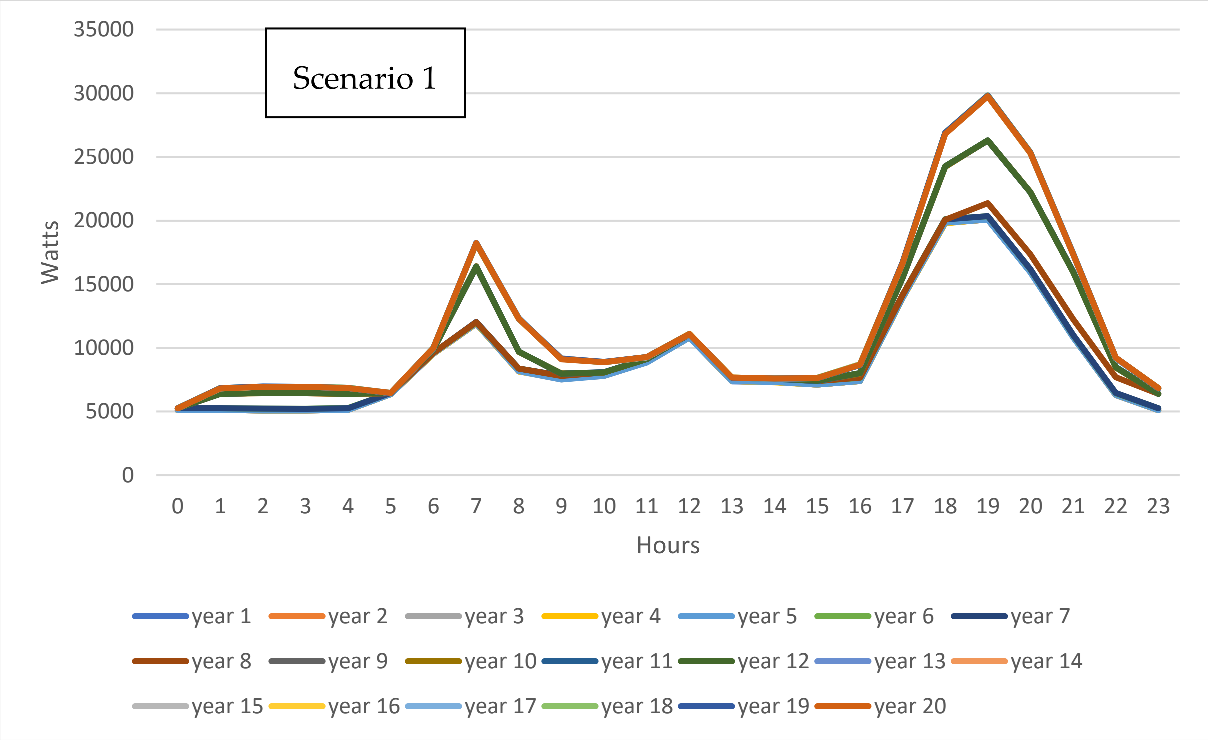
Table 6-2: Productive activities and Public services change among scenario

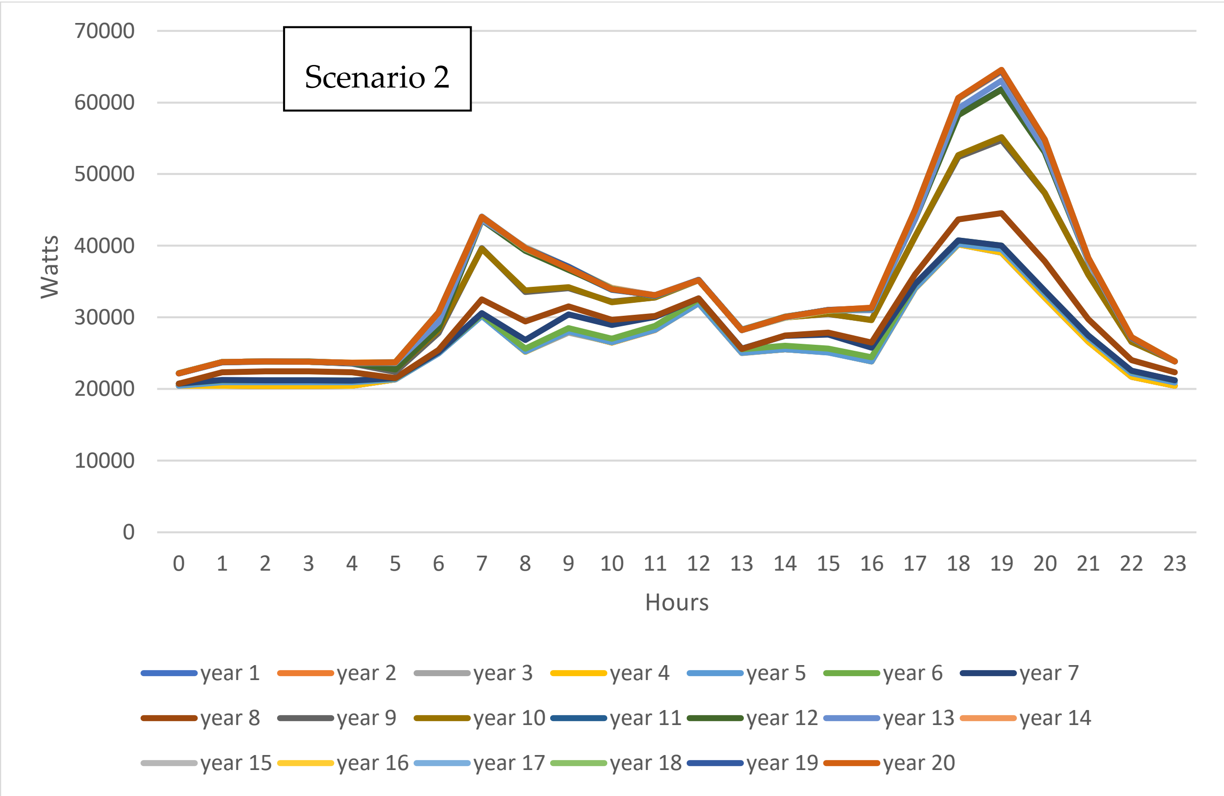
Appliance	Scenario 1			Scenario 2			Scenario 3		
	LI	MI	HI	LI	MI	HI	LI	MI	HI
Lights	4	6	8	5	6	9	6	8	12
Radio	1	1	1	1	1	2	1	1	1
Phone Charger	2	3	4	3	4	4	3	4	5
TV	1	1	2	1	2	2	1	2	2
Blender	-	-	1	1	1	1	1	1	1
Microwave	-	-	-	-	-	-	-	-	1
Security lights	-	1	2	-	2	4	1	3	5

Fan	-	2	2	2	3	3	2	3	3
Fridge	-	-	1	-	2	2	-	2	2
Hi-Fi Stereo		-	1	-	1	1	-	1	2

Table 6-3: Example of appliances variation in numbers between scenarios and between each type of households in each scenario (Low income, Middle income, High income)

The tables show clearly how each scenario differ from the other scenario in terms of the demand strength, not to ignore here also the accounting of the year of appearance of each appliance to each user.
Three Scenarios were obtained with different demand evolution over the coming 20 years as well with different peak loads. Later, the demands will be aggregated through different probability of occurrence while running the optimization tool.
The Results of RAMP for each scenario shows how the demand increases from one compared to other as well as how the demand increases over the duration of the 20 years, aligning with our expectations made and assumptions.


Scenario 1
Watts
35000
30000
25000
20000
15000
10000
5000
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Hours
year 1 year 2 year 3 year 4 year 5 year 6 year 7
year 8 year 9 year 10 year 11 year 12 year 13 year 14
year 15 year 16 year 17 year 18 year 19 year 20


Scenario 2
Watts
70000
60000
50000
40000
30000
20000
10000
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Hours
year 1 year 2 year 3 year 4 year 5 year 6 year 7
year 8 year 9 year 10 year 11 year 12 year 13 year 14
year 15 year 16 year 17 year 18 year 19 year 20

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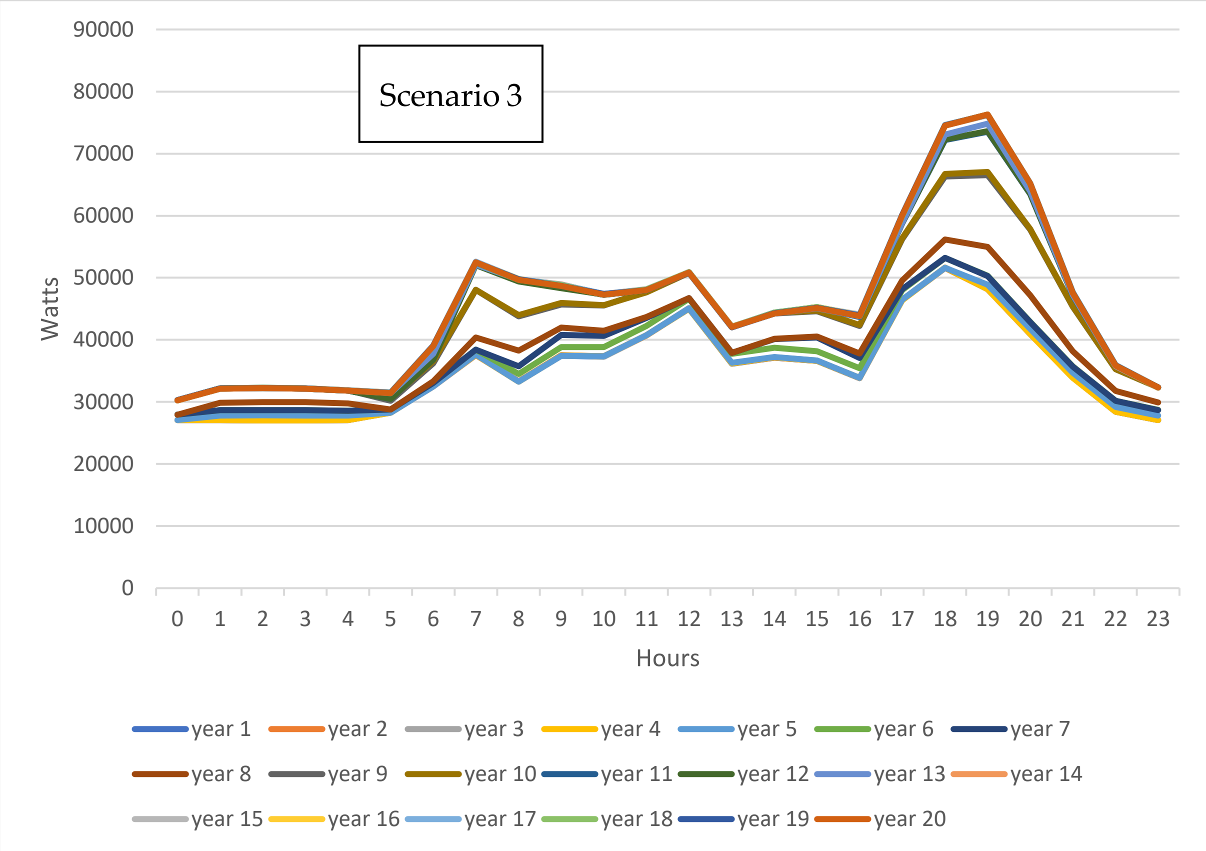


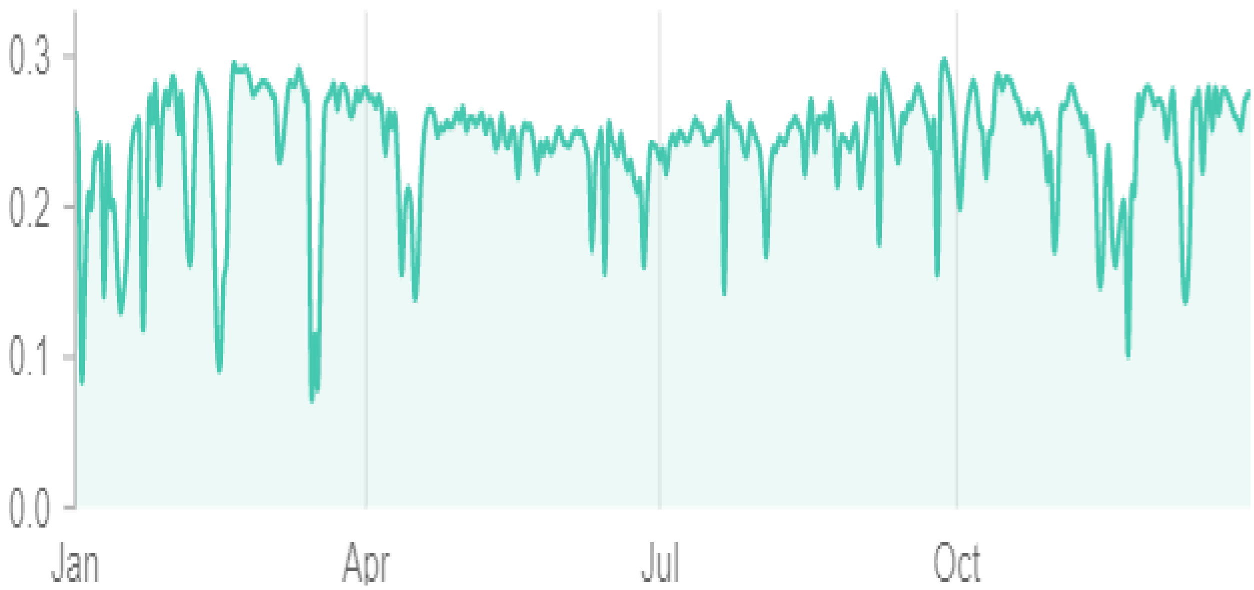
Chart 6-2: Daily average load curves for each year for the three scenarios

6.3. Energy Resource Assessment

As discussed in Chapter 1, Mozambique is rich in renewables and shows an enormous potential of resources that are yet not exploited. Hydropower is the predominant resource supplying power to the country through main projects as Cahora Bass. The Renewable Energy Atlas identified a total of 1,446 potential hydro projects with an accumulated potential of 19 GW from which, based on studies, 351 priority projects with anestimated potential of 5.6 GW were selected. The majority of projects are located in Tete, Manica, Niassa, Zambezia and Nampula provinces. According to the Atlas, about 100 sites could be developed in the near term future [42]. According to Global Renewable Atlas Mozambique has significant and virtually unexploited solar

potential. The country's global solar irradiation varies between 1,785 and 2,206 kWh/m2/year, which represents an estimated potential of 23,000 GW [43].
Wind potential according to Renewable Atlas is 4.5 GW however the wind speed varies between 4 and 6 meters depends on the site location.[44]
To the scope of this work, assessing the energy resources is essential to be able to consider the right energy resources to obtain an optimal solution for a hybrid mini grid. With respect to the non-renewable sources; diesel generators, in our village diesel can be supplied by local sellers at an affordable price of 1.1 USD/lt to fire the generators deployed. The assessment could be done relying on some open data bases, as Renewable atlas or Renewable ninja. Although FUNAE developed an Atlas platform related to the country through direct measurements [45] , in this chapter we will be depending on Renewable ninja as our data base since it provides a yearly time series of the renewable energy technology production.

The solar potential to Muoha is characterized by annual global horizontal irradiation of 1994.5 Kwh/m^2 and a daily average of 5.464 Kwh/m^2 with a specific voltaic power output of 1652 Kwh/kwp.



The wind potential is not really an asset for our area where an average wind speed of 3.64 m/s for a 20 m Height from soil which permits the disregarding of the wind potential.[46]
Regarding the hydropower potential different aspects would be taken into consideration as our area has an already installed capacity of 100 KW. Due to the scarcity of the online available data related to the hydropower that is directly connected to Muôha village we will be assessing the potential according to data issued by FUNAE of one year of power produced by the plant and also according to the past experience of Manica District river history and the climate in the area.
The climate in the district of Manica, according to Koppen climate classification is the moist temperate type. The rainy season starts in November and it ends in April and that the average annual fall is about 1220- 1290 mm evapotranspiration. [47]

Figure 6-1: Part of Manica province showing the location of Muoha village

There are many rivers and water streams with permanent running water, with suitable conditions for construction of micro hydroelectric dams. [48]

The Data provide by FUNAE for the daily energy produced and consumed for the whole year of 2018 showed that the maximum average of produced power was 7.62 Mwh and we were able to estimate through it the available energy potential by the hydropower plant related to Muôha which will be our input parameter for the MYCE tool when optimizing.

7. Scope of work

In the following chapter the framework of the procedure followed in modelling will be discussed.

Basically, with the uncertainty of the hydropower resource availability through out all the years and to be able to find an optimal solution for the mini grid that can serve Muôha village needs and demand; two configurations will be taken into consideration while employing input parameters in MicrogridsPy.

- First configuration:
  The estimation of the hydropower resource yearly output relies on the data assessed by FUNAE in 2018 of the hourly production of the 100 kw mini hydropower grid which has no interruptions or frequent shutdowns.

- Second configuration:
  The hydropower resource yearly output will experience 5 months of non producing hours, from Beginning of June till end of October, and this is due to the accounting of the dry season in the area and specifically the dryness of the tributary of Buzi River.

The two configurations allow us to study our village case in four different approaches where each approach represents a particular possible scenario for the mini grids. Later, comparison and discussion of each approach alone and all together can advise us which is the most applicable approach regarding the situation of the resources in the village and the demand evolution estimated.

The four approaches explained :

Approach	Feature
Approach number 1	- Consider normal hydropower resource availability with no interruptions - Ignore the possibility of the presence of genset in the mini grid.
Approach number 2	- Consider normal hydropower resource availability with no interruptions - Include the possibility of the presence of genset in the mini grid.
Approach number 3	- Consider hydropower resource availability with interruptions accounting to the 5 months of dry season and no output generated. - Include the possibility of the presence of genset in the mini grid.
Approach number 4	- Consider hydropower resource availability with interruptions accounting to the 5 months of dry season and no output generated. - Ignore the possibility of the presence of genset in the mini grid.

8. Energy System Model Results

The following chapter is going to tackle the Microgridspy results of each approach explained above. The focus will be mainly on the modelling of all scenarios together StSc (the stochastic case) which assists in dealing with the parametric uncertainty related to the evolution of the load demand.

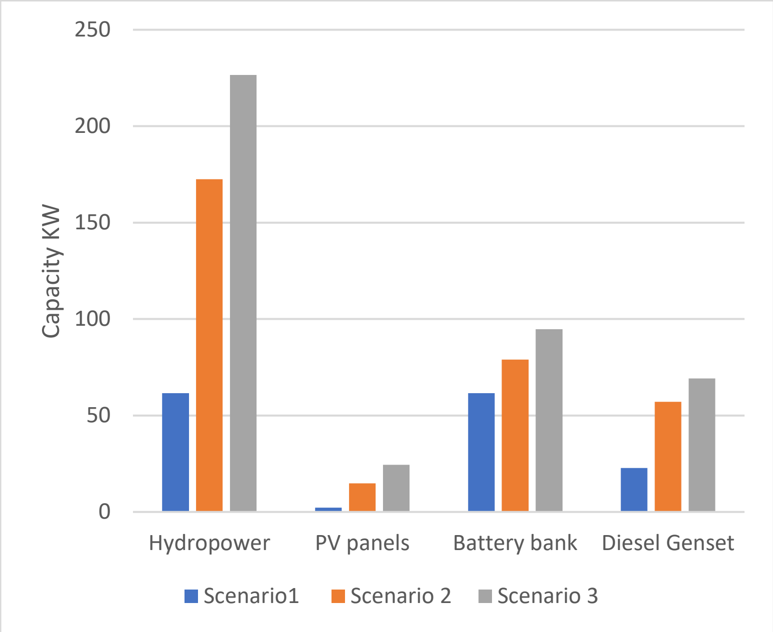
Basically, for each approach we will perform a Green field investment optimization which is the case of starting from scratch; modelling without consider any previous installed capacity. Then, a Brown field investment optimization will be deployed which is taking into account what already was installed in the village prior to this model. This will allow us to highlight the difference between the two optimizations in our case. In further analysis, only the brownfield optimizations will be under deep discussion as Green & Brown optimizations wouldn't provide a significant difference in the outcome for our Muôha case study.

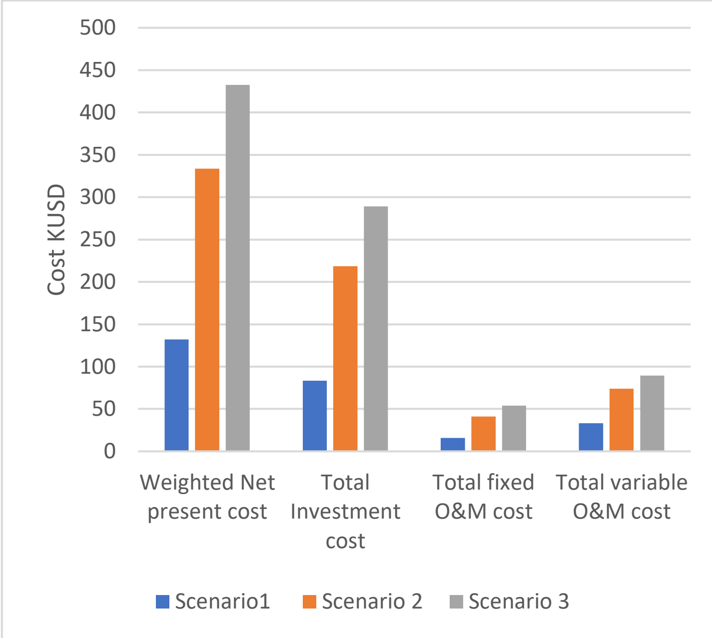
Also, a highlight will be presented for the multi-objective optimization showing the benefits resulting out of it. However, it is not going to be our focus in the discussion & conclusion section.

Prior to the presenting of the results relative to the stochastic approach; all scenarios accounted together with different possibility of occurrence, a quick observation on the behavior of each load scenario independently with our modelling scope.

For this sake, only one approach here, out of the four presented in section 6 , will be taken into consideration and it is approach number 2 which implies the considering of hydropower resource availability without any interruptions or shutdown as well as the accounting of diesel genset in the system.

The following are the results and difference among the scenarios; if it was separately chosen as or load demand, in terms of capacity, cost, and LCOE (levelized cost of electricity) which indicates vividly how scenario 3 is the highest level of demand severity.





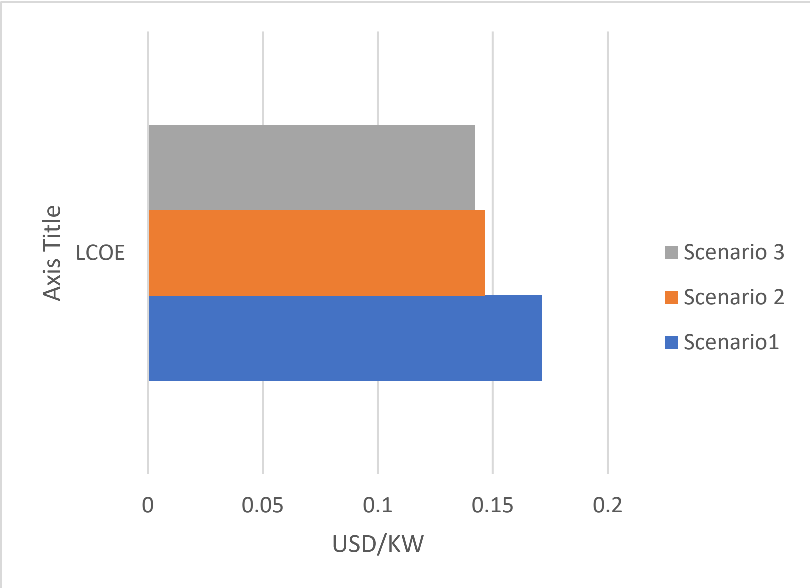
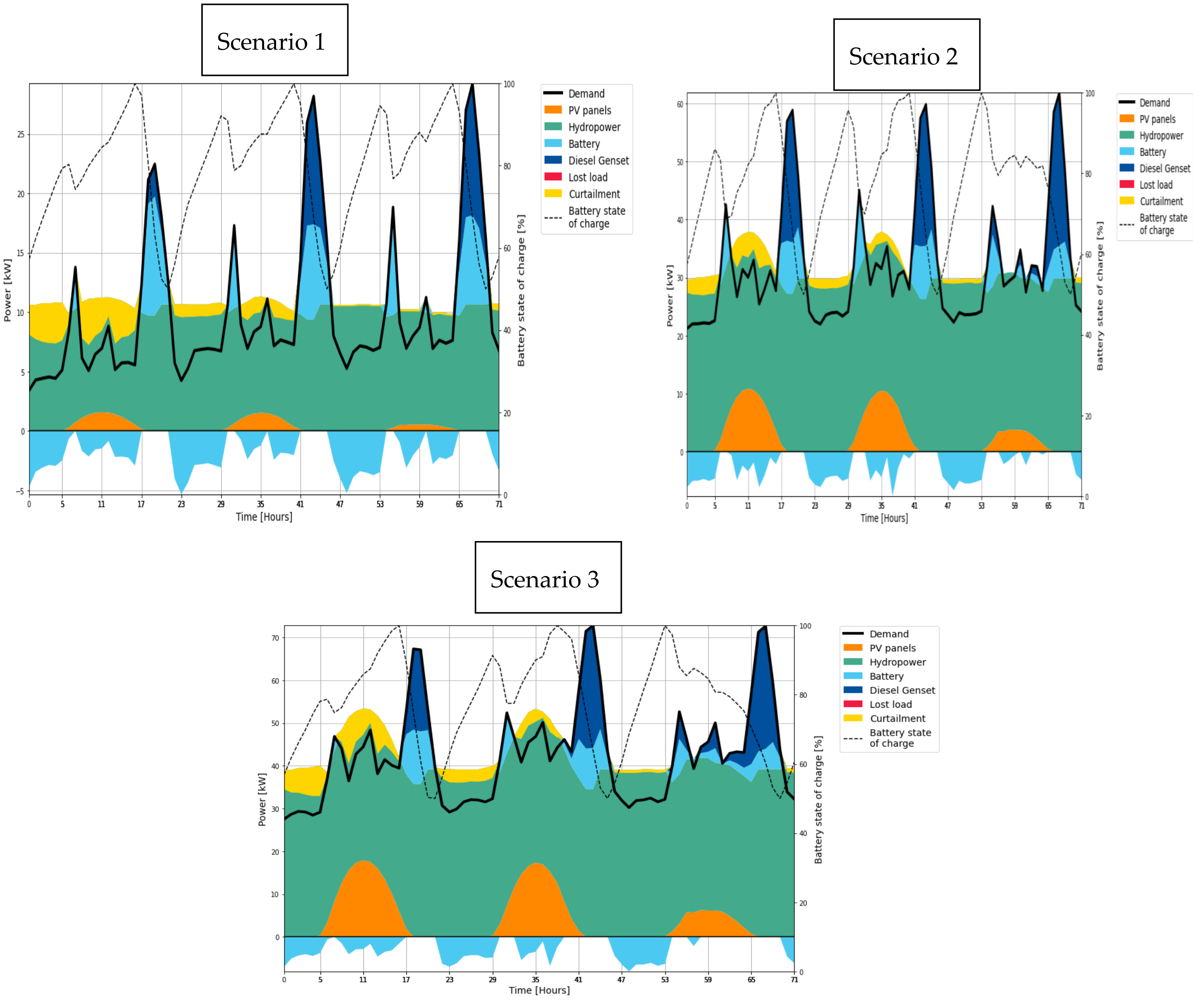


Chart 8-1: Differences in Capacity, costs, and LCOE of the three scenarios of load demands.



Figures 8-1: Energy dispatch for 3 consecutive days for each scenario

8.1. Approach Results & Discussion

For all the approaches included in this section, input parameters required by Microgridspy,other than the load demand scenarios and resource hourly output, are taken by the international references [49] [50] [51] except for unitary cost of PV is directly provided by FUNAE. In our case, lithium batteries are considered to be the battery bank.

- **Approach 1:**

When not accounting the possibility of the presence of diesel genset and also considering a normal functionality of the yearly output for the hydropower resource, we are aiming to study mainly how the minigrid would behave according to the resources availability for the capacity and other parameters such as cost. This approach also give a sight how the already installed hydropower micro grid cannot stand alone to meet the demand evolution and needs aid by other technologies. Green, Brown, & Multi-objective optimization results, considering StSc and one signle investment step decision, will be shown and differentiated.

Component	Unit	Green Field	Brown Field	MOBJ
Hydropower	kW	154.84	154.85	212.48
PV panels	kW	227.66	227.66	107.8
Battery bank	kWh	1304.32	1304.32	2008.42
Diesel Genset	kW	0	0	0

Table 8-1: Capacity installed for Approach 1

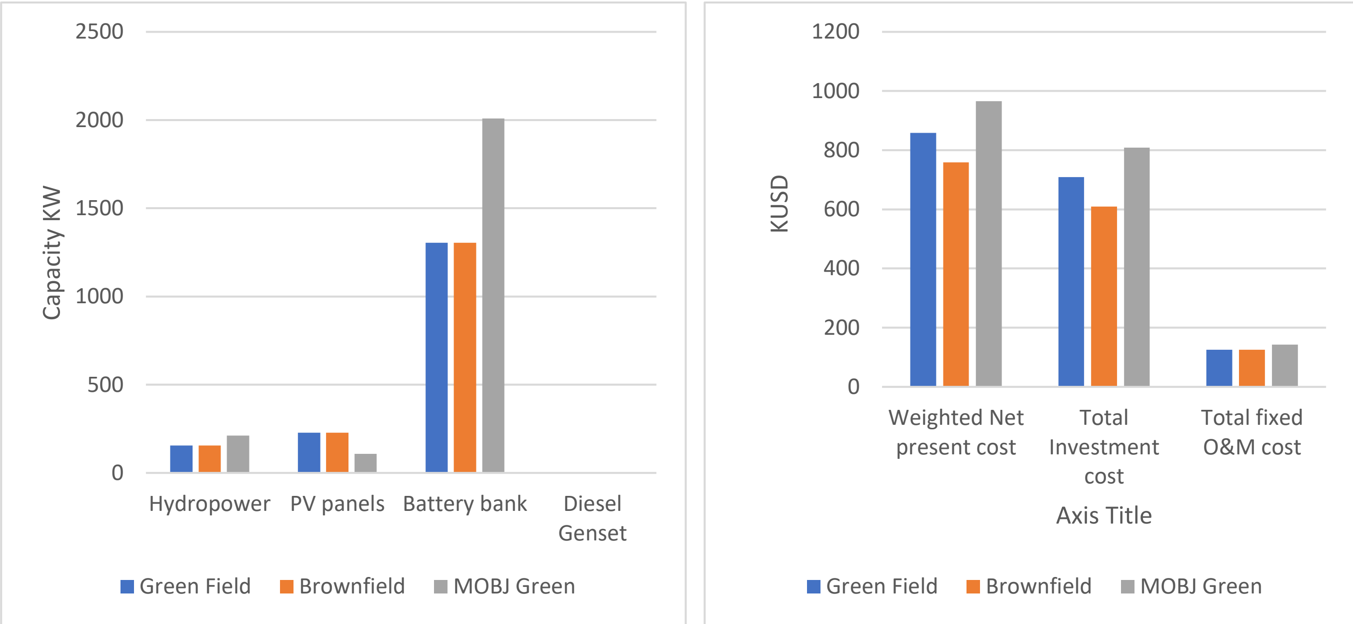


Chart 8-2: StSc results of installed capacity and cost – approach 1

Between Greenfield and Brownfield, the main aspect of the difference is shown in the weighted net present cost as expected by which Greenfield is higher in weighted NPC by almost 100 KUSD. However, a presence of a previously installed standalone micro grid hydropower of 100 KW didn't result in any change to the other technology (Solar PV) as the demand will require an additional capacity for HP (Hydropower) and a significant capacity of Solar PV with huge battery bank.

Observing, the multi objective result; a number of non dominating points were obtained by the Pareto frontier (not presented) and we have chosen a specific point that show decrease in CO_2 emissions of the system by 37%. Any other point could be chosen and this is according to the preference of the project developer. As anticipated, renewable technologies capacity will increase to favor reducing emissions. However, the cost will be the highest in this favor.

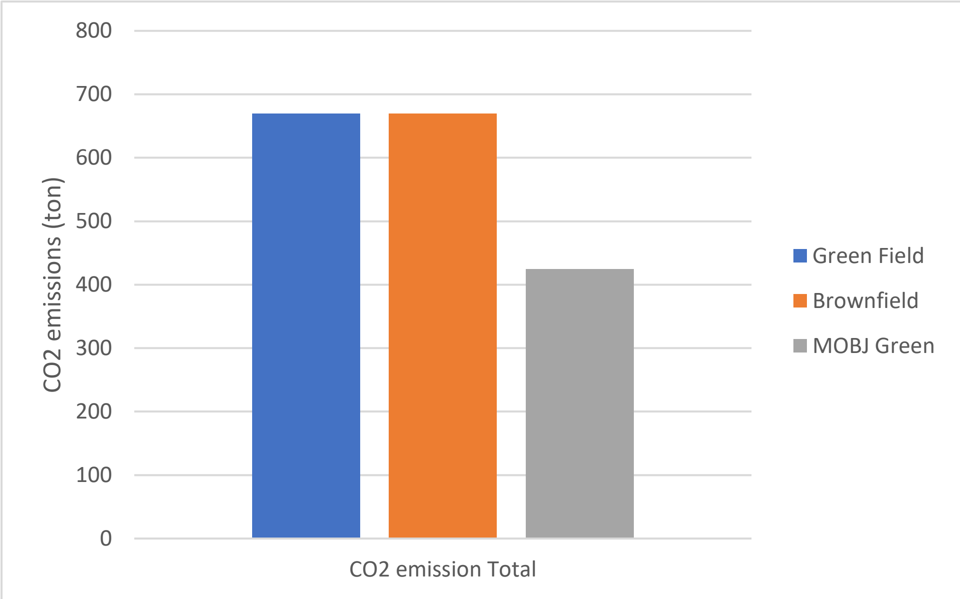


Chart 8-3: Total CO2 emissions between single and multi objective for StSc.

Regarding CO2 emissions of the single objective of Green or Brown field optimization is the same as the system didn't experience any change.

- **Approach 2 :**

This approach is capable to present a model that can include the renewable technologies with no interruptions or shutdowns specifically related to hydropower output and the possibility of setting a diesel genset in the system.

It's important to note that the MYCE showed only very little capacity expansion to the StSc when two or three single investment steps were set and this is mainly due that the capacity installed in year 1 of the project will be able to cover the demand evolution with time without the need to expand it as it would be not cost effective.

Results are shown below:

Component	Unit	Green Field	Multi Obj Green	Brown Field
Hydropower	kW	197.44	233.29	197.52
PV panels	kW	24.53	20.2	24.51
Battery bank	kWh	43.21	106.36	43.81
Diesel Genset	kW	79.05	67.58	78.92

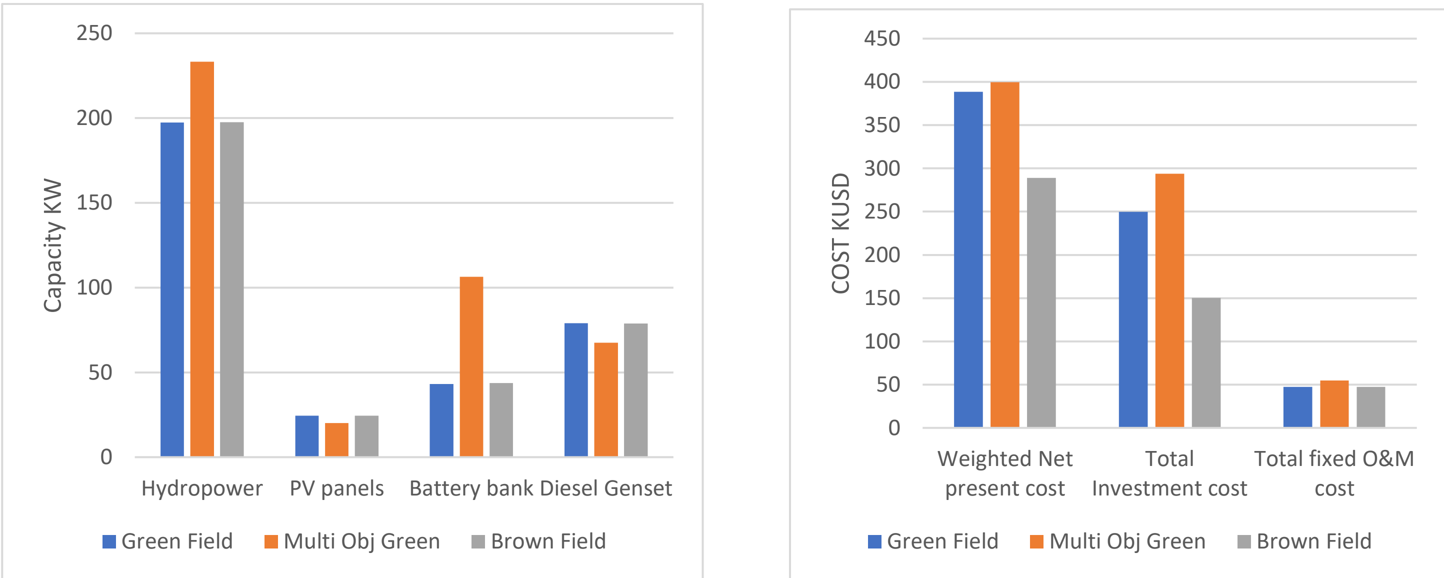


Chart 8-4: StSc results of installed capacity and cost – Approach 2

It is realized that the preference of Renewable technologies here go into a huge capacity of hydropower to be installed. However, with the diesel genset possibility to be present in the grid, the PV panels installed is very low compared to approach 1 as well as the battery bank for the storage system and a significant diesel genset is considered. This indicates that our tool (MYCE Microgridspy) sees in the hydropower resource availability as essential to cover most of the demand load evolution however it suggests also presence of a a small PV capacity and diesel genset for the aim of having a cost effective project and to work along the hydropower to satisfy the load demand.

The results shown proves that brownfield is just affecting the total investment cost and hence the NPC without influencing the capacity installation.

For the multi objective results, it serves the same as approach 1 were choosing a point out of the non-dominating points of pareto frontier increases the cost renewable technologies capacity with the battery bank and consequently the cost of the project massively in the aim of reducing emissions. From now on, multi objective results will not be shown as it is not the real focus of our study.

- **Approach 3:**

The following is an approach that doesn't account in the assessment of the resource availability only the hydropower yearly output data which was provided by FUNAE for the already installed micro hydropower plant in Muôha village. However, the assessment will consider the climate situation in the country. Dry season, as mentioned earlier, is a significant condition for Mozambique and our area of focus where it starts between May/June and lasts till end of October. This type of season usually results in the dry of the river that is connected to the turbine of the 100KW micro hydropower in Muôha. Nevertheless, even when the hydropower grid has the complete potential it suffers sometimes from shutdowns related to some operational maintenance. Therefore, the new hydropower resource assessment include the non availability of the hydropower source for 5 months and in particular from beginning of June till end of October. According to this approach, the model will give us an observation to the changes that would happen to the mini grid, seen in approach 2, with regard to the new configuration here. Results of Green and Brown fields investments are presented for the discussion:

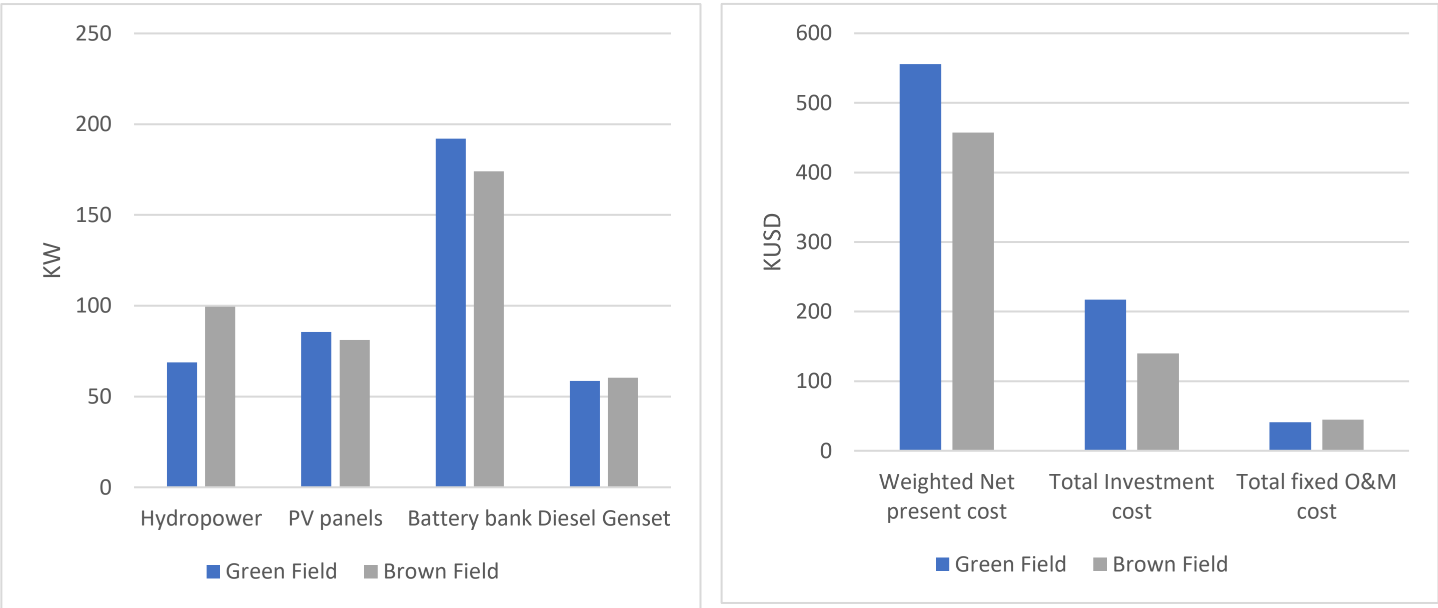
Table 8-2: StSc capacity for approach 3 investments

Component	Unit	Green Field	Brown Field
Hydropower	kW	68.75	99.54
PV panels	kW	85.63	81.06
Battery bank	kWh	192.02	174.13
Diesel Genset	kW	58.66	60.35

Approach 3 indicates that while modelling a green field the capacity considered to be installed for the Renewable technologies is significant for both technologies and even higher for PV in order to be able to satisfy the demand evolution with this new configuration of hydropower resource availability. Larger battery bank as expected with the increase of PV installed and a diesel genset also is included in the system as a back up and interfere in the months of no hydropower.

The results of greenfield changes compare to the brownfield, unlike previous approaches. Setting a brownfield with 100 KW hydropower (higher than the greenfield) still suggests to install almost the same capacity of PV and the same for diesel genset. Only the battery bank decreased but not that much. In other words, with

Chart 8-5: StSc capacity and costs results – approach 3



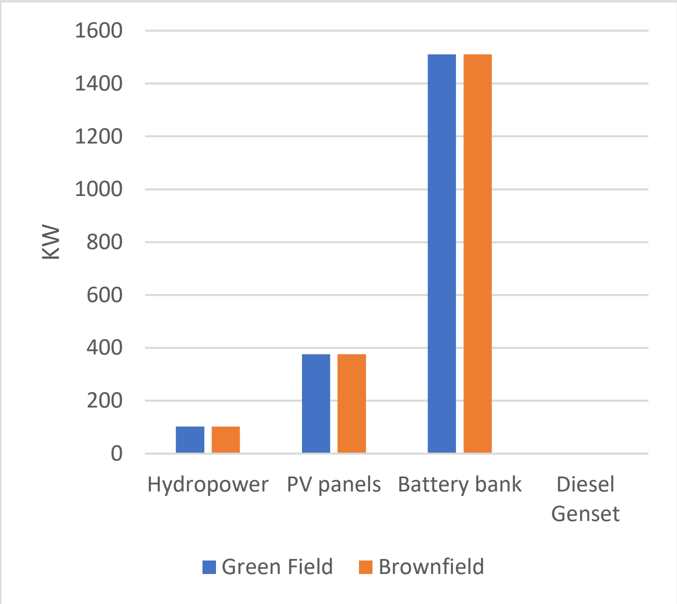
the new configuration of counting the dry season in Muôha and the already installed 100 KW hydropower, the village required the presence of PV panels with battery bank in addition to diesel genset inorder to be able to satisfy the demand in a cost effective way.

- **Approach 4:**

  After conducting approach 3 with the possibility of including diesel genset, it is essential to check how the model will be affected in case we wanted to exclude diesel generators from the grid taking into consideration the dry season effect and in particular the availability of hydropower resource for 5 months. Knowing that the tool will give a solution that allows the evolution of the demand to be satisfied, we are looking to investigate how the PV capacity will behave according to the exclusion of diesel and what is the effect on the cost.

Component	Unit	Green Field	Brownfield
Hydropower	kW	102	102
PV panels	kW	376.41	376.41
Battery bank	kWh	1510.29	1510.29
Diesel Genset	kW	0	0

Table 8-3: Capacity installed for approach 4



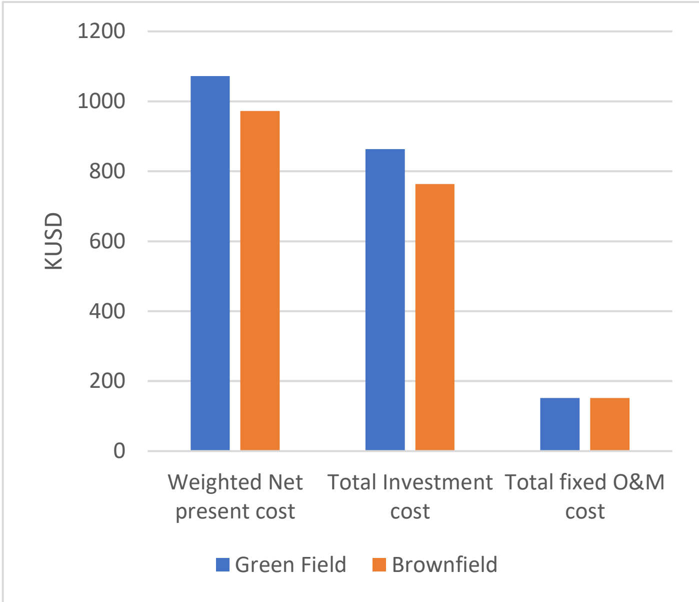


Chart 8-6: StSc results of capacity and cost – approach 4

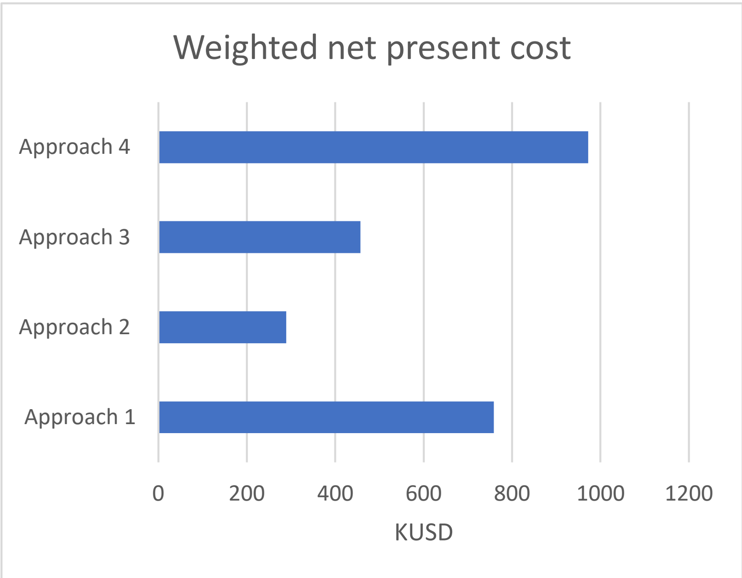
As expected an increase in Renewable Energy technologies will take place, but with the current situation of hydropower; PV panels were preferable to be installed in a very huge capacity that almost times 3 of that of hydropower. The brownfield didn't differ compared to the green field as already the latter optimization suggested to install almost 100 KW capacity of hydropower which is the same capacity set during the brownfield investment optimization. As the capacity for the renewables is so high, the investment cost is enormously huge which makes such model a doubt for any project developer.

For the sake of comparing the four approaches together and considering that we previously know the existence of a 100KW micro hydropower grid , we will analyze and compare the four approaches relying on the brownfield investments results.

In addition to the capacity and net present cost, LCOE will be shown to even check the affordability of the model optimal solution model that is suitable to our case.

Component	Unit	Approach 1	Approach 2	Approach 3	Approach 4
Hydropower	kW	154.85	197.52	99.54	102
PV panels	kW	227.66	24.51	81.06	376.41
Battery bank	kWh	1304.32	43.81	174.13	1510.29
Diesel Genset	kW	0	78.92	60.35	0

Table 8-4: Capacity of the StSc brown field investment for the four approaches



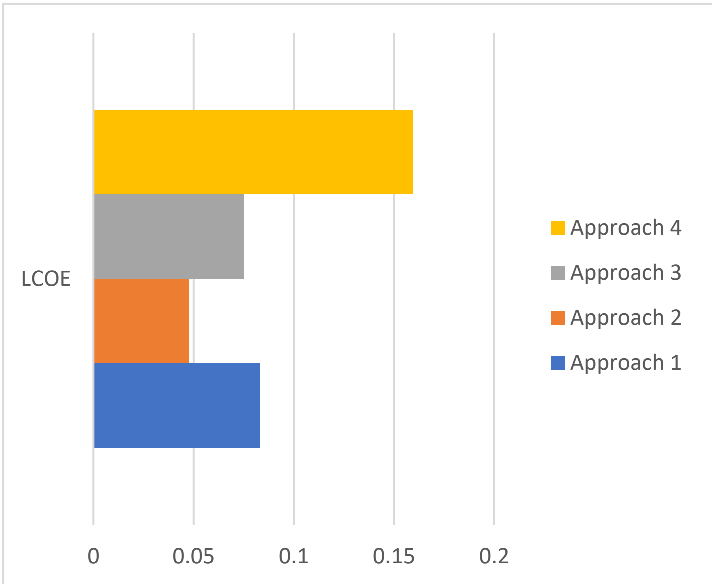
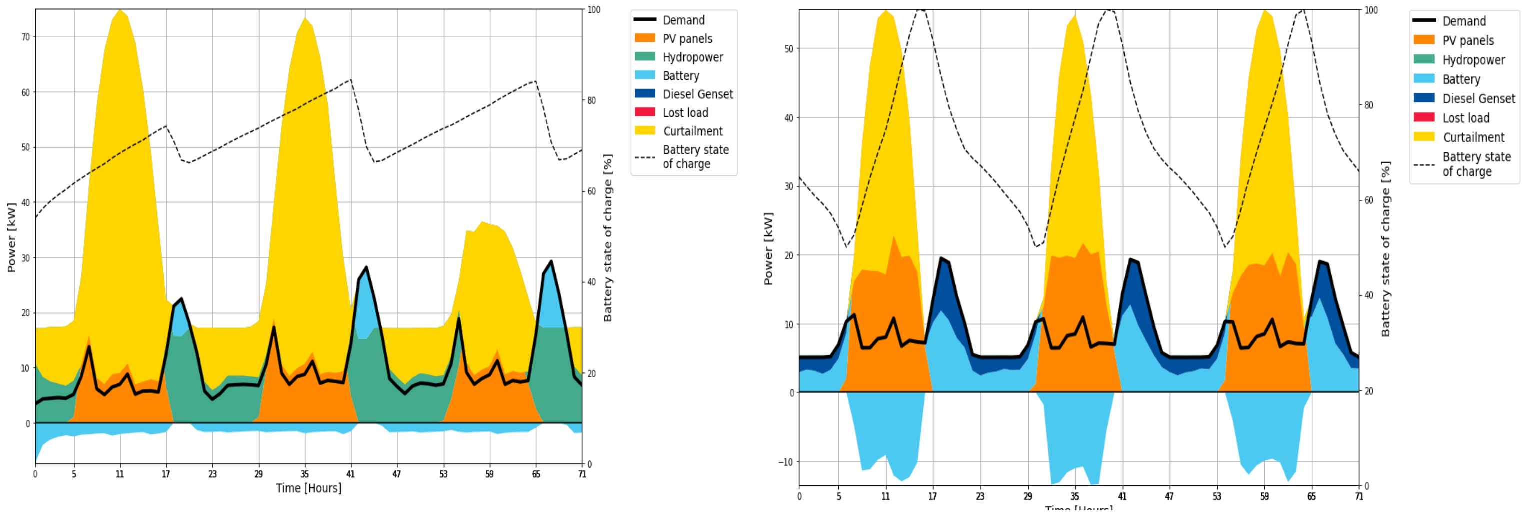


Chart8-7: StSc weighted net present cost & LCOE results for the 4 approaches

Let's consider the results of approach 1 & 2 where the configuration here examine a normal availability of hydropower all over the year and the only variable is the possibility of including diesel genset. When diesel is given the possibility to be present in the grid, the model showed an expansion of the hydropower capacity by 97 KW (from the already existing 100KW) and including a small set of PV with a fine capacity of diesel. This resulted in a huge reduction in the Net present cost compared to all approaches and specifically approach 1. Therefore, the LCOE of approach 2 gained the least value among all. On the other hand, regarding the excluding of the diesel genset in the grid, the huge capacity of the PV installed along the battery bank made the model requires really a huge investment capital compared to approach 2. The two models by that, with net present cost optimization goal indicates that the already installed hydropower 100KW cannot stand alone to meet the load evolution demand and needs support by PV and back upped by diesel genset for the sake of making it cost effective through the capital and the LCOE. Hence, approach 2 is the preferable one to be implemented with respect to approach 1.

Now, accounting to the second configuration by excluding some months for the availability of the hydropower source without preventing the addition of diesel genset; the model tends to keep the existing microgrid hydropower as it is without any expansion. It installs a substantial capacity of PV with a quite good diesel genset. For the same configuration if we remove the possibility of installing diesel genset, the model gave a solution in the aim of satisfying demand load evolution to add an enormous PV capacity with a massive huge battery bank. The issue which results in the highest net present cost and highest LCOE. Therefore, approach 3 is preferable in this configuration to be implemented.

Looking at the real situation of Muôha village, FUNAE developed an undersized micro grid hydropower of 100 KW that cannot meet the demand load evolution. Furthermore, it is with complete ignorance to the climate condition and the dry season which affect the river also without any consideration to frequent shut downs. This drives us to choose between approach 2 and 3 which are in terms of costs also the most suitable. As approach 3 is the one which accounts to the scarcity of the shutdown of the existing micro hydropower grid therefore this model would be the most relative to the Muôha case study in terms of reliability and affordability.



Figures 8-2: Energy dispatch for 3 consecutive days ath the beginning of the year (right) and in august (left) – approach 3

Approach #	Description	Capacity	Cost	Reliability
1	Diesel generators not accounted No interruptions for hydropower generation	Highest PV and Hydropower installed Huge Battery Bank	Very High	Satisfies the demand evolution over the whole period
2	Diesel generators are accounted No interruptions for hydropower generation	Renewable energy dominated by HP with very low PV installed Battery Bank is small Diesel has significant amount	Lowest Net present cost compared to the others	Satisfies the demand with dependency on the HP mainly and with diesel as a back up
3	Diesel generators are accounted Interruptions for hydropower generation with the dry season	Renewable energy is significantly high for both technologies (HP & PV) Battery Bank is higher than approach 2 as more PV is installed Diesel genset has significant capacity installed	Higher net present cost w.r.t approach 2	Reliable despite the interruptions in the dry season of the hydropower supply
4	Diesel generators are not accounted Interruptions for hydropower generation with the dry season	Ultimately high installed capacity of PV and HP Highest Battery Bank	Highest net present cost	In real application any maintenance hours intervened could lead to out of supply period

Table 8-5: summary table of the four approaches comparison

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