POLITECNICO DI TORINO

Master's Degree in Energy and Nuclear Engineering

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Remote areas of the World: metholodology for development through the implementation of renewable energy facilities

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Abstract

Climate change and the unpredictable fluctuations in oil prices have been key drivers for governments to prioritize the development of renewable energy sources. This shift towards sustainable energy has been prompted by concerns over the environmental impact of fossil fuels and the economic risks associated with their price volatility. As a result, various policies have been implemented over the past two decades to incentivize the growth of renewable energy and reduce dependence on traditional sources.

In a world characterized by a constant increase in energy use, one of the biggest challenges is to meet this demand while accomplishing sustainable goals. This aspect is particularly noticeable in developing countries, whose energy demand is rising quickly but whose resources to guarantee a steady supply of electricity are frequently lacking. The positive impact of electricity access on communities is proven by its beneficial effects on education, health, safety, and the economy. Increasing the electrification rate, allows indeed to power schools, hospitals, businesses, homes and to ensure wider access to clean water and services.

This work aims to address the issue of access to clean energies in third-world countries with the development of a multilateral methodology that takes into account not only the technical but also the economic and social aspects. In fact, in many third-world countries, technical solutions alone are not sufficient to address the issue of energy supply. Economic and social factors also play a critical role in determining whether or not people have access to clean energies. By considering these factors, the methodology developed in this work can help identify and address barriers to energy access and create more effective and sustainable solutions for its improvement. The technical aspect considers the feasibility of various renewable energy sources and their suitability to the local conditions. The economic aspect explores the affordability and cost-effectiveness of these sources. The social aspect takes into account the cultural and social practices of the local communities to ensure the energy solutions are acceptable and accessible to all.

All these matters are dealt with in the development of some case studies tailored to the needs of local populations in two countries, Uganda and Malawi. As a way to better understand the social context and thus the feasibility of the projects, some interviews were conducted with local stakeholders. This step was extremely useful in giving the work a tie to reality and understanding the actual needs of local populations in the phase of development of the case studies.

By incorporating a range of cases with varying characteristics, the study is able to provide a more comprehensive methodology and understand how it can be successfully applied in different contexts. Furthermore, by taking into account

the actual needs of the population, this study contributes to the development of sustainable and effective energy solutions that are adapted to the specific requirements of the communities they serve. In essence, this approach ensures that the proposed methodology is grounded in real-world needs, while also being rigorously validated through a careful analysis of diverse cases.

The novelty introduced by this thesis is a new approach to renewable energy projects in developing countries that provides a critical and organic review of previous works aiming to evaluate which economic strategies are the most effective based on the specific technical requirements. The literature on renewable energy projects and policies is lacking in this aspect, and this work tries to make its contribution in this sense by analyzing previous research and, starting from their critical analysis, developing a methodology that helps decision-making processes. This approach provides a comprehensive and nuanced understanding of renewable energy projects in developing countries, which can help inform policymakers, investors, and other stakeholders in making informed decisions about these projects. Through a rigorous analysis of existing literature, the thesis provides valuable insights into the factors that influence the success of renewable energy projects in developing countries and brings new understanding for future research and development in this field.

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Chapter 1

Renewable energy policies and their effectiveness

The introductory chapter of this work proposes a study of the policies that have been adopted in some developing countries to boost renewable energies. Together with the financial and political measures, ways to increase the social acceptance of such undertakings are examined. For a fuller understanding of the most effective strategies to be used, both instances of successful and unsuccessful cases are provided.

In the following sections, an analysis of the main financial schemes is carried out, followed by a review of the main policies adopted in selected nations. The last section is dedicated to a summary with the purpose of determining the main steps to be followed to achieve integration of renewable energies in developing economies, both from a techno-economic and a social point of view.

1.1 Conceptual framework

The issue of climate change and the high volatility of oil prices have compelled governments to implement policies to support the growth of renewable energies over the last two decades. Those policies have first been implemented in European and North American countries and afterwards in numerous other nations throughout all continents.

When it comes to developing countries, an important aspect to consider is the rate of electrification. There is still a substantial disparity in the access to electricity between developed and developing nations and between the urban and rural areas of the latter. At the global level, the World Bank's most recent data for 2020 show that access to electricity is around 90%. Regionally, this figure varies greatly, from Europe and North America, where it has long been fixed at

100 percent, to Sub-Saharan Africa, where it barely exceeds 48 percent. In this region, the urban-rural divide is marked by a 78 percent to 29 percent gap [1]. Figure 1.1 depicts the percentage of people who had access to electricity in 2020 by macro-region and globally.

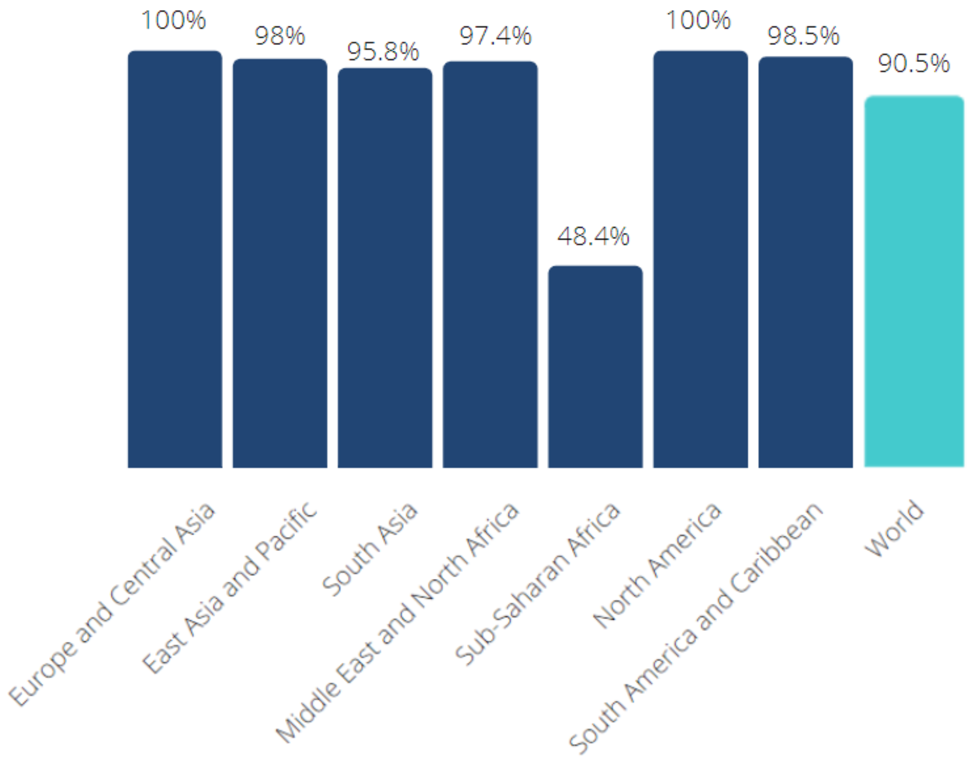


Figure 1.1: Access to electricity by macro-regions

Source of data: World Bank

Electricity plays a role of major importance in communities since it helps their development, supports education, and creates a safe and healthy environment. Significant improvements on the side of electrification have been made since the turn of the millennium as a result of the governments' efforts in the implementation of dedicated policies.

1.2 Renewable energy policies and auctions

In the next few pages, a report of the policies and auctions that have been primarily implemented worldwide is presented.

1.2.1 Feed in Tariffs

Feed-in tariffs, abbreviated as FITs, are incentive mechanisms that encourage the generation of electricity from renewable energies by allowing power providers to sell the electricity produced by certified power plants to off-takers at a fixed price for a set period of time. FITs use a method based on prices, which are established according to the type of technology. The goal is to attract investors, who could be Independent Power Producers, companies, or private developers [2][3]. Independent Power Producers (IPPs), also called Non-Utility Generators (NUGs), are private entities that operate in an unbundled market; they own electricity generation facilities and sell the energy to utilities, governmental buyers, and end users. IPPs can be private services, be owned by cooperatives or even consist of non-energy industrial facilities that produce their own electricity and feed the excess into the grid [4].

Although FIT schemes are extremely useful in promoting the use of Renewable Energies (REs), some criticisms have been leveled for economic reasons since, if they promote more expensive technologies, this can result in an increase in electricity bills. Moreover, FIT schemes, have been criticised for not producing enough competition [2].

FITs have been primarily implemented in developed countries, in particular in Europe, where they have contributed enormously to the markets, in particular in Germany and Spain. Italy has seen the implementation of FITs since 2005, the year in which the market for solar photovoltaic exploded [2]. The knowledge thus acquired, was ready to be exported to developing countries.

The establishment and modification of tariffs play a crucial role in determining whether or not FIT policies are successful. Therefore, in order to establish efficient FIT schemes, technical knowledge and experience in the sector are required. However, in some developing nations some of the needed competences may not be available [2].

Taking Africa as an example, some critical institutional frameworks, low FIT rates, and difficulties in implementation led to the failure of many policies. The choice of the stakeholders is central to overcoming the main challenges, avoiding delays in the deployment of a technology, and reaching a good percentage of projects that become commercial. In fact, many policies present a common liability: they attract investors' interest but the projects do not become available for commercial use. A solution to this issue could be the introduction of some penalties for those projects that do not meet the scheduled deadline [2].

A vital aspect of the design of FIT schemes is that they are designed and revised according to the changing environment and that they are aligned with the priorities of the specific country. They should be flexible and address specific technologies in order to minimize the risk for the investors [2].

1.2.2 Auctions

A viable alternative to FITs is an auction mechanism, which reduces investors' risk and guarantees the improvement of efficiencies due to price competition. When compared to feed-in tariffs, the prices generated by an auction system better replicate technological changes. However, to make the auction mechanism reliable, the selection process and the bidding mechanism have to be as transparent as possible [2].

Auctions, like FIT schemes, can provide sellers with consistent earnings. In order to achieve that, they have to be coupled with Power Purchase Agreements, which will be discussed in the next section.

Auctions can establish the amount of power that has to be generated in order to help policymakers meet the goals for the generation of electricity from renewable sources. They can also discover real prices if they are designed for that purpose, allowing for a simple and cost-effective deployment of renewable energies. Their design is quite flexible, and, thanks to this aspect, they can aid in achieving larger policy goals. This is one of the reasons why auctions for renewable energies are widely used worldwide [5].

Auctions can be adjusted in order to prioritize those projects that have the highest probability of becoming operational. Moreover, in order to allow future bidding rounds, the auctions should no longer be stand-alone but highly flexible so as to be able to include new players, even the small ones [5].

1.2.3 Power Purchase Agreements

Power Purchase Agreements, here called PPAs, are contracts established between the renewable power generator and the purchaser in which the latter provides some services to the former, such as forecasts of production and unbalances, daily transmission of market offers, and cash flow management. The agreed prices can be fixed in order to reduce the volatility of energy prices, or they can be variable between a minimum and a maximum according to the electrical market. Generally, PPAs last for a decade and a half, and they can involve the participation of the customers, which represent the demand. PPAs are particularly useful in the absence of other kinds of incentives since they allow the establishment of future revenues. This aspect makes them beneficial, especially photovoltaic and wind plants that have much higher investment costs than operational ones. Incentives of type *feed-in* and auctions are kinds of PPAs with the participation of a public service, with the purpose of ensuring the payment of an established tariff or a minimum charge to foster the project's bankability [6].

1.2.4 Net metering

Net metering is a possible alternative to the previous schemes but it can also be used in combination with them. It is an energy billing mechanism that enables those consumers who produce a part or all of their own electricity to use it at any time rather than at the moment of generation only [7], using the grid as a storage system. Energy system owners receive credits for any excess electricity they generate and feed back into the grid. The credits can then be used to offset the owner's electricity bill when they draw power from the grid.

This method allows for a more efficient use of the energy on the national grid since it guarantees greater supply stability. The policy is more attractive when the household electricity bills are considered in the evaluation of the exported energy credits [2].

1.2.5 Financial measures implemented in developing countries and possible bottlenecks

As mentioned before, many financial measures are applied in developing countries only after they have been tested in nations with stronger financial, political, and bureaucratic structures. All of the economic schemes have their advantages and disadvantages, however, whichever one is implemented, the lack of finance and access to capital for the companies investing in REs is accounted for as one of the main bottlenecks encountered in emerging nations. The following lines give an overview of some of the measures put in place in developing nations in addition to the implementation of FITs or auction schemes.

The first step that can be taken is the institution of a carbon market, in which the traded goods are carbon credits and carbon offsets. The aim is to create new market opportunities while mitigating the climate crisis [8]. The institution of international carbon trading dates back to the 1997, with the Kyoto Protocol. Yet it has seen a revival of interest recently that has been sparked by a global shift in public opinion about climate change and an increase in the general understanding of climate concerns [9]. Another mechanism resulting from the Kyoto Protocol is the Clean Development Mechanism (CDM). It promotes a sustainable development for emerging nations while helping developed countries meet their targets for emissions reduction. For each project, the Certified Emissions Reductions (CERs) are quantified as the avoided greenhouse gas (GHG) emissions. Each CER is purchased as a tonne of abated carbon equivalent [10]. Such reduction is calculated by considering the project baseline, obtained as the difference between the emissions the project would have without CDM implementation and the theoretical emissions [11].

Focusing the attention on Sub-Saharan Africa, it can be noticed how this region would have the opportunity to use renewables as primary energy sources. In particular, the potential for solar PV is extraordinary. Tough, most of the people who live in remote areas still have poor access to electricity even if the region has the potential to reach the 80% or more of the population currently without any access to electrical power [2].

1.3 Countries analysis

This section presents a review of papers dealing with the policies adopted in some countries to develop renewable technologies. Many of the reported papers are reports from the World Bank. The World Bank is the biggest financial institution for global development, whose aim is to put an end to poverty and promote worldwide the general improvement of wellness. It helps the governments of developing countries face national and international challenges through financing and expertise [12].

1.3.1 Vietnam

Vietnam is a country in southern Asia with many different cultures and traditions. With a population of over 99 million people and an area of 331,236 square kilometers [13] it is one among the World's most populous countries.

Since the implementation of the *Doi Moi* economic reforms in 1986, Vietnam has progressed from being one of the world's poorest countries to a middle-income country with a resilient economy [14]. Other aspects have been propelled alongside economic development. Indeed, living standards improved significantly as a result of greater access to infrastructure, and rural areas developed rapidly as a result of improved sanitary services and water supply in remote locations [15]. The purpose of the country is to become a high-income nation by 2045; to achieve this, a certain amount of development in different aspects is still needed. Among the challenges, some of the most crucial ones are related to environment protection and the development of clean energy systems. Looking at the pie chart reported in Figure 1.2 it can be seen the share of the contribution of each form of energy in the energy mix of Vietnam in 2016. The contribution of renewables was still extremely limited. One step in that clean development direction was made in 2022 with the establishment of a carbon market with the support of the World Bank [16]. The World Bank acts on several fronts for the country's development. In particular,

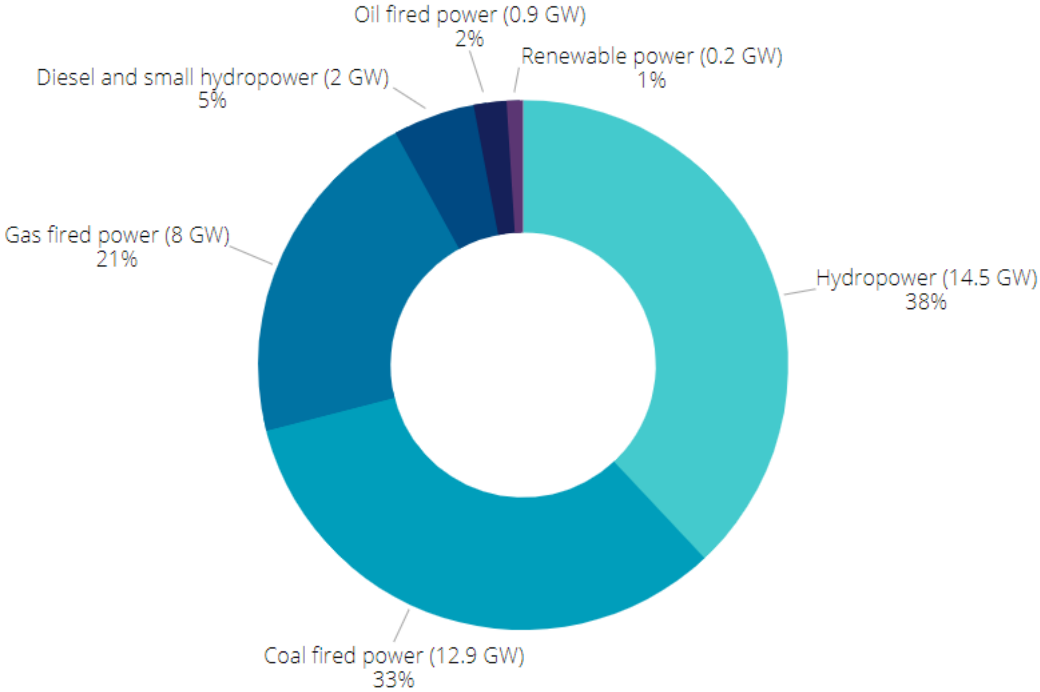


Figure 1.2: Vietnamese energy mix in 2016

Source of data: World Bank

two road maps are analyzed below, regarding the installation of solar photovoltaic and offshore wind, respectively.

Solar PV At first, the World Bank Group focused its attention on solar photovoltaic potential as a means of development for the country. The paper considered in this section, published in October 2018, is entitled *Vietnam: Achieving 12 GW of Solar PV Deployment by 2030 – An Action Plan*. It investigates the key actions that need to be taken to reach the power installation target, in particular strategies to grow experience and lower costs while maximising the economic benefits [15]. Vietnam is already an exporter of photovoltaic technology that provides around 7% of the global production, and this share is even intended to increase. Therefore, it should be easy for the country to shift towards a domestic use, with the further benefits of creating some 25,000 full-time equivalent jobs and raising the country's Gross Domestic Product (GDP) by 0.25% by 2030 [15].

At the time of the study, the local banks lacked expertise and long-term deposits that made it necessary to rely on international banks and investors [15].

The study points out that, in order to obtain lower tariffs, areas with high solar irradiation, such as the south of the country, should be preferred. At the same time, a highly competitive system between companies should be created in order to reduce capital and operational expenditures by favoring economies of scale and a balanced allocation of contractual risk between the power producers and the government. Long PPAs, auctions, and FIT schemes help encourage qualified independent power producers to invest. The reduction of the perceived risk resulting from the development of the technology and from a suitable auction scheme helps reduce the price of the technology itself. The Vietnamese financial sector has been quite week in the past years but after the approval of the *Financial Strategy to 2020* in 2016, it became able to open its doors to competitive technologies like photovoltaic [15].

In 2018, the rate of penetration capacity for Variable Renewable Energies (VREs) in Vietnam was lower than 1 percent, as shown in Fig. 1.2. International experience has shown that there is ample room for increasing the grid integration of the technology, although over-generation should be prevented to avoid the risk of disruption, which can be obtained by limiting the generation from dispatchable resources. System flexibility is key to reaching a high penetration of VREs. In fact, when good flexibility is achieved, the main grid can handle up to 15-20% of the total generation from VREs without requiring implementation. In such a context, battery storage should be promoted, while the reserves - spinning and non-spinning - should be priced [15].

Photovoltaic systems can be strategically installed, connected to different high-voltage substations, or associated to hydropower schemes as Floating Solar Photovoltaic (FSPV). For what concerns rooftop installations, high-definition images can be used coupled with ground surveys.

Before 2005, the installed PV capacity was derisory, at around 1.1 MWp in the whole country. In the following years, the installed power had a slow increase until 2018 when, thanks to the World Bank contribution and the Vietnamese government efforts, it experienced the first significant step compared to the previous year, reaching 106 MWp of installation. Nevertheless, despite this leap forward, the installed capacity remained small compared to nations with similar resource potential, like the Philippines and Italy. Compared to Italy, for example, the installed capacity was around 1% [17].

A sharper increase occurred in 2019 when the total capacity reached 5 GWp, of which 4.5 were newly grid-connected solar plants and 0.4 GWp represented rooftop solar systems [17]. The fast growth was boosted, among other things, by the *Prime Minister's Decision No. 11/2017/QD-TTg of 2017 on the Mechanism for Encouragement of the Development of Solar Power Projects in Vietnam*, which has been effective from 2017 to 2019 with the aim of encouraging the development of solar projects. It contains provisions for funding, investments, and incentives, including FITs and import duty exemptions [18]. In contrast with the *FIT 1* implemented under Decision 11, in April 2020, a new FIT scheme, called *FIT 2*, was issued by the government for grid-connected PV systems.

The primary issue when dealing with FIT mechanisms is that they can be confusing if not properly managed, resulting in a decrease in investors' interest and confidence. In order to facilitate fast ramp-up of solar generation, the government's intention is to switch to a competitive bidding mechanism, at once with the provision of a clear development path for a sustainable program [19].

In the context of the development of a road map, investigation and research are crucial to collect reliable data and provide well-founded reports. Despite all the efforts made in that direction, the road to the achievement of a development of the technology commensurate with its potential is still studded with barriers in different aspects: institutional, technical, financial, and economic. Hence, to guarantee a technological development, the government has to focus its attention on the adjustment of policies based on the specific needs of the moment [17].

Wind As for solar, the World Bank has lately defined a road map for the development of offshore wind in Vietnam. The country has a consistent wind resource that would allow it to generate up to 30% of the country's electricity if properly exploited. The paper considered for this part is titled *Offshore Wind Roadmap for Vietnam*, drawn up in 2021 by the World Bank. The cited work consists in the analysis of two scenarios, respectively called "Low-growth scenario" and "High-growth scenario", both considering floating and conventional installations and nearshore ones [20].

As mentioned for solar PV technology, the government is responsible for the implementation of financial strategies aimed at decreasing the cost of capital and catching private investors' attention. In fact, looking at the Northern European countries that have a successful story of offshore wind installations, it can be noted as their governments played a significant role in encouraging private investors to develop wind farms through a strategic policy framework and a program of spatial planning able to take into account both the stakeholders' needs and the environmental issues [20].

Vietnamese projects differ from the European ones for the wind speed, which is on average lower and makes the use of specific rotors necessary. The most interesting option for those is represented by Chinese suppliers' designs, which would be useful to reduce the costs, which are otherwise quite high in the early years. Furthermore, in order to decrease the cost of capital and to improve efficiency, the projects should share a common transmission line instead of building their own one to shore [20].

Differently from what happens with solar technology, Vietnamese companies are not yet prepared for rotor production in the near term. Cooperation between domestic and foreign firms would be advantageous because the former have more extensive knowledge in the field and the latter face fewer entry barriers in the market. In addition, it could be useful if local oil companies with their expertise entered the market in the field of installation and decommissioning [20].

For what concerns the economic aspect, the reduction of risk and the increase in the availability of finance help reduce the Weighted Average Cost of Capital (WACC). Learning and competition also have an impact on the reduction of costs. Moreover, not to let the price fall on the customers, public policies need to be developed. Otherwise, the only financial support for projects would come from the Vietnam Electricity Company. If the projects have a beneficial impact on the environment or the climate, they can be fund by bonds and securities addressed as *green debts instruments*. [20].

Together with the green debt instruments, the green equity instruments are implemented as ways of providing financial support. They relate the equity issuances of the companies that use their capital for green projects [20].

As for the study carried out for solar energy, a mapping phase is introduced. There are three categories of maps, respectively indicating the technical potential, the LCOE, and the main constraints, from an environmental, social, and technical point of view [20].

1.3.2 India

Continuing on the Asian continent, India's example contrasts with Vietnam's in terms of the willpower required to develop a green energy system. Many studies and reports dealing with development of projects under the Clean Development Mechanism exist, but the process of implementation looks more troubled than the Vietnamese one, due to several economic interests that divert the attention from the green goals.

India is the second-most populous country in the world, and it has been characterized by extensive industrialization and urbanization in the last decades. Between the 1980s and the 2010s, the country's GDP grew significantly. This resulted in an increase in energy consumption, though the energy demand per capita remains low compared to the global average due to the nation's large suppressed energy demand, with some 400 million people lacking access to electricity [21][22]. Historially, the main players in the production of power have been coal, oil, and gas, and this configuration of the energy mix is not easy to change in the near future since the growth in energy demand is likely to cause a further increase in the use of fossil fuels [21]. The majority of the country's emissions are due to the energy sector; although its emissions intensity has declined over time as a result of increased energy efficiency, the energy mix stagnation and the rising power demand have a negative impact on the emissions problem [21][22].

By the end of 2007, the total installed capacity was around 140 GW, with a major contribution from thermal technologies, as can be noted in Fig. 1.3, which reports the share of every energy technology. India is one of the countries with the highest potential for REs, however they are still extremely under-exploited.

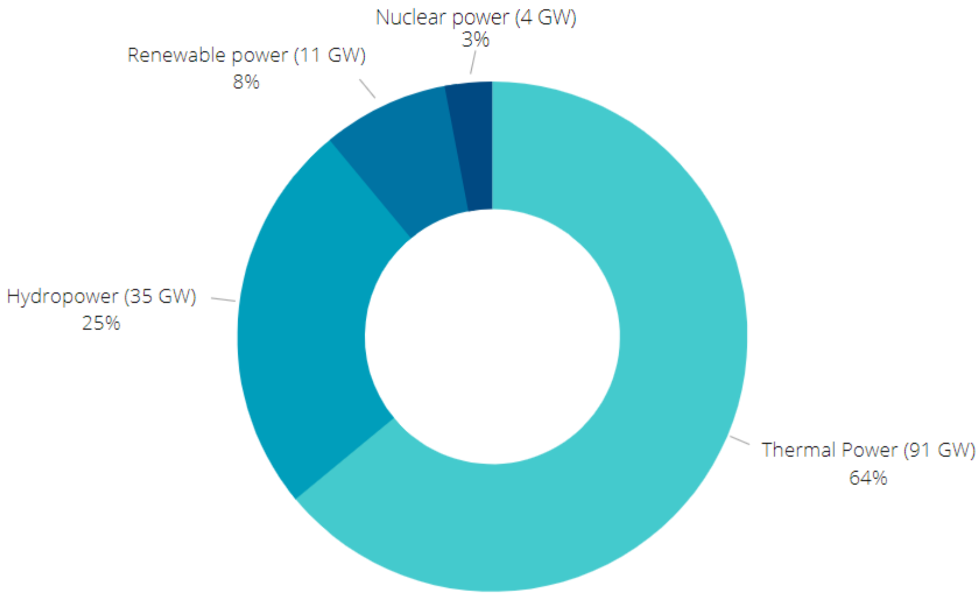


Figure 1.3: Indian energy mix in 2007

Source of data: Ministry of Power - Government of India

As disclosed by an article published in 2008 in the journal *Energy Policy*, the total potential for hydro in the country is 150 GW but only 23% was exploited by that time. Among these, small hydropower (SHP) schemes contributed only 6% of total hydro capacity [23]. Despite the numerous studies carried on concerning small-hydro technology development, a recent study published in February 2022 by the journal *Energies* with the title *Levelized Cost of Electricity Generation by Small Hydropower Projects under Clean Development Mechanism in India*, assesses that the total SHP potential is around 21 GW, while the currently installed capacity is less than 5 GW [24].

Some projects under CDM have been realized, but it is not easy to assess the baseline of carbon emissions, making it hard to receive the Certified Emissions Reduction. The projects developed in the early 2000s were not suited for the needs of rural areas. In fact, developers were not attracted to those regions due to the poor availability of infrastructure, and this led to a slow and disorganized development of CDM projects. On the management side, the most successful projects turned out to be the ones run by cooperative ventures rather than by profit-making organisations [25].

The policies implemented by the government play an important role, helping to break down the barriers that inhibit the projects' realization and encouraging the participation of the private sector, which is still very low in the renewable energy field [25][23]. Nonetheless, the government's efforts are focused more on the industrial sector than on reducing emissions. Indeed, alongside with support to CDM, India still finances fossil fuels exploitation. CDM has been an incentive in renewable initiatives but not a real driver for investment decisions, since the country has been a prominent voice in emphasizing that industrialized nations need to act first to reduce their emissions, having the highest historical contribution to GHGs release, to compensate for the industrialization of developing countries [22].

The Indian government has been harshly criticized for some projects' detrimental health and environmental effects and some frauds in carbon reduction assessment. The role of the state should be to create an enabling policy environment and to establish a procedure to attract private finance and achieve technological development, while in India the most industrialised regions had been prioritised to attract the biggest number of investors. Some areas have instead been deliberately neglected in order to protect bureaucratic interests: this un-governance is chosen in cases in which fossil fuels plants development is threatened by renewable projects. A political decentralised system could give space to projects promotion, however local institution can be susceptible of corruption too [22].

To meet both environmental and social needs, the national power supply, as well as the institutional aspect, must be profoundly transformed. The above-mentioned article *Levelized Cost of Electricity Generation by Small Hydropower Projects under Clean Development Mechanism in India* provides a methodology for the assessment of the parameters useful to reduce the Levelized Cost Of Energy (LCOE) of small hydropower plants with the aim of providing cost-cutting methods to the developers. The work encompasses the evaluation of CERs and of the capital, operational, and maintenance costs [24].

1.3.3 Indonesia

Indonesia is a country in Southeast Asia made up of thousands of volcanic islands. It has a diverse population that speaks over 300 languages and lives in both cosmopolitan cities and rural villages. Indonesia is currently the third-most populated democracy in the world, and its economy has a strong impact at the global level. It is, in fact, the largest economy in the area and a member of the G20 group, an international forum bringing together the world's leading economies. The largest component of the economy is manufacturing. Another important sector is represented by exports of crude oil, natural gas, rubber, palm oil and cocoa [26].

The Covid-19 pandemic has inflicted deep wounds on the socio-economic fabric of South-East Asian countries, imposing an abrupt halt to the vigorous growth that has characterised those economies over the past decade. Indonesia was one of the most affected nations by this phenomenon, with a government incapable of counteracting both the rising tide of disease and the economic downfall. The economic recovery began in 2021 as a result of the leading sector of manufacture and raw material exports. The government developed a plan for the country's modernisation under the banner of human capital development and of innovation [27].

Of crucial importance for the country is also a revision of the energy supply policy. The domestic energy infrastructure is weak, and the oil reserves might run dry by 2030. The primary solutions to the growing demand for energy of the last few years were the progressive growth of energy procurement on international markets and the massive domestic production of coal, which reached 616 million tons in 2019, which is almost ten times the production in 2000. Due to this decision, now Jakarta is one of the most polluted cities in the World, according to the 2020 Air Quality Index [27].

Fossil fuels, thus, continue to account for the majority of the total energy investment, while geothermal receives the majority of funding directed to renewable sources. Nonetheless, as a member of the G20 and as president in 2022, the country must ensure a transition to green energy and a sustainable recovery. In 2020, the government announced that the country was going to almost double its renewable share by 2025, bringing it to 23% of the overall energy production. At that time, the installed renewable power was 11.5 GW, equivalent to 11.2% of the overall energy mix. Coal and gas, instead, represent together some 80% of the country energy generation [28]. The share of each renewable in 2020 is reported in figure 1.4 as percentage of the total renewable contribution to the energy mix [27]. Hydropower is the most developed, while variable renewables acount for only 4%.

Fossil-free recovery The paper entitled *Using Public Funding to Attract Private Investment in Renewable Energy in Indonesia* by the International Institute for Sustainable Development written in the beginning of 2022 presents a strategy for the promotion of renewable energies and a way to attract investors, as reported in the following section.

To meet the targets, huge private and public investments are needed in order to counterbalance the absence of strong policies, regulation, and an effective pricing structure. Using public money in the form of direct financial injections, budget transfers, and tax incentives at the national and regional level can help encourage private investments in renewable energy sources. Also the international community significantly promoted the development of renewable energies in Indonesia through

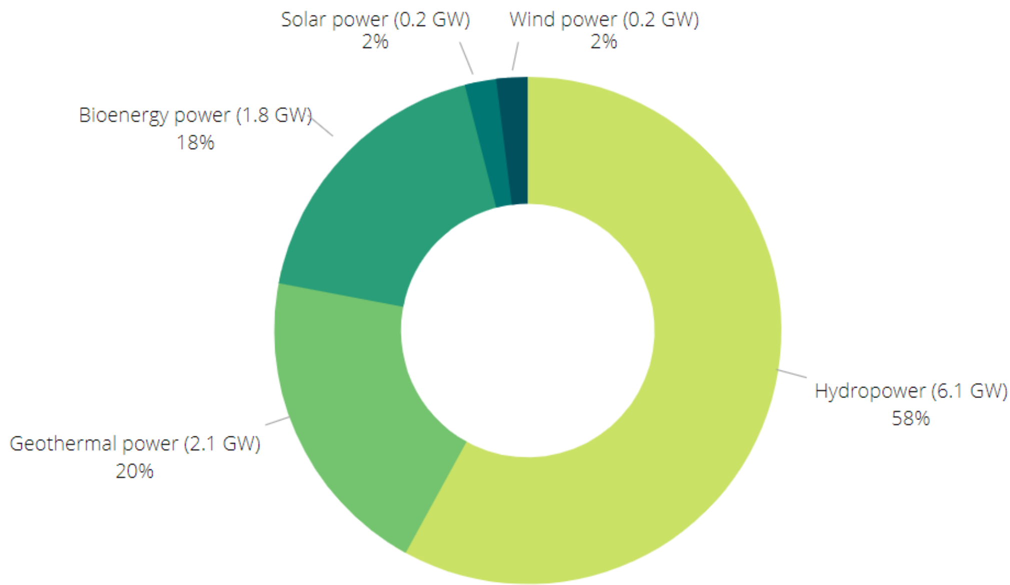


Figure 1.4: Indonesian share of renewable in 2020

Source of data: Ministry of Energy and Mineral Resources - Republic of Indonesia

initiatives and financing that, combined with the state budget, spurred private investments even more [29].

The way the government can attract investors is by allocating public money in order to de-risk private finance through direct budget transfers, equity investments, and public debt issuances. In general, when a government prioritizes and supports a sector or technology, this has a de-risking effect. Through subsidies it is possible to signal which are the national priorities and influence investment decisions while, through auctions, it is possible to provide competitive costs [29].

Numerous projects and initiatives have been implemented in order to reach the 23% share target by the agreed time, yet numerous roadblocks are still present. In the first place, the electricity structure is not cost-effective and varies considerably in the different regions. Furthermore, there is the issue of fossil fuels that are not only used to produce energy but also subsidized. Concerning the regulatory framework, renewable energy policies are fragmented and changing. This aspect, combined with the high perceived risk, makes Indonesian energy projects not financially viable in the eyes of investors. Another important feature in developing such a regulation is transparency, which is currently missing since data on financial flows, sources, and public funding allocation are frequently inaccurate [29].

To stimulate and enable renewable energy projects development and funding, the government has established the Public Financial Institutions, which represent a group of entities whose function is providing and managing public funding [29].

1.3.4 Pacific Island Countries

The Pacific Islands Countries, also referred as PICs, constitute a region in the Pacific Ocean that groups together Melanesia, Micronesia and Polynesia. They have developing, mostly subsistence economies whose principal sectors are agriculture, fishing, and services, in particular those related to tourism. They import a big amount of fuels, whose prices affect them negatively [30][31]. Due to their small population, scarce resources, remote location, propensity for harsh weather occurrences, and reliance on foreign aid and trade, these nations share many of the same challenges [31].

Concerning the energetic and environmental aspects, some CDM projects can be implemented, taking into consideration other projects realized in other small island nations. Generally, the most implemented projects are the large-scale ones, which result advantageous thanks to the scale economy. Nevertheless, despite the presence of abundant renewable resources, lack of expertise, absence of supportive regulations, skilled labor scarcity, weather susceptibility and poor infrastructures all contribute to the rise in investment risk and expense. For all these reasons, together with the controversial issue of land availability and the prohibitive conditions for what concerns the monitoring and verification of carbon reduction with an imprecise measure, many of the CDM projects do not find a fertile ground. In particular, the renewable projects often take a back seat to some projects defined as "high priority" that are related to the increase in efficiency of fossil fuel plants and the reduction of power losses from electricity transmission and distribution grids. Some agricultural projects can be attractive as well due to their low investment costs and the capability of incorporating renewable generation. Also some projects in the field of the waste management are ready to be developed from the technological point of view [31].

Many delays have occurred in the implementation of such projects due to the still high perceived risk, the absence of a common methodology and the lack of expertise and capital for financing. Reforms that encourage investments should be implemented and the nearby nations Australia and New Zealand could make their expertise in the fields of technical and institutional capacity available. Moreover, it has been discussed the possibility of establishing a central hub of information to increase the knowledge on the topic and reduce the perceived risk [32].

Grid-connected PV systems Despite all the challenges in the development of CDM projects, grid-connected solar photovoltaic (GCPV) systems are spreading in Pacific Island Countries in both urban and peri-urban areas, as reported by an article published in the journal *Renewable and Sustainable Energy Reviews*. GCPV systems allow users to purchase electricity from the grid at night and sell PV energy to the utility at an agreed-upon rate during periods of excess production during the day. The reduction in PV prices alone is not sufficient to boost the grid-connected PV technology, since its market depends both on the technological progress and on the regulatory ad financial support. FIT schemes can be used to lower the perceived risk by the application of fixed prices to long contractual periods. After FIT has operated for a few years, governments may consider Solar Grid Parity, which occurs when the cost of electricity bought from the grid is equal to the levelized cost of PV energy generation [32].

In the past, stand-alone systems were already widely used in dispersed areas, but with the introduction of development agencies and the inclusion of private investors, stand-alone systems have been introduced also in cities. The solar technology in PICs is particularly attractive for the abundance of solar resource coupled with the decrease in PV module prices but, despite its attractiveness, the countries still lacked an established framework for renewable technologies at the time of the publication, in 2011. As said in an IPCC (Intergovernmental Panel on Climate Change) report, one of the major deterrent to the development is the lack of education and training. In order to mainstream GCPV, a multidimensional approach is needed to deal with all the technological, economic and human issues.

1.3.5 Peru

Peru is one of the nations in Latin America with the historical lowest electrification. In 1993 the electrification rate in rural areas was around 8% [33], while in urban areas it was already 90% [34]. In recent years the rural electrification has grown, reaching 78% in 2015 and 96.8% in 2020, [33][34], however, this rise is still insufficient to deem the country fully electrified. In order to have an idea of the rural situation in Peru, some data from the World Bank are reported. In 1960, the total population was slightly over 10 million people, of which 53% constituted the rural portion. In the years, the trend has inverted, with the tripling of the population and the percentage of rural inhabitants decreasing to 22% in 2022 [35][36]. The following chart shows the growing trend of the population in the country and the decrease of rural population from the 1960 to nowadays. Peru still has several million people without access to electric power, despite the fact that the electrification rate is rising and the rural population, which has the lowest electrification, is declining in percentage.

Between 2006 and 2013, numerous stand-alone PV system initiatives have been carried on in the context of the Rural Electrification Projects. The Rural Electrification Projects were two, RE1 and RE2, developed respectively in 2005 and 2006 by the collaboration of Peruvian government with the World Bank and with the

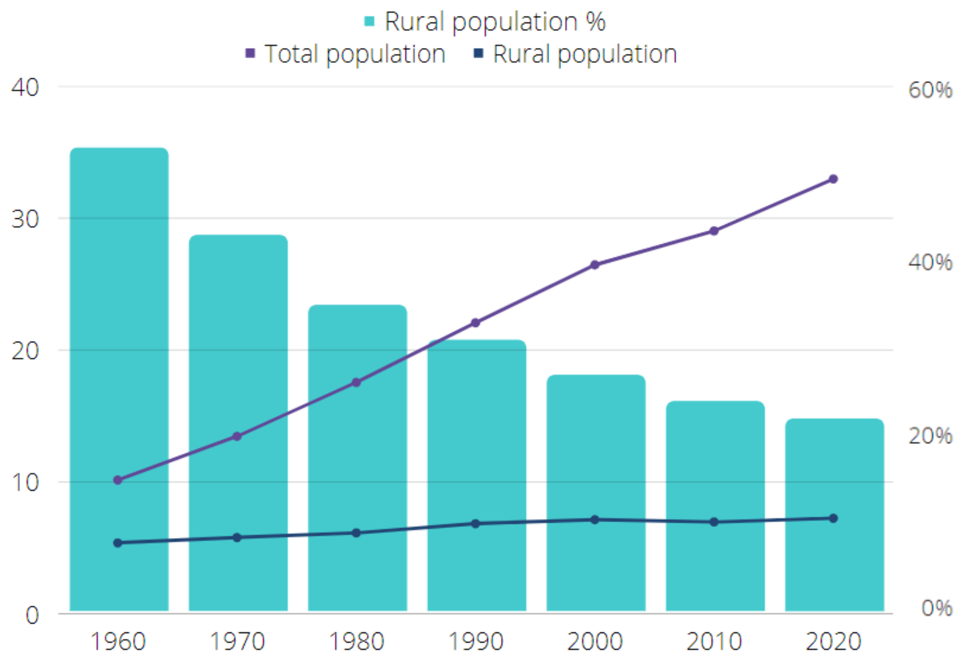


Figure 1.5: Trend of growth of Peruvian population

Source of data: World Bank and Worldometer

aid of the Global Environment Facility (GEF). It was crucial the establishment of a regulation able to create standards, tariffs and subsidies. Before that, the regulatory framework was incomplete and this limited the growth of off-grid renewable market [37]. In addition, in 2014 the so-called "massive program" started with the aim of introducing 150,000 to 500,000 new photovoltaic installations in remote areas. The typical installations consist of solar panels with capacities up to 60 Wp and batteries whose size varies from 60 to 100 Ah [33]. In the same period the National Rural Electrification Plan (in Spanish: Plan Nacional de Electrificacion Rural, PNER) for the period 2013-2022 has been implemented to promote rural electrification by means of renewable energies. Of the total USD 1280 million invested in rural electric systems, 294 million were intended for solar photovoltaic, 53 million for small hydro and 42.5 million for wind power systems [38]. The program was created with the intent of developing a long-term perspective, but the numerous changes in the political system hindered the development of a strong policy line in a climate of growing mistrust towards formal institutions.

Many of the implemented projects failed in few years. In particular, the lack of maintenance and the low technical standards led to the premature failure of batteries. Furthermore, at the time of the realization of the "massive program", the real number of households without access to electricity was still unknown. The program required the consideration of the socio-economic background of the projects areas but no practical indications had been provided, causing the failure of many of the projects and some defaults in payments. OSINERGMIN (Organismo Supervisor de la Inversión en Energía y Minería), the electricity regulatory organism of Peru, conducted some punctual revisions that detected that 34% of the systems were not operative. [33].

To make a project functional, it should be followed at national and regional level and suited for the country needs and it should be implemented including also the community. In general, the population of Peru looks favorable to off-grid photovoltaic installations, due to their need for communication technologies. The local population that benefits from those kind of projects is normally poor, therefore it is fundamental to ensure both funding for the initial investments and cross-subsidy funds. A fundamental aspect in this process is the level of awareness of the country's elite on environmental issues [36].

Solar Home Systems Despite all the critical issues of the implemented programs, Peru presents some examples of successful solar projects, as reported by the Energy Sector Management Assistance Program (ESMAP), an intergovernmental organization connected to the World Bank. The paper from 2019 *Off-grid innovation improves thousands of lives in rural Peru* traces the steps of the implementation of Solar Home Systems (here referred as their acronym SHSs). The strength of the project lies in the training of local companies, the provision of online tools for the management of solar homes and the promotion of activities for the population, with live theatre performances to encourage people to adopt electrical equipment.

SHSs consist in stand-alone PV systems able to fulfill the basic electrical needs of off-grid houses equipped with a system of batteries and a charge controller. The pilot project gave promising results, so much so that about 1,500 families purchased electrical appliances [37].

1.3.6 Colombia

Colombia is another of the countries in Latin America that implemented initiatives for the advancement of rural electrification and the application of policies and renewable auctions. The period between the 70s and the early 90s saw a fast expansion of the service coverage and of the installed electric capacity. In fact, the generation capacity, which was around 2,200 MW in 1971, quadrupled reaching 8,400 MW in 1989 while the number of households with access to electricity grew from 1.4 to 4.5 million in the same period. Consequently, the percentage of population with power availability increased from 15% to more than 60%, while in rural areas the rate established around 45%. In 1993, a World Bank's paper reported the study

Figure 1.6: Example of a solar home system

Source: ESMAP, World Bank [37]

of a project for a further electrification of the rural areas. Nevertheless, the energy sector was in crisis due to a still low internal generation and to low financial results. This brought the government to stop its support to the sector during the national crisis. The above-mentioned project was promoted with the aim of implementing the Government's actions with the support of the World Bank [39].

Colombian renewable auctions In more recent years, after all the rest of Latin America had implemented renewable energy auctions, the Colombian government eventually focused its efforts on the promotion of renewable energies, as reported by the International Renewable Energy Agency (IRENA) [5].

As reported in the chart in figure 1.7, the country energy mix was primarily built upon hydropower, which means that the supply reliability, rather than the built capacity, is determined on the amount of energy available over a specific time period, making the generation vulnerable to drought periods. Auctions were needed to attract investments on non-hydro renewables [5].

In the case of Colombia, a system of auctions can help reducing the system's constraints and easing the strain on the water reservoirs. The auctions that have been implemented are of the stand-alone type, which means that they are independent from each other. They are addressed to generators, distributors and retailers, who belong to the two groups of sellers - the first ones - and buyers, which comprises the other two. Both categories consist mainly of private firms. In the first auction implemented in December 2021 the participation was on voluntary basis.

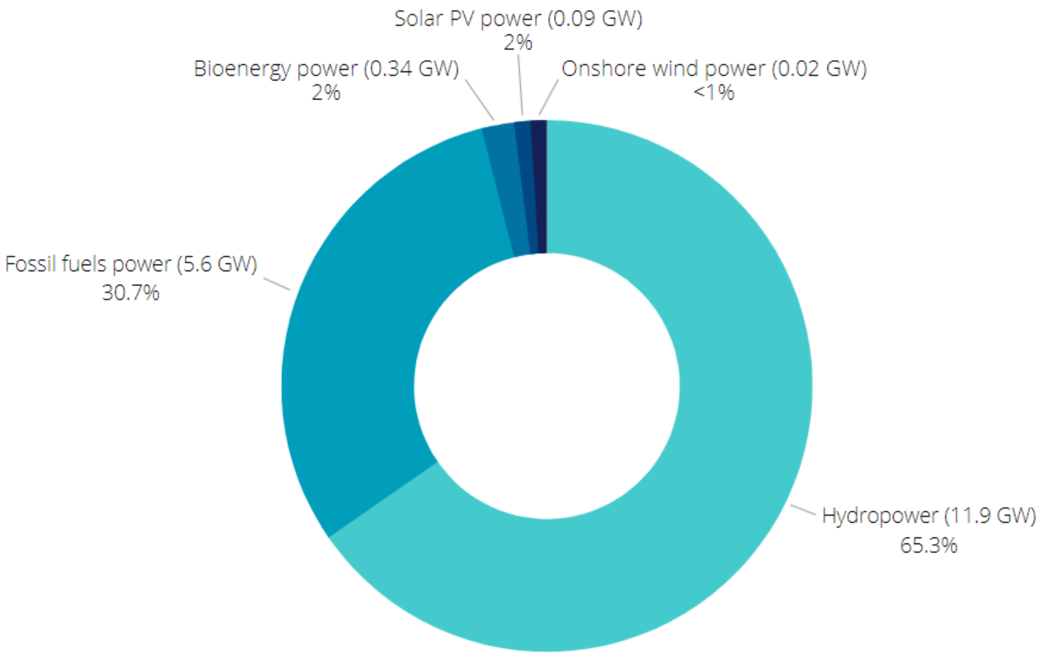


Figure 1.7: Colombian energy mix in 2019

Source of data: IRENA

In the one of January 2022, the voluntary nature was maintained but the constraint of mandatory introduction of at least 10% of energy purchase from non-hydro renewables was added incentivise buyers to participate. The two auctions, in fact, differ in the technological aspect, since the first one was technology neutral and the second one was, instead, made for non-hydro renewables only. The minimum size of the projects was lowered from 10 MW to 5 MW. In addition to the technological aspect, also the bureaucratic one has undergone some changes. In fact, the first auction had complex qualification requirements and a strict documentation to be provided and required the payment of a fee from both the buyers and the sellers side. In the second auction the requirements were less strict and this increased the investors' interest. Moreover, the first auction posed several limits: on the number of players owning both generation and distribution companies, on the concentration of bids from few players and on the share of the single bids. The second one set the only criterion of impossibility to award a single bidder with more than 40% of the volume. Obligations had to be submitted by both buyers and sellers as financial guarantees to avoid under-bidding and under-contracting together with a start-up guarantee with the aim of minimising construction delays and under-building in new plants [5].

A general aspect that needs to be considered in the design of an auction is the specific condition of the country in which it is developed, considering not only the resource but also the confidence of investors and the policies developed by the government in support to renewables.

Analysing the case of Colombia, it can be noticed that the country has high solar irradiance, being close to Equator, and in the northern part it also has an extraordinary wind resource. Though, considering the electricity market, despite its stability since the 90s, some incumbents opposed to the development of renewable auctions. A stable policy plan, coupled with a strong political commitment is of central importance for the success in long terms of the auctions. In the design of an auction it is also important to promote the community participation and to foster equity, for instance taking into account the energy-poor areas, like the northern part of Colombia [5].

1.3.7 Kenya

Moving to the African continent, the next analysed country is Kenya. Since its independence from Britain, its economy grew as a combination of privately owned and state-run businesses, with a predominance of private companies that benefit from a large amount of foreign investment. Most of its economic growth has been linked to the country's ability to enhance its energy resources. The emphasis has been put on the generation of hydroelectricity, but energy access in rural areas is still limited since the majority of the electricity is absorbed by the two major metropolitan centers of Mombassa and Nairobi. Moreover, with the support of the World Bank, the geothermal resource in the Rift Valley started to be exploited in the 1980s to further supply the power demand of Nairobi. However, in the late 90s, a harsh drought occurred in the northern side of the country, leading to blackouts that endured till the beginning of the 21st century [40].

In the past decade, the country has implemented a series of reforms on the political and economic fronts with the aim of sustaining economic growth and social development. Despite that, there are still challenges related to poverty and inequality, climate change, weak private investments, and economic vulnerability to both internal and external shocks [41].

FITs to promote renewable energies In the field of renewable energies, Kenya implemented a scheme of FITs, whose effectiveness is studied in a report written by the Strathmore University of Kenya.

The study demonstrates how, often, the interest of investors does not coincide with the commercialization of the initiatives. In fact, ten years have passed since investors' interest was triggered by the policies before the actual realization of the projects. In 2019 the generation from renewables supported by FITs was 10.3 MW, equivalent to the 0.7% of the 1551 MW target. One of the main reasons for this delay is the inadequate knowledge in policy design and implementation [2]. The projects' capacity at every stage of development is reported in fig. 1.8.

Concerning the renewable resource, the country actually has the potential for

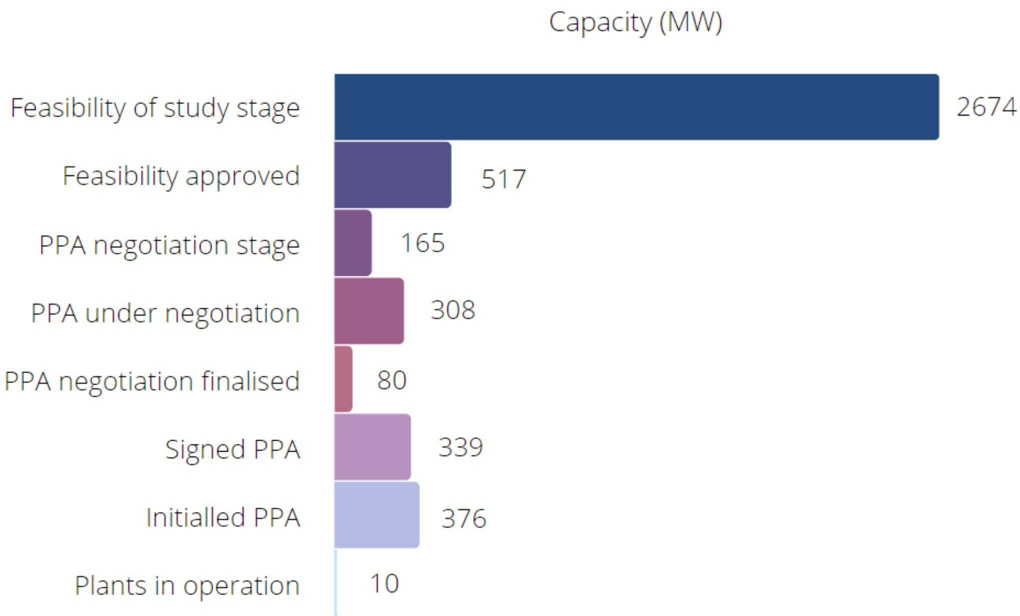


Figure 1.8: Kenyan FIT projects capacity divided by stage

Source of data: Article "The effectiveness of feed-in-tariff policy in promoting power generation from renewable energy in Kenya"

renewable generation, having large availability of solar, hydro, wind, geothermal and biomass. The Government adopted the 7th of the 17 United Nations Sustainable Development Goal whose main purpose is to "ensure access to affordable, reliable, sustainable and modern energy for all" by 2030 [42]. As part of it, it was promoted the creation of solar-fed mini-grids for rural electrification together with the development of wind and geothermal technologies. One of the main reasons that pushed the Government to focus its attention on the implementation of FITs for the development of renewable energies, was the occurrence of frequent power shortages due to the high dependence of the power system on hydropower that, as mentioned before, is severely affected by droughts. Other reasons for the implementation of the FIT policy were the reduction of greenhouse gases emissions and the creation of new deployment and income [2].

In 2008 the Kenyan Government implemented the first FIT scheme for renewable technologies. Afterwards, it has been modified many times during the years. In 2017 a new revision of the FIT policy was published according to the *Least Cost Generation Plan 2017-2037*, however, five years after, there is still a power gap between the demand and the supply. This was primarily caused by some pricing uncertainties, lack of transparency, absence of private investors and even deliberate delays by developers that wanted to take advantage from the reduction in the cost of the technology [2].

Through some interviews the authors of the paper were able to detect some of the reasons behind the unsuccess of the Kenyan FITs. They were actually successful only in generating the private sector's interest but not in achieving a true increment in renewable generation. The low tariffs did not attract the private developers and the policy did not set a limit on the number of players, aspect that might lead to the construction of many plants with consequent overproduction despite the scarce demand for additional energy. No punitive actions were imposed for those IPP that did not meet the deadlines or lacked technical or financial capacity. The bureaucracy is confusing and inefficient and the regulatory bodies lack coordination. Documents were poorly drafted, causing misunderstandings. From a technical point of view, introducing intermittent technologies in an unstable grid is extremely challenging [2].

Some solutions have been proposed to improve the efficiency of FITs. One of those was to limit the access to FITs to small projects (1 to 10 MW) in order to focus the attention on sources in which the country is reach and for which little interest has been shown historically. Another proposal was to shift to an auction mechanism, in particular for larger projects and for intermittent technologies since FITs were not generating enough competition. Auctions can be considered as a solution but a transparent selection and bidding process have to be ensured. The use of mini-grids was considered as an option as well to reach areas not covered by the national grid or to increase the supply where there is more demand. However, one of the most serious bottlenecks is the lack of capital. For this reason, RE companies should be allowed to have a wider access to funding [2].

1.3.8 Uganda

As the majority of nations of East Africa, Uganda's power is mainly generated by biomass. Access to electricity in the country is extremely low, but clear information is lacking on these kind of data. In fact, the values oscillate between a minimum of 20% basing on the Rural Electrification Agency (REA) and a maximum of 42% according to the World Bank [43][44]. The electricity demand is growing at an annual rate of 10-12% and this is creating a gap between the supply and the demand that, combined with the poor maintenance of the grid and the insufficient infrastructures, leads to frequent power cuts [45][46].

The country's most important economic sector is agriculture, which is responsible of the 53% of earnings and that employs 73% of the population. Another leading sector in the economy is tourism, which is expected to grow in the next years, in line with the *National Development Plan III 2020/21-2024/25* [45].

The country is rich in energy resources, which are distributed uniformly on its area with an overall power generation potential of 5.3 GW [45]. Besides biomass, which contributes to over the 90% of the total consumed energy, the other renewable energies are under-exploited. The potential for hydropower is quite large, but only some 10% of the estimated 2 GW of potential is employed for energy production, contributing very little to the national energy supply. In 2014, it represented the 1% of the national energy mix but the 90% of the electricity generation. In particular, small hydro has the power of contributing significantly to the electrification of rural areas. The estimated geothermal resource is 450 MW and is located in the Ugandan Rift Valley. The government has started some studies on drilling projects for its exploitation. If properly exploited, it could complement the current generation technologies. The solar resource is extremely high, with mean annual values of 5.1 kWh/m^2, making it very favourable for any kind of solar installation. PV panels first started to be used in the 80s to satisfy the need of lighting and refrigeration for vaccines in health centers. Wind has a moderate speed, adequate for small applications for power generation and for water pumping [46][47][48].

The annual growth in energy demand makes new investments necessary. The first attempt to boost the Ugandan energy sector dates back to the 1999, when the Electricity Regulatory Authority (ERA) approved the Electricity Act, a legal and regulatory framework to liberalise the electricity sector by supporting private investments and introducing some competition in the vertically structured Uganda Electricity Board. An Independent Regulator was in charge of generation, transmission, distribution and sale, import-export included, while the Rural Electrification Agency and Board provided guidelines to promote rural electrification [47].

In 2001 the Government launched the *Rural Electrification Strategy and Plan* (RESP) that lasted until 2012. Its aim was to install new power plants with the support of the World Bank's *Energy for Rural Transformation* (ERT) program, but it did not meet the expectations and only 7,000 out of the predicted 80,000 plants were realised [48].

In 2002 and 2007 Energy and Renewable Policies were introduced. They established licenses of the duration of 40 years and the institution of a Tribunal dealing with electricity disputes. The 2002 policy aimed at sustaining the electricity supply industry and improving the sector's efficiency. Subsequently, in order to provide price certainty to generators, a Renewable FIT scheme was introduced in 2007, while the Global Energy Transfer Feed in Tariff (GET FiT) Program was developed to attract investments from both local and foreign private companies [47].

Starting from 2015, the 17 Sustainable Development Goals (SDGs) have been promoted with the aim of setting an end to poverty and inequality through short- and long-term solutions to address the needs of rural African people living on less than $1-2 per day. The main challenge is the modification of the biomass technology because, as currently used, it contributes to massive deforestation [48].

One of the major barriers to the development of clean energies is the promotion of investments in fossil fuels by the government through incentives [48]. A crucial step would be the transfer of subsidies from fossil fuels to renewable energies, but the confirmation of the presence of 6.5 billion barrels of oil, of which 1.4 are recoverable, led to a peak production of 230,000 oil barrels per day, and the hope is to discover even more reserves. In fact, Uganda has an 88% success rate in finding oil, compared to a global average of around 25%. Moreover, the Oil and Gas sector is likely to provide big employment opportunities [45].

1.3.9 Malawi

Malawi is one of the poorest countries in the world, with a $300 GDP per capita and a largely agricultural-based economy. Among the nations of the Southern African Development Community (SADC), Malawi has one of the lowest rates of electricity access, with an average annual consumption of 85 kWh compared to the 169 kWh of Eastern Africa. On average, its access to electricity was around 15% in 2020 but this figure drops to less than 7% in rural areas [49].

In a country with very low income levels, energy expenses make for a significant portion of household income. The government is working to eradicate poverty over the long term, and as part of that effort, it is addressing energy poverty. Yet, many issues need to be addressed to reach such a goal. The demand for energy is low, but the installed generation capacity is even lower by some 10%. The peak of underproduction was reached in 2017, when the national company for electricity generation (ENGECO) was capable to generate only 145 to 150 MW of the required 300 MW. Years of outdated regulations led to few benefits for rural electrification, with some inefficient efforts for the extension of the national grid. In 2018, a new National Energy Policy and the Renewable Energy Strategy were launched in the context of the Action Agenda Malawi's Sustainable Energy for all with a view to creating programs to advance off-grid renewable technologies. The involved technologies are hydro, solar and wind, but their scale is yet quite limited, for which expansion legislation changes are needed. The challenge for policymakers is to balance the two competing goals of addressing the social requirements of a population in rapid expansion and boosting the economy at the same time [50].

The nation is rich in coal and is supplier of 1.2% of the Uranium used globally [51]. Hydro, fossil fuels and biomass are the most used energy sources. Biomass are used in home and rural context, while the energy of the national grid is produced by hydro and fossil fuels. In Fig. 1.9, the Malawian electricity production by source in 2019 is reported.

The reliance on biomass and hydropower makes the country extremely vulnerable

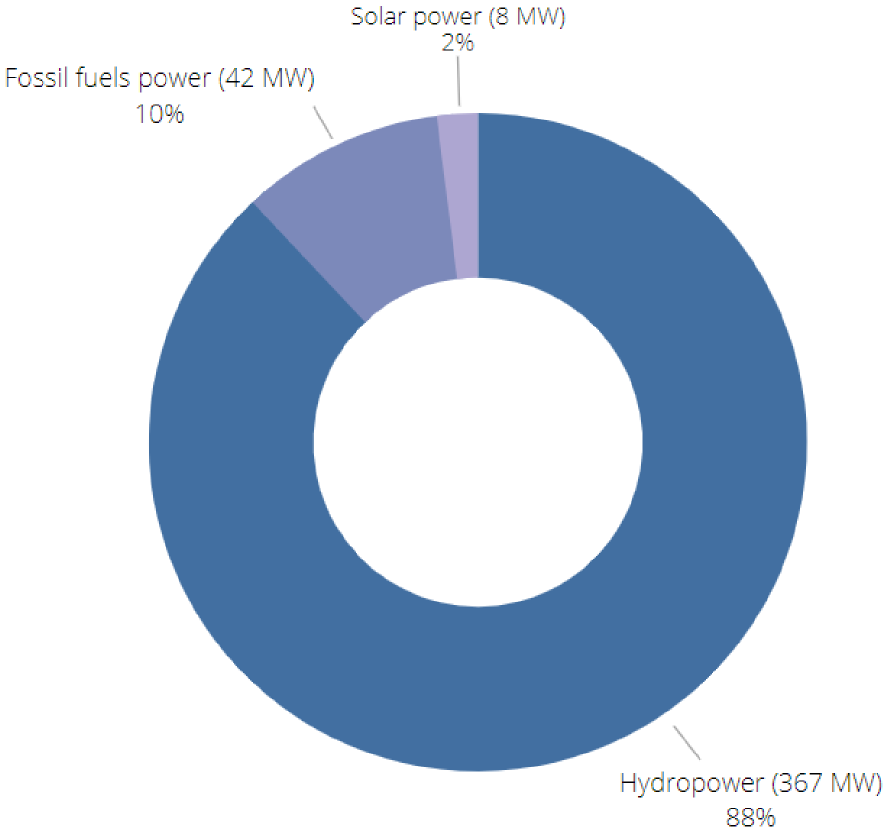


Figure 1.9: Malawian mix for electricity production in 2019

Source of data: Global Petrol Prices [52]

to changes in rain patterns. The wide use of biomass is one of the major causes of deforestation, which contributes to further aggravating the modification of rain patterns already influenced by climate change. The exploitation of other energy sources is therefore a crucial topic. The country has a huge potential for solar energy, but the source is still not properly exploited. The grid-connected generation is small compared to its potential, and the off-grid one is still low despite its growth from 0.2 MW to 10.4 MW between 2007 and 2016. IPPs would be interested in developing such technology, but few steps have been taken in that direction by the government [50]. The first solution used to provide electricity to remote villages was the use of diesel generators, which are now gradually being replaced with less polluting energy sources.

Mini-grids Addressing energy poverty is one of the main goals of the country, in accordance with the United Nations program Sustainable Energy for All (SE4All). Among the options studied, what seems to be promising is the development of mini-grids, a cross between the expensive extension of the national grid on a large scale and stand-alone solutions, which are limited to households and institutions [53]. They are particularly suitable for those rural and peri-urban areas that are not expected to be connected to the grid in the near future. Mini-grids can also be interconnected or tied to the grid in order to deliver a high-quality service and reduce the load on the grid. In Malawi, several universities and institutions have been involved in their planning and design, but they remain underdeveloped. Among the African countries Malawi and Mozambique are the ones with the lowest penetration of the mini-grids due to their poor regulatory framework [53].

A study conducted by the University of Strathclyde and the Community Energy Malawi for the Scottish Government assesses the growing consensus on mini-grids in the country. Throughout the country, tens of isolated mini-grids are present and operational. Owned by the government or by private or charity entities, they represent a good way of involving the private sector. Currently, foreign donor grants are used to support most energy projects in Malawi, which is widely criticized. Surveys detected that the communities are satisfied with the development of mini-grids because they enable the improvement of communications, the use of appliances such as TV and computers, and the use of lamps to work or study even during the night. Women's lives are made easier since they no longer need to walk long distances to fetch firewood or water thanks to the use of electric kitchens, which also reduce indoor pollution, and water pumping systems. In general, what is pointed out is that mini-grid customers have significantly higher incomes compared to unelectrified villages and that their health conditions have improved in a noticeable way. However, after about a year of installation, the connections and wiring in some communities were vandalized. [50].

The purchase of appliances, in particular TVs, radios, fans, and refrigerators, has grown significantly since the installation of the mini-grids, but there are still some issues that need to be addressed. In fact, often the power is sufficient just for lighting and does not allow for the simultaneous use of fridges, cookers, and water pumping. Furthermore, it is intended only for domestic use, whereas some customers would prefer to use it for business purposes as well. In terms of capacity building, twenty technicians attended a seven-day course on the fundamentals of electricity, solar PV system design, system components, maintenance, and health and safety. Nevertheless, the general perception is the lack of training and some safety issues [50].

Despite the evident benefits brought by mini-grids, they are poorly supported by the government, which is focused on expanding rural electrification; moreover, the regulatory framework is inadequate, and the development models are not business-oriented. Many players are involved in the development of mini-grids, but they lack communication and coordination, which results in their inability to influence the process of policy making. Even where mini-grids were implemented, some problems occurred, mostly due to the way projects were introduced to people who expected the electricity for free and were not prepared to pay for it. In fact, many people think they are too poor to afford energy services, while the key point is to find an affordable amount they can pay for their consumptions in order to both sustain economically the installation and increase the sense of ownership [50].

From a technical standpoint, what is impeding mini-grid development is a lack of knowledge and the absence of modern technologies on the market. Another risk is the arrival of the main grid to the mini-grid site, making it useless. However, because ESCOM (Electricity Supply Commission of Malawi) is currently experiencing power shortages and frequent outages, this difficulty can also be viewed as an opportunity since mini-grids placed at the edges of the main one can contribute to its stability and to provide additional power [50].

Bureaucracy can be a barrier to development, as it can take one or two years to obtain permission for such a facility in the country. This is primarily due to the fact that the licensing process is the same for all the projects with capacities below 2 MW, while in other countries the procedures are diversified based on the capacity range. Funding opportunities are limited, and high rural poverty further limits the ability for operators to recover from initial investments [50]. Policies and mechanisms are fragmented and unclear, which represents an obstacle for the development and integration of mini-grids. Planning processes are often inadequate and the communities are not adequately involved [53].

In terms of emissions, mini-grids equipped with photovoltaic technology can help reducing the global carbon footprint, but can have local impacts due to the manufacture of batteries and PV panels themselves [50].

Hybrid systems in mini-grids Old diesel generators for rural lighting have a strong negative impact on the environment both on a local and a global scale, which is why they are gradually replaced by renewable systems or hybridized. When comparing the LCOE of Hybrid Renewable Energy Systems (HRES), it is clear that hybrid installations are more convenient than diesel-only or PV-only installations. Diesel mini-grids present the highest LCOE because of their dependence on the fluctuation of fuel prices, while renewable-dependent ones are highly site-dependent due to the distribution of the resource on the territory. HRESs, able to operate in grid-tied and off-grid modes in a sustainable way, are instead able to minimize the negative environmental aspects, such as CO_2 emissions from diesel use, and improve the stability and reliability of the system, a characteristic that is hard to find in solar schemes. The cost of electricity is therefore lowered and can be further minimized if the surplus energy is used. Case studies of HRES with solar

PV, wind, biomass, and hydro technologies equipped with batteries hybridizing diesel generators can be found in the literature. Diesel plays a backup role [53].

Batteries are of fundamental importance in such systems, but they need to be replaced every 6 to 8 years, which causes environmental damages if not properly disposed, causing soil contamination [53].

A successful combination may be the integration of more than one renewable resource with diesel generators in order to maximize the benefits and minimize the costs [53].

1.4 Best practices and strategies for target achievement

After researching how policies have been put into practice in various nations with varying economic, political, and historical backgrounds, it is simpler to understand what actions should be taken to achieve the goal of expanding renewable generation. The road ahead is more difficult to travel in developing countries due to all of the challenges that must be handled, such as unskilled labor, a lack of capital, and political and social instability. Nevertheless, some guidelines can be created to aid in the construction of an efficient policy plan.

On a financial level, a winning strategy can involve creating a FIT scheme first to reduce the perceived risk and then implementing an auction system to spur competition among businesses and keep prices low. Additional de-risking methods are the allocation of funds and the institution of cross-subsidies to convey investments in areas of national priority. When working with a new technology, it is crucial to determine the Levelized Cost of Energy in order to recognize the potential cost-saving strategies.

With regard to the technical aspect, it is useful to produce spatial maps of the renewable resources. Then, the best installation options have to be identified, that is, determining whether a specific location is better suited for on-grid or off-grid plants and for which energy source.

On the bureaucratic front, the legislation has to be as precise and clear as possible, and all the information has to be freely available and easily accessible. The organizational organs should have a decentralized and flexible structure, and they ought to be tailored to account for local requirements and opportunities. Institutions must ensure a just and fair distribution of the projects.

If a country lacks capital, it is crucial to rely on international banks and investors to lower the perceived risk. When expertise is lacking, the contribution of foreign companies can be required for the production and installation of equipment. However, they should be flanked by local firms, for whom it is easier to enter the market. Following this initial step there should be a transition period of re-skilling of local businesses, such as by transforming outdated oil enterprises into renewable ones, and involving them in the plants' maintenance operations.

Seen from a social perspective, the involvement of the population is key to the success of these kinds of projects. Their participation should be required through surveys about their habits and their readiness to become engaged. Moreover, some promotional activities can be organised to foster people's participation and awareness on the exploitation of renewable resources ans the use of electrical appliances.

Chapter 2

Identification of suitable areas for the implementation of diversified installations

The work continues with the development of a method targeted at the identification of suitable areas in which to investigate the installation of various types of technologies in diverse social contexts.

The present chapter is organized into two main sections: the first is the theoretical explanation of the implemented method, while the second is aimed at its practical application to the two countries that were selected for this study. The chosen nations are Uganda and Malawi, both belonging to the region of sub-Saharan Africa. They were selected because of previous relationships with stakeholders operating on the territory. This made it feasible to conduct interviews and get accurate data on the actual needs of the community as well as any potential barriers to the development of projects in particular areas.

The two countries present some of the lowest rates of electrification in the entire globe, as reported in Sections 1.3.8 and 1.3.9. In terms of connecting to the main grid, this is a challenge, but it also offers chances for innovative electrification techniques.

2.1 Theoretical framework

The method here developed helps identify suitable areas for projects' installation through the analysis of some aspects concerning the human and natural spheres. Parameters and constraints are considered in relation to the kind of renewable resource, the terrain morphology, and the characteristics of the local human settlements. After defining the aspects of interest, they were scored in order to reward or penalize the areas depending on their values. The constraints and the score definition method are going to be deeply described in the following sections. Here, a brief overview of the implemented method is reported.

The two technologies under consideration in this study are solar photovoltaic and onshore wind, which exploit sources that fall under the category of variable renewables.

Concerning the ground morphology, it is closely related to the studied technology. The terrain slope, in particular, is a factor examined in determining the viability of wind turbines. Another factor to consider is the presence of natural reserves and protected regions where the development of energy plants may be prohibited.

An important aspect of the analysis is represented kind oh human activities. They are, indeed, crucial to the development and construction of power plants, for whatever energy purpose they are intended. In the case of a large utility power plant, it is crucial to verify the stability of the grid in order to ensure that the produced electricity is properly transmitted and distributed without shortages. If the purpose of the plant is, instead, to serve a village, it is necessary to establish its size by estimating the needs of the community and whether it is going to be built on- or off-grid by evaluating the distance from the distribution grid. Human activities are here analyzed in terms of population density, kinds of communities, and infrastructures in the area of interest. Belonging to the category here defined as infrastructures is the electric grid, whose extension is considered.

Resuming, the analyzed aspects are:

- Solar resource;
- Wind resource;
- Terrain morphology;
- Population density;
- Extension of the distribution grid.

Once all of the evaluation parameters have been decided upon, they are numerically analyzed and used to calculate spatial scores for each variable taken into account. To exclude those regions that are especially unfavorable under a chosen feature, some thresholds are included. The study conducted by IRENA and USAID about investment opportunities in Latin America for grid-connected and off-grid solar and wind projects is taken as a reference for the allocation of the scores [54].

After the evaluation of all the parameters individually, they are combined to compute the final score, a term used in this work to indicate the average between all the scores of the variables involved, case by case. For this purpose, it is crucial to get data with the same spatial resolution. Here, data are provided for each square kilometer of the country's map.

The present study takes into consideration two types of technologies, which, as already mentioned, are solar PV and wind turbines. For what concerns the possible combinations, four are considered:

- On-grid solar PV;
- Off-grid solar PV;
- On-grid hybrid;
- Off-grid hybrid.

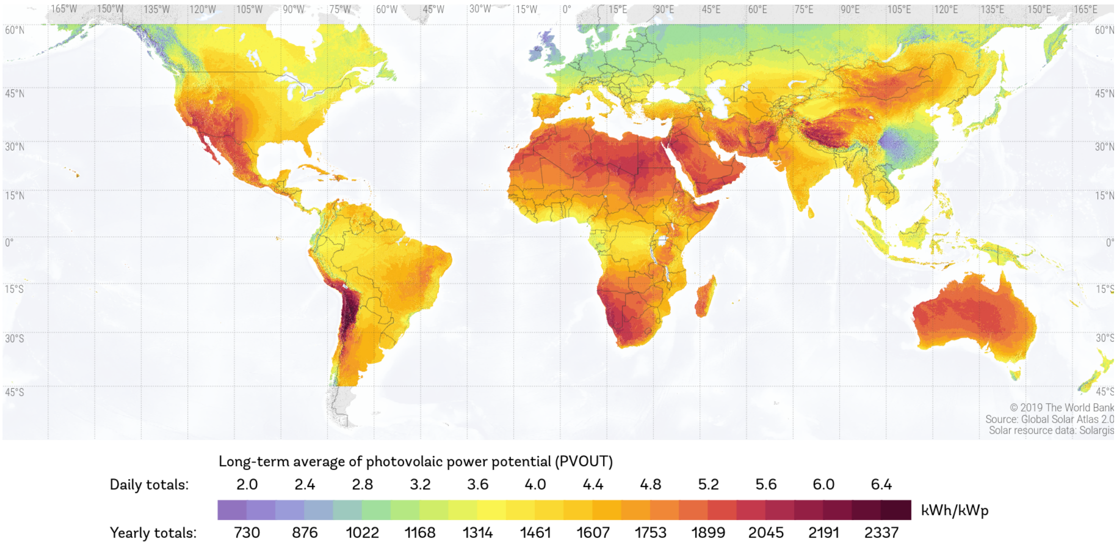
As hybrid plant it is intended a system that involves both the presence of PV panels and wind turbines.

The choice to not include wind power alone depends on basically two reasons: first, the already-mentioned ease and versatility of installation of PV panels compared to wind turbines, which makes the latter more expensive in comparison; and second, because of the predominance of solar over wind potential for energy production occurring in the majority of third-world countries. For a better comprehension of this concept, maps of the potential power density across the world of the variable renewables are included in Fig. 2.1. What can be noticed is how, in the Equatorial belt, where most of the third world countries are located, the solar resource is predominant compared to the wind resource. A later analysis on optimal sizing, conducted in Chapter 5, will assess the actual viability of each technology depending on the location's resources.

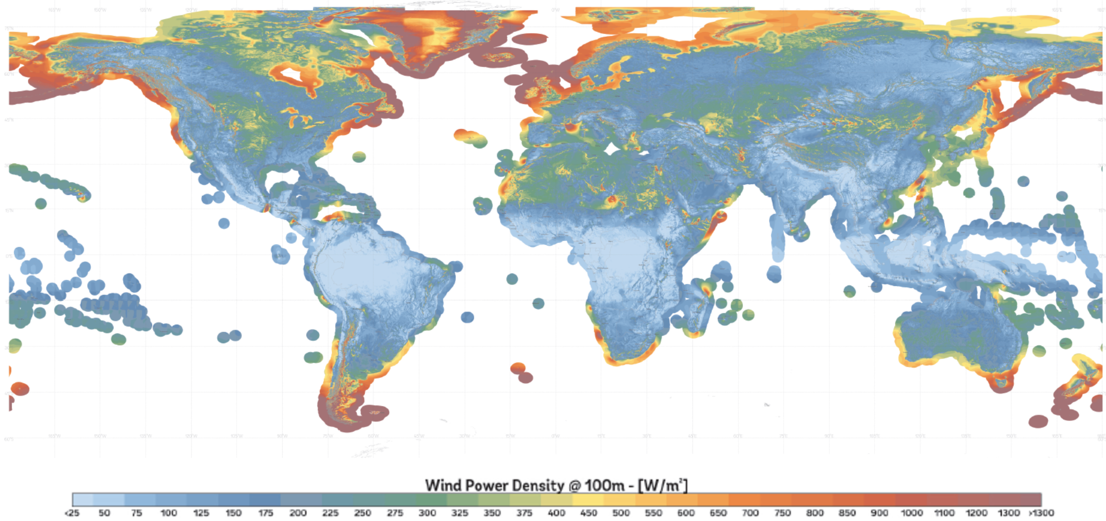
2.1.1 Building of the dataset and imposition of constraints and thresholds

Building the datasets for all the variables that will be analyzed requires gathering the data and applying the necessary constraints. As already mentioned, imposing constraints on the selected variables is useful to understand which locations are most advantageous under different aspects.

Solar resource The global horizontal irradiation is the parameter taken into consideration for the evaluation of the feasibility of the installation of solar PV panels. Although the solar source has different intensities depending on the location in the world, the solar radiation is a global phenomenon, and solar panels can



(a) Photovoltaic power density



(b) Wind power density

Figure 2.1: Power density maps

Source: **(a)** Global Solar Atlas **(b)** Global Wind Atlas

work even with little irradiation. In fact, there is evidence of working solar panels installed all across the globe. For this reason, no constraints are applied to this dataset.

Wind resource When it comes to wind energy, the analysis becomes more challenging because more variables can be considered compared to solar energy. The power production is certainly related to the wind speed, but it also depends on the features of the turbine itself and its power curve. In fact, the productivity of the turbine depends on the size and geometry of its blades, on the hub height, and on the capability of the turbine itself to adapt to the wind conditions. Moreover, the power produced does not increase linearly as the wind speed increases but depends on it according to a cubic relationship, as shown by the next equation:

$$P = \frac{1}{2}\rho A v^3 \tag{2.1}$$

As a result, each turbine performs best in a specific range of wind speeds. The behavior of the turbine when the wind speed varies can be explained by the plot in Fig. 2.2.

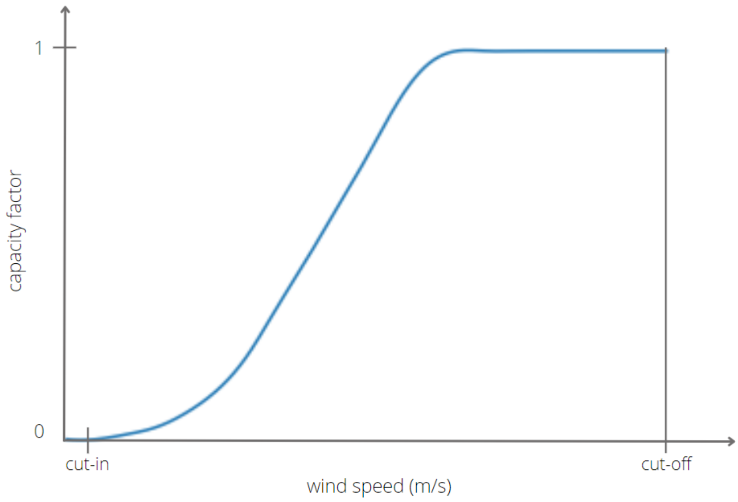


Figure 2.2: Power curve of a generic wind turbine

For the reasons mentioned above, wind speed is not used as a direct parameter for the selection of the area. Instead, its average value is considered in order to understand the class of turbine that has to be used and, subsequently, to get its capacity factor, defined as the ratio between the actual energy output and the maximum theoretical output that would be produced at full capacity:

$$c_f = \frac{E_{tot}}{E_{max,th}}. \tag{2.2}$$

Following the collection of data for the capacity factor, areas below a certain threshold are excluded. This consideration is particularly useful for those regions with limited wind potential and with high disparities in resource distribution.

Terrain morphology The installation of the technologies is influenced by the morphology of the areas under consideration. In particular, flat terrain makes it easier to construct wind turbines. In fact, slopes greater than 20% are generally not recommended for wind turbine installations due to increased stability and safety concerns [55]. This constraint does not apply to PV panels because, in the case of adverse terrain morphology, rooftop solar systems can still be considered.

Population density The density of the population is considered a parameter in the exclusion of some areas. A cut-off value should be decided upon in order to exclude those areas that present an extremely dispersed population. This is done for two reasons. The first is social and involves the need to ensure that the plant is accessible to a large number of people; the other one is related to the need of reducing the computational cost. Therefore, restrictions are set to determine whether it is worthwhile to build a power plant in a certain location or not.

Extension of the distribution grid When it comes to the assessment of the viability of a grid connection for a plant, the key parameter to be studied is the distance of the chosen spot from the distribution grid. Based on the size of the grid in the country being studied, it is possible to determine the cut-off value that distinguishes between on-grid and off-grid installations.

2.1.2 Allocation of scores to each variable

After building the dataset and discarding the most unfavorable locations, a scoring system is created with the aim of determining, in this instance, the most favorable locations for the installation of each type of technology involved in the analysis. The range of variation for each variable is taken into account, along with any imposed thresholds and restrictions.

A division is made between the values that are preferred to be high and those for which it is preferred that they be smaller. As shown in Equation 2.3 below, the score for each location on the map that falls into the first type is given by the ratio between the difference between the punctual value and the minimum value and the maximum span:

$$S = \frac{v_i - v_{min}}{v_{max} - v_{min}}, \tag{2.3}$$

where S represents the score value and v stands for the variable under consideration; the subscripts i, max and min represent, respectively, the current value and the boundaries of the range under consideration.

If the variable falls under the second case, the previously calculated fraction is subtracted from 1, as follows:

$$S = 1 - \frac{v_i - v_{min}}{v_{max} - v_{min}}. \tag{2.4}$$

The score assigned to each data point will be explained in the following paragraphs.

Solar resource The global horizontal irradiation belongs to the first type of parameter and no constraints are imposed on it, as explained in Section 2.1.2; therefore, its score is calculated as follows:

$$S_{GHI} = \frac{GHI_i - GHI_{min}}{GHI_{max} - GHI_{min}}. \tag{2.5}$$

Wind resource The capacity factor, like the global horizontal irradiation, belongs to the first category, since having a higher capacity factor means having a higher power production. In this case, there is a constraint on the minimum that results in having a dataset with a minimum value equal to the threshold one. In the formula, v_t, where t stands for the threshold value, is substituted to v_{min} in the formula:

$$S_{cf} = \frac{cf_i - cf_t}{cf_{max} - cf_t}. \tag{2.6}$$

Terrain morphology As seen in the previous section, the feasibility of wind installations is related to the terrain slope. The variable falls into the second group, since the installation of wind turbines becomes more challenging as the steepness increases. It also presents a ceiling value that is substituted to v_{max}:

$$S_s = 1 - \frac{s_i - s_{min}}{s_t - s_{min}}. \tag{2.7}$$

This score has been assigned only to those locations for which the wind capacity factor is also taken into consideration.

Population density For the population density value, a distinction is made for its evaluation according to the kind of technology under consideration. Although the application of a lower constraint makes all the areas with a value higher than the threshold worth considering, it is scored in different ways when it comes to solar or wind energy. When considering the installation of PV panels, the density of the population does not represent an obstacle, thanks to the versatility of the technology itself, which can be installed both at ground and rooftop level. For this reason, no score is calculated on the population for solar panels. However, when it comes to wind energy, a highly dense population may hinder the building of the plant because of its higher space requirements and because of its related issues, such as noise. In this case, the score is computed in the following way:

$$S_p = 1 - \frac{p_i - p_t}{p_{max} - p_t}. \tag{2.8}$$

Grid distance In the selection of the most suitable areas, the distance from the existing grid has an impact on those cases in which its expansion may be required. Thus, a score is assigned to this parameter only in the case of grid-connected installations while, for off-grid plants, that is not required. The parameter clearly falls into the second group, as a major distance from the grid requires a higher expense for its expansion. The score is computed as follows, considering the upper constraint that distinguishes on-grid from off-grid:

$$S_d = 1 - \frac{d_i - d_{min}}{p_t - p_{min}}. \tag{2.9}$$

2.1.3 Computation of the final scores

Following the computation of scores for all the factors in each map point, a final score is calculated based on the technology and kind of installation. This is done by computing the average of all the values corresponding to the single scores of every involved variable. Then, the value is expressed as a percentage.

To be noted that the process of score allocation is done in order to assign each location to a single kind of plant, to avoid uncertainties in the phase of decision of the type of installation.

On-grid solar PV For solar systems, the metric involved is the global horizontal irradiation, and because the plant is on-grid, the score for the grid distance is also included. The final score results in the average of the scores for the global horizontal irradiation and the grid distance:

$$S_{pv-on} = \frac{S_{GHI} + S_d}{2} \cdot 100[\%]. \tag{2.10}$$

Off-grid solar PV The solar resource is the sole factor considered in this situation, hence the following formula is used to determine the final score:

$$S_{pv-off} = S_{GHI} \cdot 100[\%]. \tag{2.11}$$

On-grid hybrid When it comes to on-grid hybrid systems, several parameters are considered. The final score is computed as the average of the single scores for solar irradiation, wind capacity factor, grid distance, population density, and slope.

$$S_{hybrid-on} = \frac{S_{GHI} + S_{cf} + S_d + S_p + S_s}{5} \cdot 100[\%]. \quad (2.12)$$

Off-grid hybrid In the case of an off-grid hybrid system the score is computed similarly to the previous one but without considering the data for the grid distance.

$$S_{hybrid-off} = \frac{S_{GHI} + S_{cf} + S_p + S_s}{4} \cdot 100[\%]. \quad (2.13)$$

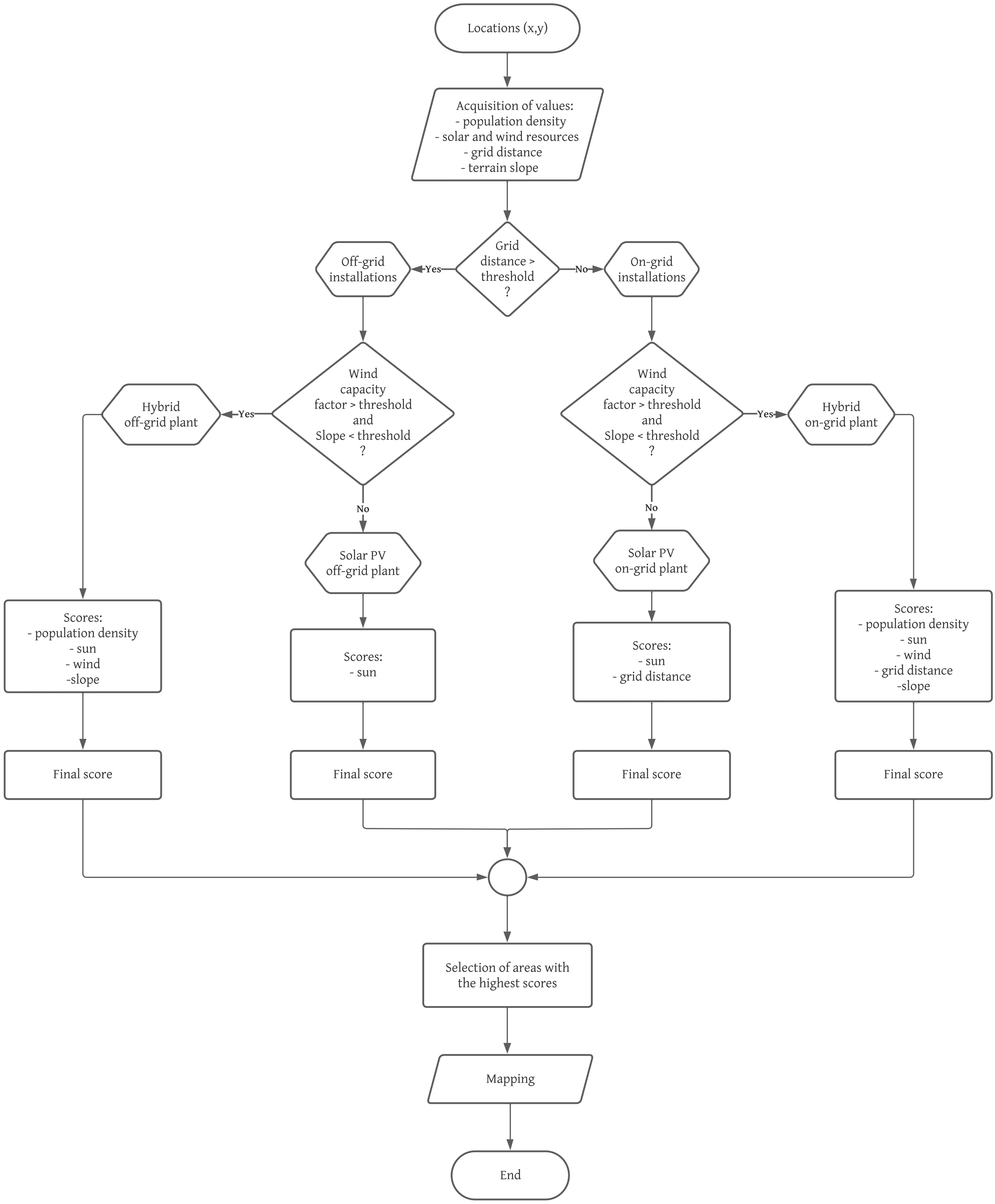
After the computation and allocation of the scores to each of the selected kinds of plants, the score values are mapped. Before that, in order to restrict the number of locations to just the most favorable ones, only the sites with a total score above a certain percentage of the maximum one are taken into account.

The flow chart attached in the next page can be taken as a reference for a better understanding of the steps taken in the development of the method described in the previous pages.

Table 2.1 is reported as a further resume of the variables involved for each kind of installation and the positive or the negative impact they have, as they increase, on the result. In green are the ones belonging to the first type, who have a positive impact on the global score as they grow; in red are the variables belonging to the second type, for which the score increases as they decrease.

Plant \ Variable	GHI	Wind cf	Slope	Population density	Grid distance
PV on-grid	X	-	-	-	X
PV off-grid	X	-	-	-	-
Hybrid on-grid	X	X	X	X	X
Hybrid off-grid	X	X	X	X	-

Table 2.1: Variables for calculation of scores



Flowchart: procedure implemented for the allocation of the scores and selection of the areas

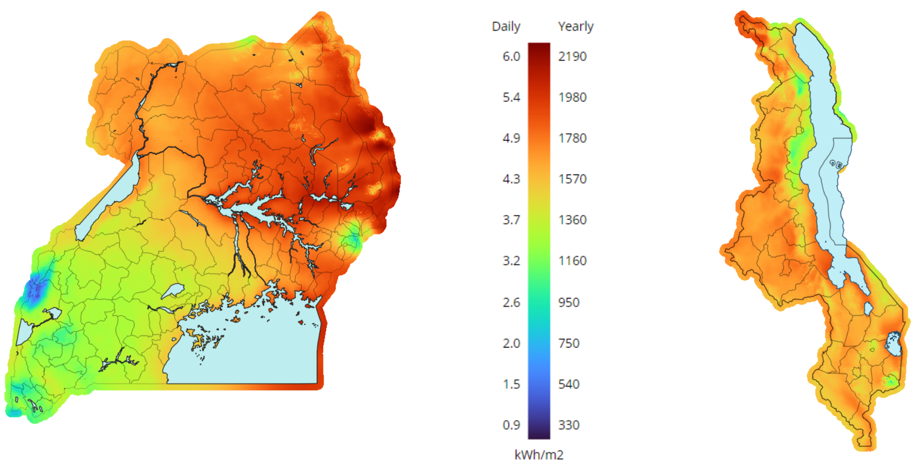
2.2 Application of the methodology to selected countries

This section is aimed at the application of the described methodology to two countries: Uganda and Malawi. All the steps previously explained are now going to be reported again with actual calculations. The whole process of score allocation and calculation has been implemented in Python, after elaborating the datasets in the open-source software QGIS and transforming them into *csv* files.

2.2.1 Data acquisition

In the first place, all the data are collected in order to build the dataset. They are gathered in the form of shapefiles and mapped in QGIS. As soon as they are collected, all the layers are transformed in to vectors in order to have them in a form that allows to perform calculations and to extract the needed values.

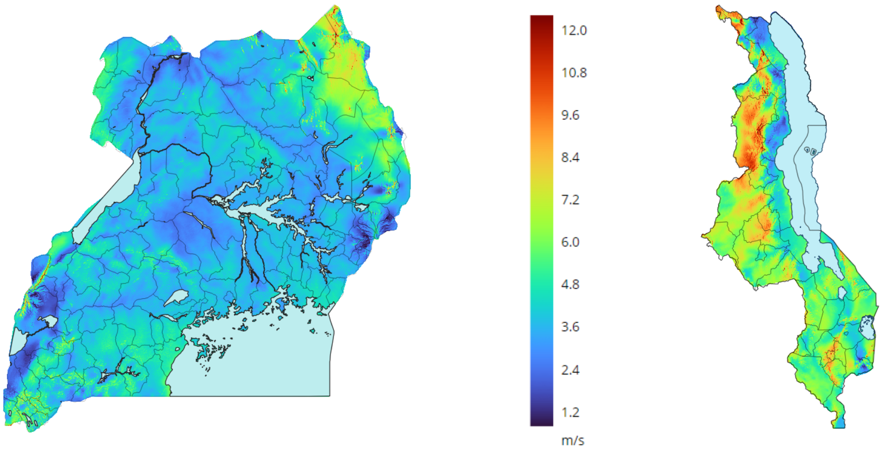
Solar resource Data are taken from the *Global Solar Atlas* [56] mapping tool for the global horizonatl irradiation and plotted in QGIS. The result is shown in Fig. 2.3.



(a) Ugandan GHI (b) Malawian GHI

Figure 2.3: Global horizontal irradiation maps

Wind resource In the consideration of wind energy, the tool used is *Global Wind Atlas* [57], which allows to download different kind of data, including the capacity factors for different classes of turbines. To understand which class to choose, the wind speed is analyzed in first place, as shown in Fig. 2.4.

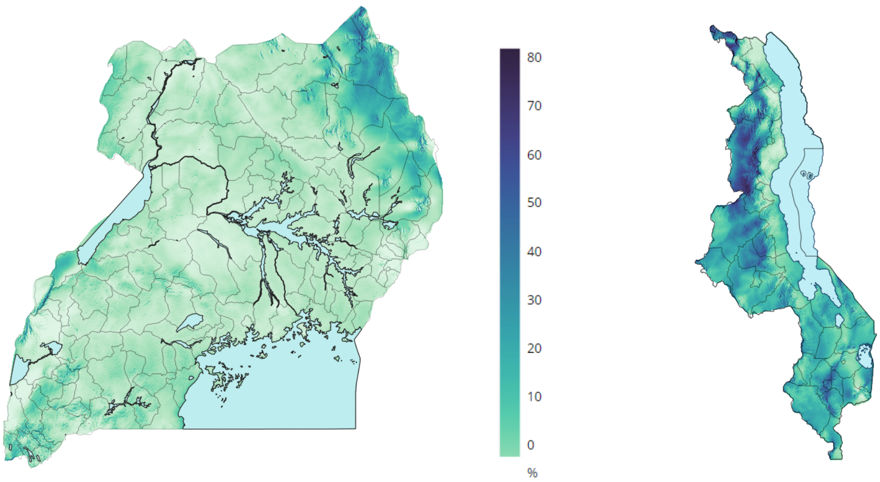


(a) Ugandan wind speed

(b) Malawian wind speed

Figure 2.4: Wind speed maps

Figure 2.5 reports instead the mapping of the capacity factors.

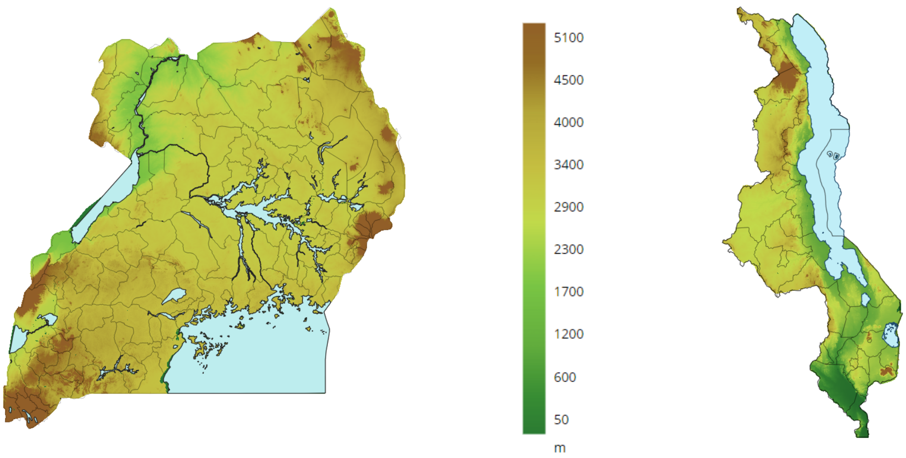


(a) Ugandan wind capacity factor

(b) Malawian wind capacity factor

Figure 2.5: Wind capacity factor maps

Terrain morphology No data are available for the terrain slope alone, therefore it is computed starting from the raster files for the elevation taken from the *Global Wind Atlas*, shown in Fig. 2.6.

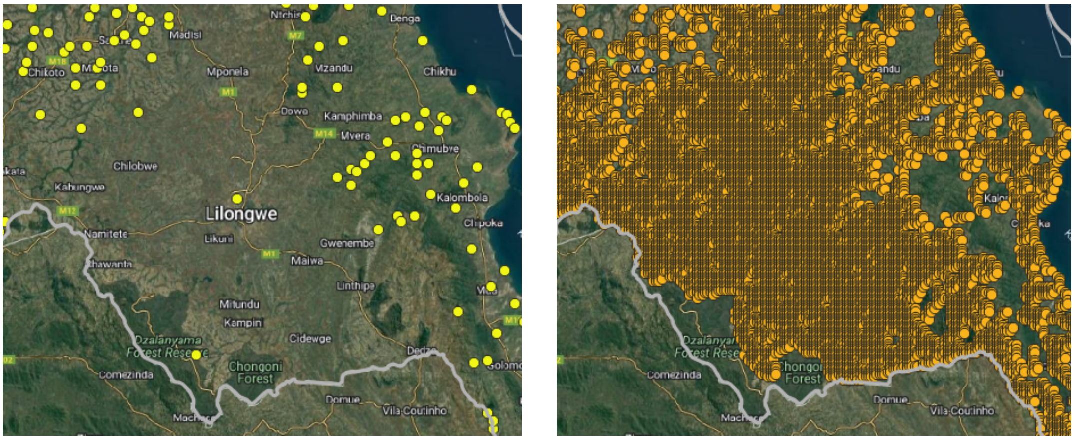


(a) Ugandan terrain elevation (b) Malawian terrain elevation

Figure 2.6: Elevation maps

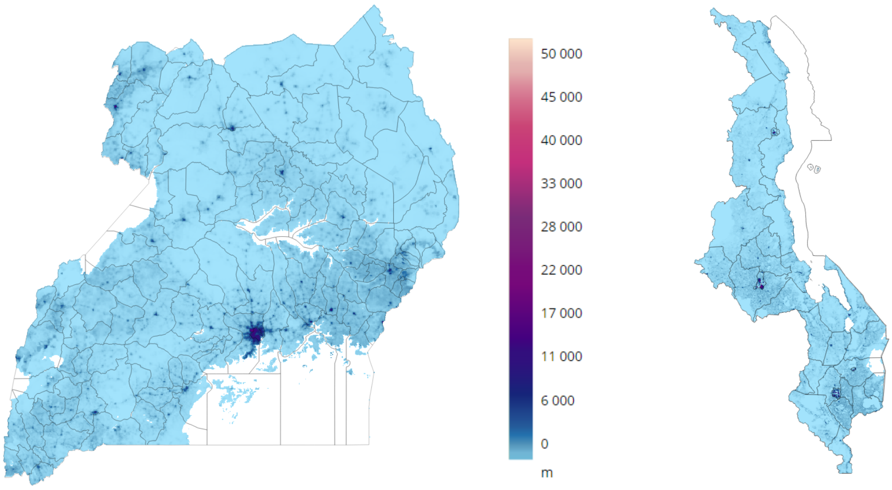
Once the raster file is imported in QGIS, the tool *Slope*, available under the section *Raster/Analysis* is used. To perform this step it is necessary to make sure that the raster file is projected in metric coordinates. Slope values are then obtained.

Population density For the evaluation of the population distribution and density, data are collected from *WorldPop* [58]. Two approaches have been evaluated for its analysis. One implies the aggregation of the data regarding cities and villages in the center of the inhabited area, while the other one consist in the consideration of data for every square kilometer, independently from the presence of inhabited centers. The first one requires a lower computational cost, having less data to analyze but, on the other hand, the information on the actual spatial distribution of the population is partially lost. This problem shows up in particular for big cities, where a single geographical point contains an aggregated information for a much wider area. For this reason, the second method is preferred, even though it has a higher computational cost. To better explain this choice, the images in Fig. 2.7 are reported. Seeing the different resolution of the two maps, it is easy to understand that the one on the right gives a better representation of the actual situation. The actual distribution of the population in the two countries is shown in Fig. 2.8



(a) Population distribution aggregated values (b) Population distribution for each kilometer

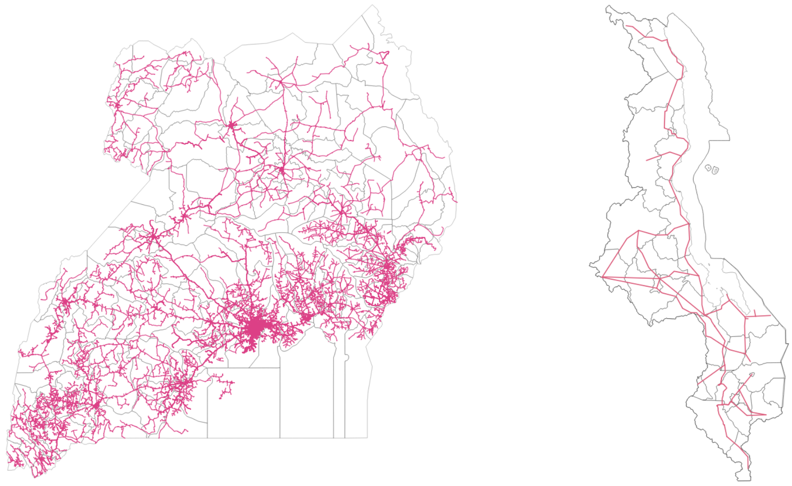
Figure 2.7: Comparison of the population distribution with different methods



(a) Ugandan population density (b) Malawian population density

Figure 2.8: Population density maps

Distribution grid Data for the distribution grid extension are collected from the website *Energydata.info* [59] for both countries. Maps are reported in Fig. 2.9. After gathering this piece of information, the two maps are combined with the population density ones in QGIS in order to implement the calculation of the distance of every populated spot from the distribution grid. This calculation is implemented through the *Field calculator* tool of the software by writing the



(a) Ugandan distribution grid (b) Malawian distribution grid

Figure 2.9: Distribution grid extension maps

following formula:

```
distance($geometry,geometry(get_feature('layer_name','ID','#')))
```

in which:

- `$geometry` stands for the population density layer, used as base to store the values for the distance;
- `layer_name` is the name of the layer used for the grid distance vector file;
- `ID` is the name of the unified field that contains the information for the grid extension;
- `#` is the number corresponding to the layer ID.

2.2.2 Constraints and thresholds

This section aims at explaining the constraints applied to all the variables taken into account for the analysis.

Solar resource As explained above, no thresholds are applied to the solar resource. As a reinforcement to this statement, if examining the global horizontal irradiation in Fig. 2.3, it can be noticed that its variance is limited, therefore it is not worth it to reward locations according to this parameter.

Wind resource The chosen threshold for wind energy, that discriminates between areas in which it is worth it to install wind turbines and areas for which it is not, is assumed as the double of the mean capacity factor. This value corresponds to around 10% for Uganda and 45% for Malawi.

Terrain morphology The threshold figure for the terrain slope is 20%, as explained in Section 2.1.1

Population density The value set as threshold for the population density is its mean value along the country's surface. This figure is equal to 201 people/km^2 for Uganda and 194 people/km^2 for Malawi. Only the values above these are accepted for the analysis. The choice fell on the mean population density since this figure, in the considered countries, represents a small percentage of the maximum value, namely 10% Uganda and 4% in Malawi.

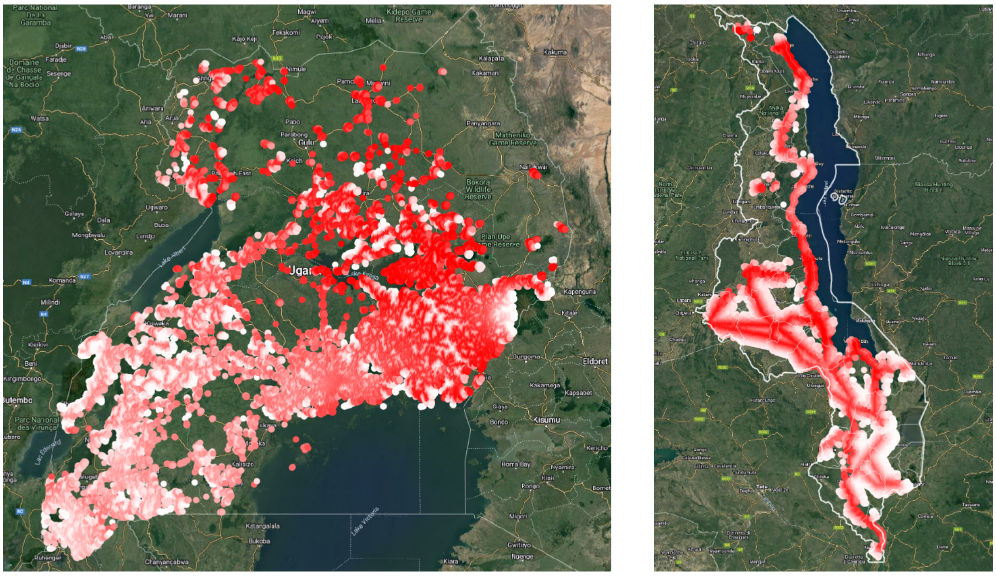
Distribution grid In the present study, the discriminant between on-grid and off-grid projects is set at one-fourth of the maximum distance that can be identified between a geographic point and the grid. The maximum distance is 40 km in Uganda and 66 km in Malawi. Thus, the discriminant values are respectively equal to 10 km and 16.5 km.

2.2.3 Scores allocation and mapping

The scores are allocated as described in Sections 2.1.2 and 2.1.3 and then plotted. The following maps have been colored to emphasize the variation in scores. They show all the locations that are suitable for each type of installation in each of the two countries, with the suitability increasing as the saturation of the spot's color increases.

On-grid solar PV The distribution of the spots suitable for the installation of solar PV panels connected to the main grid is reported in Fig. 2.10. It is possible to observe how this distribution follows the path of the main grid. This is particularly visible in the case of Malawi, comparing this image with the one in Fig. 2.9. The color scale goes from white, which stands for the areas with a lower score, to red, which instead represents the most suitable ones.

Off-grid solar PV As in the previous image, the color scale intensity follows the increase in score. As the Ugandan power grid is more spread, it results in a lower number of spots for off-grid installation, whereas in Malawi, where the grid is less branched, the number of spots suitable for off grid installations is higher in



(a) Uganda (b) Malawi

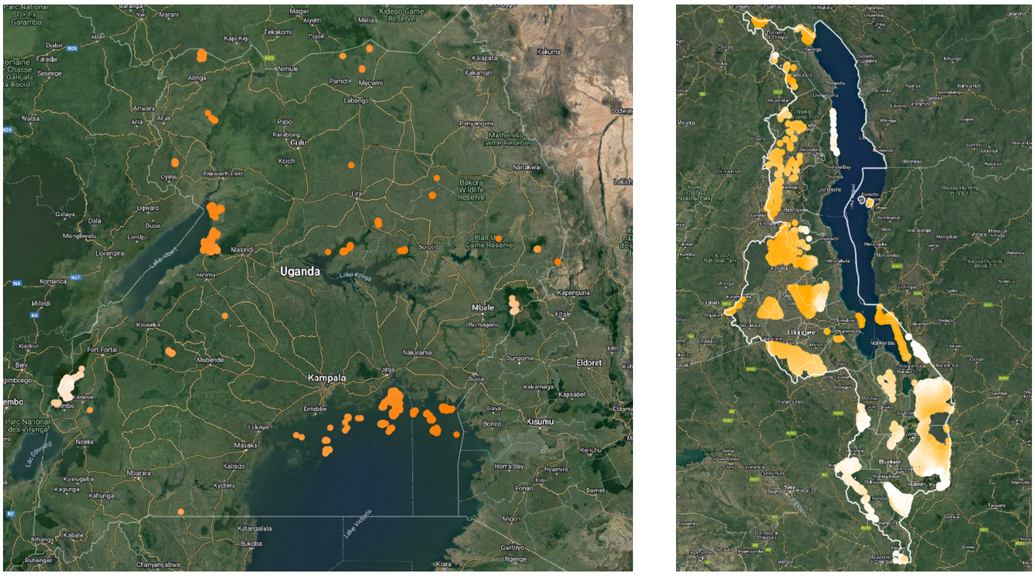
Figure 2.10: Suitability of locations to on-grid solar PV

comparison and in the same order of magnitude of the on-grid spots. The maps are visible in Fig. 2.11.

On-grid hybrid The same approach is followed for hybrid plants. Linked to the grid extension, a higher number of spots is noticeable in Uganda, while a limited number is present in Malawi, as shown in Fig. 2.12.

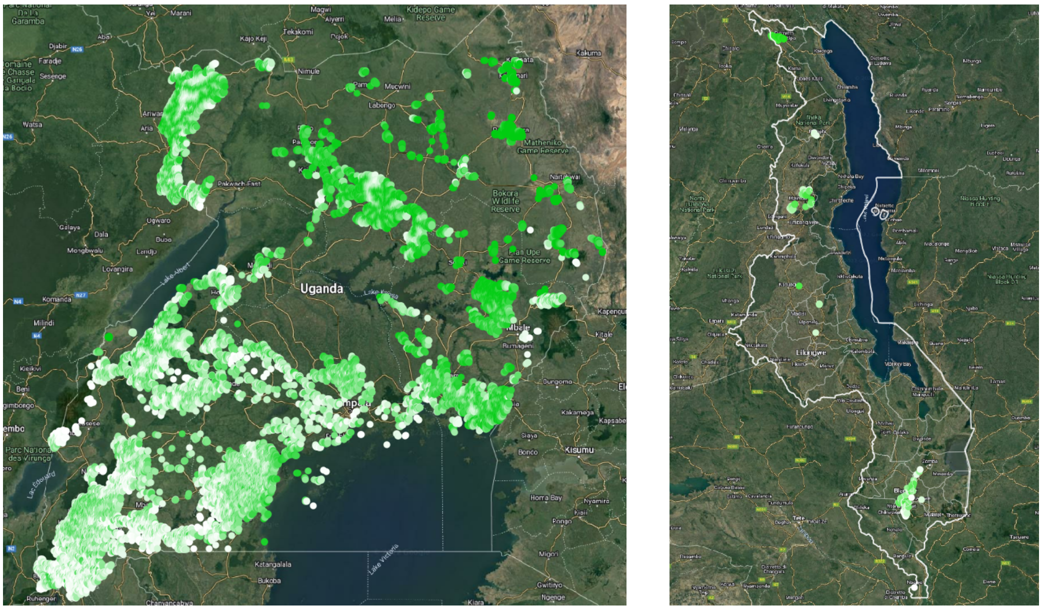
Off-grid hybrid As it can be noted in Fig. 2.13, the number of locations suitable for the installation of off-grid hybrid plants is limited. This is primarily due to the fact that, the places not reached by the national grid are also the ones with the most unfavorable terrain, for example mountainous areas, where also the installation of wind turbines becomes challenging.

Identification of the most suitable areas After the computation of the scores, the most suitable values are chosen by considering the highest scores for each of the 4 kinds of installations studied. For each kind of technology, a threshold comprised between 75 and 95% of the maximum score is set in order to obtain a sufficient number of values comprised among the ones with the highest scores, that means considering the most suitable locations only. The final maps are reported in Figure 2.14.



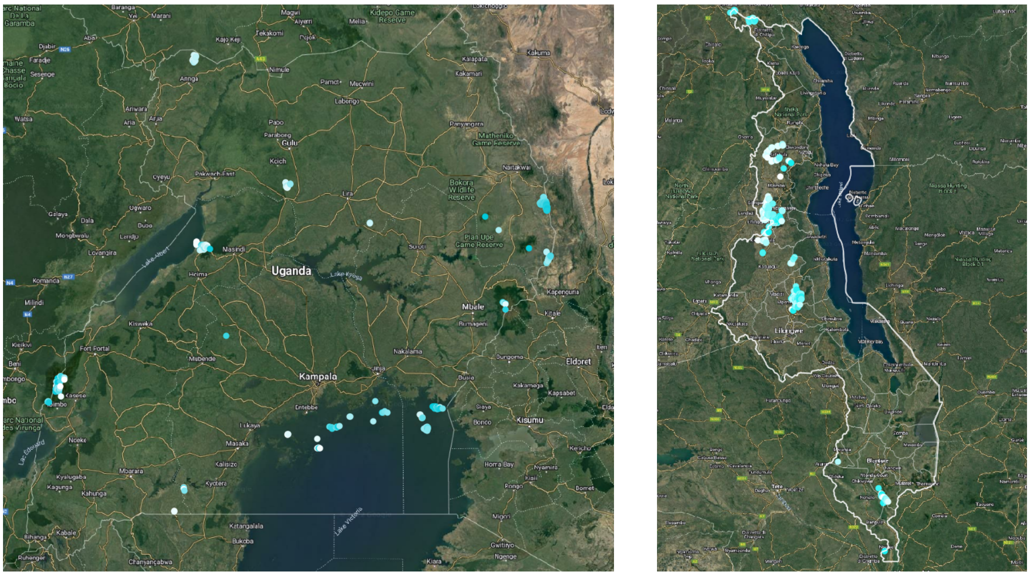
(a) Uganda (b) Malawi

Figure 2.11: Suitability of locations to off-grid solar PV



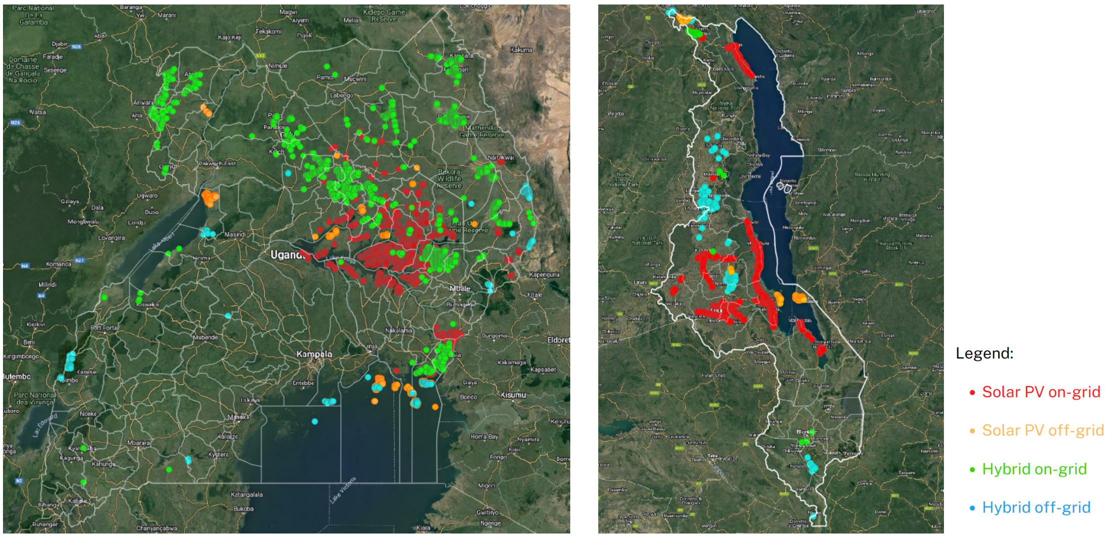
(a) Uganda (b) Malawi

Figure 2.12: Suitability of locations to on-grid hybrid



(a) Uganda (b) Malawi

Figure 2.13: Suitability of locations to off-grid hybrid



(a) Uganda (b) Malawi

Figure 2.14: Most suitable areas for each kind of installation

Chapter 3

Choice of the case studies and identification of loads

This chapter is aimed at the selection of specific locations for the development of some case studies and at the identification of the possible loads for each system. The purpose is to explore different options in terms of technologies, environment, and social context.

After a first section constituting the background of information and actions needed for the development of each case study, other three follow, one for each case study, whose implementation is described in detail.

For the selection of the specific locations, the knowledge about the territory provided by local stakeholders that had been interviewed was exploited.

3.1 Local background

At first, the territory has to be analyzed in order to find possible locations for the installations. This step depends on the sensitivity of the analyst and the purpose of the work. It can be chosen to upgrade existing installations or to construct new ones, to build utility-scale facilities that serve the national grid or smaller plants to meet the needs of local communities.

This work focuses on the development of power systems for local communities, taking into account the current infrastructure and services already present on the territory as well as considering the possibility of building new ones. The reasons for this choice are basically two. One is the social aspect, which is key to the development of this methodology. The second reason is the instability and lack of reliability of the national grid, which makes it challenging, if not counterproductive, to construct big plants whose energy needs to be transported over long distances. In fact, both the selected countries suffer from frequent power shortages and struggle with electricity distribution.

The locations are identified by matching the feasibility maps in Fig. 2.14 with the information gathered through the interviews in order to find suitable locations from both a technical and a social aspect.

Following the identification of the locations, a consumption analysis is carried out. It is thus necessary to identify the possible loads and their occurrence in order to compute the daily and annual profiles. This last information is going to be used in a later step addressing the plant's size optimization, addressed in Chapter 5.

With regard to the estimation of loads, papers and previous works on similar projects are taken as references.

3.2 Case study 1: School in Nainaivi Island, Uganda

The first case study is located in Nainaivi Island, sited in Ugandan portion of Lake Victoria. Its coordinates are:

- Latitude: 0.05° north
- Longitude: 33.61° east

3.2.1 Analysis of the area and social context

Examining the map of Uganda, it can be noticed that many of the islands present in Lake Victoria, on the south-east of the country, are suitable for the installation of off-grid PV plants - Fig. 2.10 and 2.14. The national grid, Fig. 2.9, is not present in the minor islands, and no evidence was found about the existence of local mini- or micro-grids. Therefore, since those islands are inhabited, it was chosen to select one in order to implement an off-grid photovoltaic project.

The picked out spot is Nainaivi Island, whose location is reported in Fig. 3.1. As it can be seen in Fig. 3.1(b), the island is characterized by a predominantly rural area and a settlement in the center-north. The island has an area of around one square kilometer and a population of about 200 inhabitants. This data is calculated through the mapping of the population density in QGIS.

The focus of this case study is the village's primary school, called Serinyaby Primary School. No information is available about the number of students attending the school; therefore, this number is estimated. According to the website Statista, roughly half of the Ugandan population is between the ages of 0 and 14 [60]. Considering that primary school lasts 7 years in Uganda [61], it is deduced that around 25% of the total population of the island may attend the school, which means around 50 kids.

(a) Map of Uganda (b) Zoom on the island

Figure 3.1: Location of the first case study

Source: **(a)** Google Maps **(b)** Mapcarta - The Open Map

The school is supposed to have two classrooms of 25 students each, an office, two restrooms, and a kitchen where lunch is prepared.

3.2.2 Power consuming appliances

The appliances examined for the load profile estimation are divided into categories basing on their purpose: lighting, computers, internet connection, and cooking.

Lighting It is considered that there are around 30 LED lamps in total, of which 8 illuminate each class, 2 the small office, 2 the toilets, and the other 10 the kitchen and other common spaces. According to the report *LED there be light: South Africa*, each lamp for school lighting consumes around 25 W [62].

Computers and internet connection The school is equipped with three computers, one per class plus one in the small office. The power consumption for each computer is considered to be around 75 W, according to the website *Energyguide* [63].

In regard to the internet connection, the school is equipped with a router consuming 10 W of power [64].

Kitchen For what concerns the school's canteen and kitchen, it is considered that around 50 meals are cooked per day through two 4 induction plates cookers. The total consumption, in terms of energy, is shown in table 3.1, which was calculated using the report *Enabling combined access to electricity and clean cooking with PV micro-grids: new evidences from a high-resolution model of cooking loads* [65]. In two case studies, the report details the most common types of dishes prepared in central Africa and the average energy consumption for cooking. In particular, the study about Mama Kevina Hope Center, a residential structure for children with disabilities in Tanzania, is taken as a reference. In Table 3.1, reporting the average

Process	**Time [min]**	**Power intensity**	**Power [kW]**	**Plates number**	**Energy [kWh]**
Water boiling	20	HP	2.30	2	1.50
Rice cooking	30	LP	1.20	2	1.20
Vegetables/ potatoes/ proteins cooking	20	MP	1.80	2	1.20
Soup preparation	40	LP	1.20	2	1.60
Total energy [kWh]	**5.60**				

Table 3.1: Cooking consumption in Nainaivi school

energy use for a meal preparation, *HP*, *MP* and *LP* stand for, respectively, high, medium, and low power.

3.2.3 Load profiles

Daily loads Once all of the appliances have been identified and their individual energy consumption values have been determined, the total daily load of the system can be calculated by summing up the energy consumption values of each appliance over the course of the day. This computation involves adding up the hourly energy consumption values of each appliance.

In addition to calculating the total daily load of the system, a base load is also added to account for the system's daily losses. This base load represents the minimum energy consumption required to keep the system running even when no appliances are in use, such as the energy consumed by system components like transformers or circuit breakers. In this case, the base load is calculated as 5% of the maximum load of the system, which equates to a value of 0.2 kW. Table

3.2 reports the loads in kilowatts (kW) and the number of hours per day in which they are active. This step is performed according to the Ugandan primary school schedule, which runs from 08:00 to 17:00 [66].

Load	Power [kW]	Schedule	No. hours
Lighting	0.75	08:00 - 17:00	9
Computers	0.225	08:00 - 17:00	9
Internet	0.01	08:00 - 17:00	9
Kitchen	2.8	11:00 - 13:00	2

Table 3.2: School daily consumption

The process of calculating the daily profile of the load involves combining the information about the energy consumption of each appliance that has been organized into the precious table. The daily energy consumption profile is then represented graphically in a chart, as shown in Fig. 3.2.

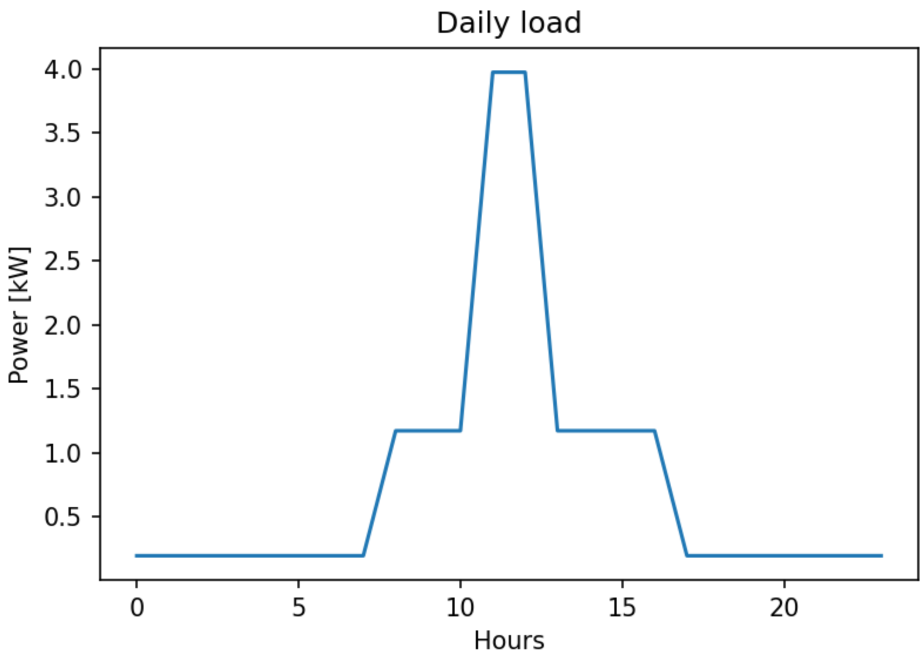


Figure 3.2: Daily school load profile

Weekly load Due to the scheduling of the school's weekly routine which includes closure on weekends, the functioning of the system does not remain consistent throughout the week. The daily profile is in fact repeated during five days, followed by two days with no load, as shown in Fig. 3.3.

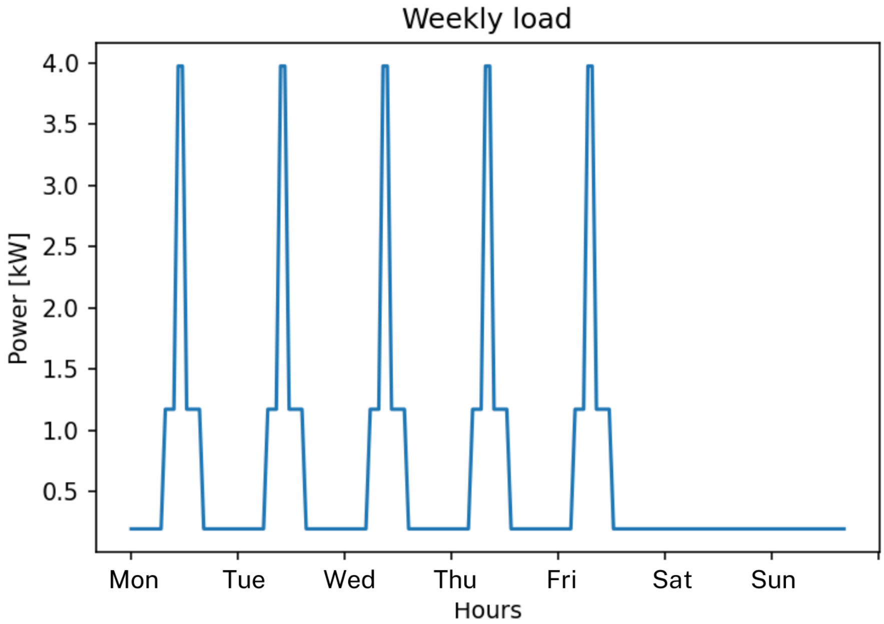


Figure 3.3: Weekly school load profile

Annual load Ultimately, the annual load is computed, by considering national school breaks, whose calendar is provided by the Ministry of Education and Sports [67]. Precisely, the school year is divided into three terms, that are reported in Table 3.3.

Term	**Period**	**no. school days**
# 1	February 6th May 5th	65
# 2	May 29th August 25th	65
# 3	September 18th December 8th	60

Table 3.3: School calendar

3.3 Case study 2: Bidibidi refugee camp, Uganda

The second case study is located in Yumbe District, Uganda, precisely inside the refugee camp of Bidibidi, whose coordinates are approximately:

- Latitude: 3.53° north
- Longitude: 31.35° east

3.3.1 Analysis of the area and social context

Thanks to the interviews with the known stakeholders present on the territory, the presence of a refugee camp in the north-western part of Uganda became known. It hosts more than 270,000 South Sudanese refugees fleeing the civil war in an area of around 250 km2, which makes it one of the largest refugee camps in the world. It is divided into small villages centered on a central one that houses minor infrastructures. The refugee camp is developing into a real city with its own internal market, associations, schools, health care facilities, and farming systems thanks to the efforts of the Ugandan government and several NGOs.
The location of the camp is reported in Fig. 3.4 together with a photograph of one of the settlements. About the settlement structure, some information was gathered. There are around sixty villages grouped into three main clusters. The chief cluster is where the community leader lives and is the most equipped from a technological point of view. The others have some infrastructures as well, among which are some youth centers and some women's associations, whose details are provided in the following lines.

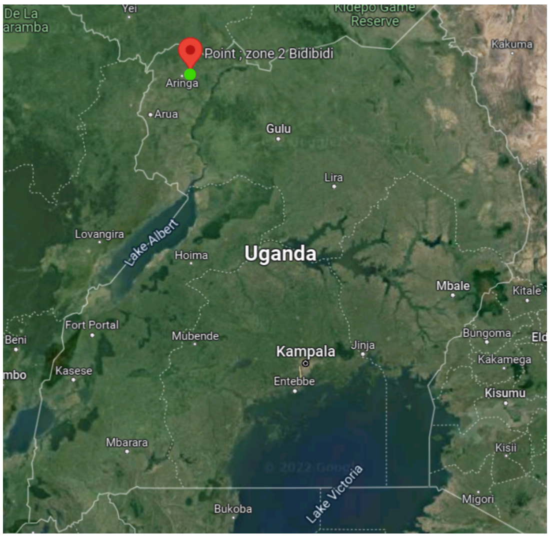
In regard to the youth centers, they are equipped with a couple of desktop computers, printers, and music speakers and host some activities, such as theater courses.

Women's associations, instead, are used to organize meals for the community. The cook in Uganda, as well as in and other countries of Sub-Saharan Africa, represents an issue because of the use of solid fuels that are highly polluting in indoor environments and often lack.

The rationale for the second case study comes from the combination of the need for clean cooking with the necessity for young people to have their own meeting place. Therefore, it was decided to feed with renewable power the youth center and a new shared kitchen equipped with electrical appliances that can be used not only for the community meals but also for everyday food preparation.

A service like this may serve between 500 and 1500 people, considering to have a walking distance from the cooking center of no more than half an hour.

In regard to the kind of power plant, the area is suitable for hybrid on-grid



(a) Map of Uganda

(b) Zoom on the refugee camp

Figure 3.4: Location of the second case study

Source: **(a)** Google Maps **(b)** Frédéric Noy photographer [68]

installations. In fact, the site is close enough to the main grid to consider its expansion over a distance of around 3 km.

3.3.2 Power consuming appliances

The installed appliances are reported in the following lines, divided basing on the end use, the youth center and the shared kitchen.

Youth center The youth center equipped with five 170 W desktop computers [63], and a 40 W printer [69]. An internet connection is present too, with a power use of 10 W [64]. During the afternoon theater activities of the duration of around two hours are conducted and, for the purpose, a pair of 100 W music speaker is used. The speakers are used also at night, together with a 150 W projector [70], for cinema activities. The space is illuminated with six 25 W LED lamps [62].

Shared kitchen The shared kitchen is equipped with 25 cooking stations, each with two induction plates. Its consumption of the community shared kitchen is computed the same way of the school's one in section 3.2.2, referring to the paper

[65]. Tables 3.4 and 3.5 show the average energy consumption for the preparation of standard kind of meals with a double plate induction cooker.

Process	**Time [min]**	**Power intensity**	**Power [kW]**	**Energy [kWh]**
Milk/tea heating	5	HP	1.80	0.15
Bread toasting	5	MP	1.30	0.11
Total energy [kWh]	**0.26**			

Table 3.4: Cooking consumption for standard breakfast preparation

Process	**Time [min]**	**Power intensity**	**Power [kW]**	**Energy [kWh]**
Water boiling	20	HP	1.80	0.60
Rice cooking	20	LP	0.75	0.25
Vegetables/potatoes/ proteins cooking	15	MP	1.30	0.33
Soup preparation	30	LP	0.75	0.38
Total energy [kWh]	**1.55**			

Table 3.5: Cooking consumption for standard lunch and dinner preparation

3.3.3 Load profiles

In this section the consumption is calculated hour by hour. In the computation of the daily load, the youth center and the shared kitchen are considered separately at first to show the difference in their profiles, and after they are summed to compute the total one.

Youth center daily load Following, the hours of use of each appliance are reported. The computers are considered as turned on all day, while the printer only during two hours, in the afternoon. The internet connection, instead, is considered as working day and night. The music speakers work during two hours in the afternoon and three ours at night, for a total of five hours per day, while the projector works only at night during three hours. The lighting system is considered at its full power during theater and cinema activity and at half power consumption during the rest of the day. It is switched off at night. Table 3.6 resumes the previous explanation, with the power in kilowatts consumed by each appliance and its daily use. The load profile of the youth center is reported in Fig. 3.5.

Load	**Power [kW]**	**Schedule**	**No. hours**
Lighting half power	0.075	08:00-15:00 17:00-21:00	11
Lighting full power	0.150	15:00-17:00 21:00-00:00	5
Computers	0.850	08:00-00:00	17
Printer	0.040	15:00-17:00	2
Internet connection	0.010	00:00-23:00	24
Music speakers	0.100	15:00-17:00 21:00-00:00	5
Movie projector	0.150	21:00-00:00	24

Table 3.6: Youth center daily consumption

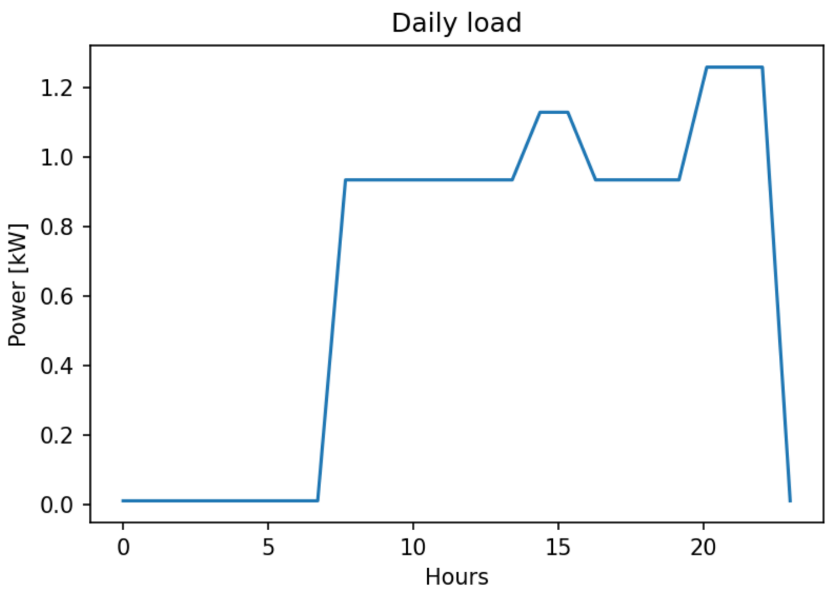


Figure 3.5: Daily youth center load profile

Shared kitchen daily load Regarding the use of the shared kitchen, an approximated estimation of the possible consumption is made by considering that around 100 people, mostly women, may access the kitchen to cook, alternatively, breakfast, lunch or dinner. Every woman cooks for its whole family, for a total of about 500 people being served by the kitchen every day.

Concerning the cooking habits, since the population is mostly rural, the two most important meals of the day are an early breakfast and dinner, since farmers work all day away from home. Therefore, it is evaluated that at breakfast and dinner time the turnout will be higher and that at breakfast some people will also cook some food for the rest of the day. The rate of affluence is considered as:

- 45 people per hour during breakfast time, preparing both breakfast and some other meals for the day;
- 10 people per hour during lunch time
- 25 people per hour during dinner time

Table 3.7 resumes what just said, reporting the power consumption in kilowatts, the affluence rate, and the average time of use of the kitchen. The consumption is calculated by multiplying the number of people using the kitchen by the power consumption of every meal preparation.

The kitchen load profile per day is showed in Fig. 3.6.

Meal	Affluence [ppl/h]	Power [kW]	Schedule	No. hours
Breakfast	45	33.00	05:00-08:00	3
Lunch	10	17.50	11:00-04:00	3
Dinner	25	41.00	18:00-20:00	3

Table 3.7: Shared kitchen daily consumption

Total daily load After the computation of the single profiles, the total one is computed by summing them up, hour by hour. As for the previous case study, section 3.2.3, a constant power loss equal to 5% of the maximum is added, resulting in a shift towards the upward direction of the curve of about 2 kW.

The final load profile is plotted in Fig. 3.7. The resulting shape is analogous to the shared kitchen one, the latter being an order of magnitude greater than the one of the youth center.

Weekly and yearly load The load shape reported in the previous paragraph is suitable both for week days and weekends and for every season of the year. As a result, the load over a year is simply the repetition of the daily load for each day of the year.

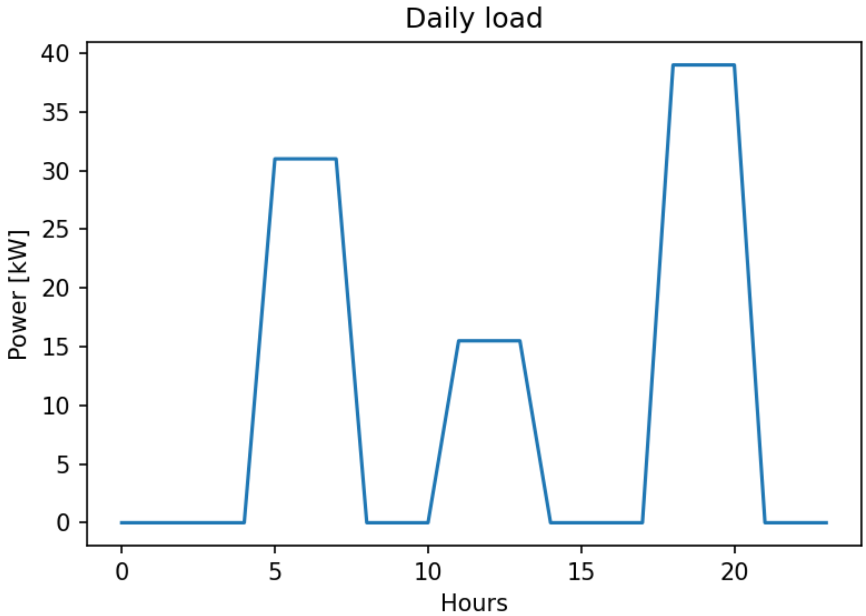


Figure 3.6: Daily shared kitchen load profile

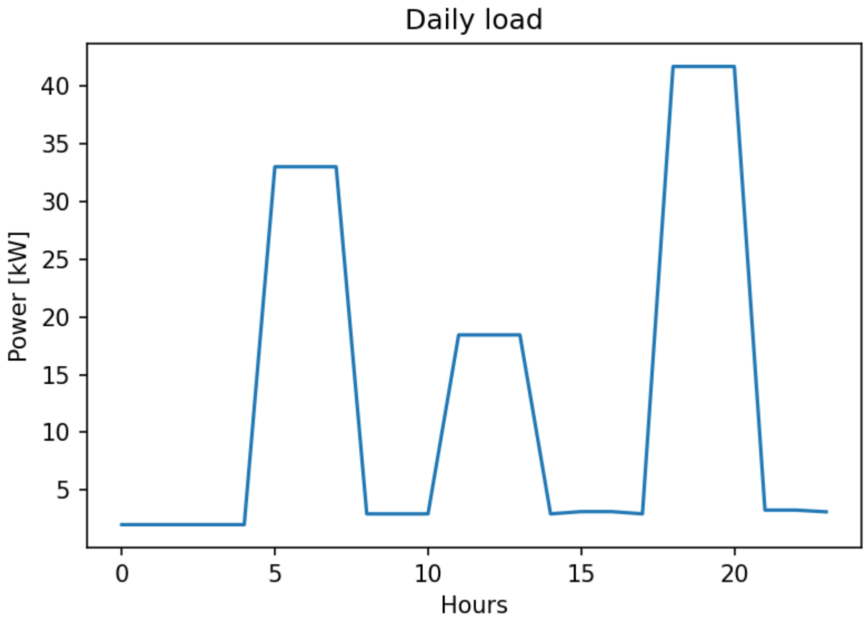


Figure 3.7: Total daily load profile

3.4 Case study 3: Water well and small office in Champira village, Malawi

The third case study is located in the Malawian village named Champira, whose location is, approximately:

- Latitude: -12.33° north
- Longitude: 33.62° east

3.4.1 Analysis of the area and social context

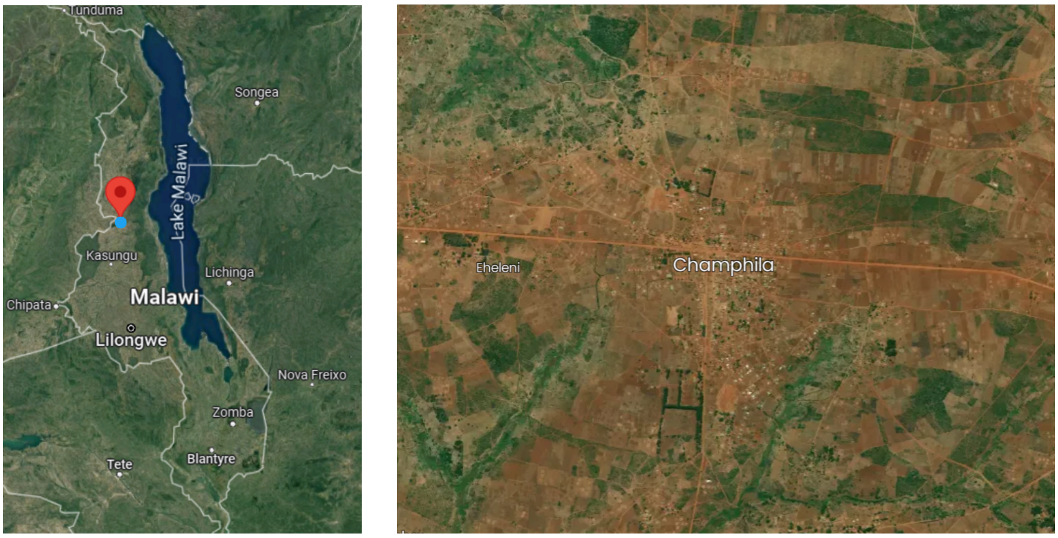
The issue of electricity access in Malawi is extremely pronounced. The country has an unreliable distribution grid and most of the energy is not produced locally but imported from Mozambique, having to submit to another country's decisions. Besides inside the big cities, the population is predominantly rural and aggregated in small villages. According to the interviewed stakeholder, the rural population experiences relevant uneasinesses, which are exacerbated by the climate change. The need for firewood and water scarcity leads to soil desertification, which produces floods during rainy seasons due to a lack of vegetation. Agriculture is subsistence-based and inefficient. Drinking water provision is frequently problematic: although there are manual wells, the depth at which the water is frequently drawn is not insufficient to guarantee that the water is clean.

Because of he mentioned reasons, the third case study is focused on water provision. The main aim is to access clean water at higher depths through an electric well for drinking purposes. Moreover, a positive side effect of having a larger access to water is its availability also for agriculture.

The chosen area, whose location is reported in Fig. 3.8 is suitable for the installation of a hybrid off-grid system, in reference to Fig. 2.14. From the zoom on the village, it can be noticed the rural kind of establishment, surrounded by farming fields.

In order to develope a project tailored on the needs of the community, it was decided to build a water well able to supply both the home and farming needs, fed by a wind turbine and an agrivoltaic PV plant. The decision to install agrivoltaic is based on its agricultural benefits, particularly in hot weather. Indeed, the shading produced by PV panels reduces the temperature below them, and therefore the evapo-transpiration phenomenon, allowing for less water consumption.

Along with the well installation, it is planned to build a small office that will serve as both a control center for the plant and an internet access point for the local people, with some PCs available.



(a) Map of Malawi (b) Zoom on Champira village

Figure 3.8: Location of the third case study

Source: **(a)** Google Maps **(b)** Mapcarta - The Open Map

3.4.2 Power consuming appliances

Power consuming appliances are reported as follows. The examination of the well and of the office appliances is done separately.

Water well The well is the most energy-consuming component and the focal point of this case study. To determine its energy consumption, it is necessary to calculate its extraction rate by establishing the water needs of the population, explained in the next few lines. At first, the number of people served by the well is established. Afterwards, the water need per person, in terms of both personal and agricultural water, is calculated.

Through QGIS's population density map (Fig. 2.8) it is estimated that there are around 3,000 people living within 4 kilometers of the well.

WHO assesses 50 to 100 liters per day as the bare minimum amount of water per person to meet the most basic living needs [71]. In this work the upper value of this figure is considered, resulting in a total of 300,000 liters a day.

Regarding agricultural water, an estimation is made by considering the data reported in the study of the Water Footprint Network for Kenya [72]. The study reports the total population and the total blue water footprint for agriculture. By dividing the two figures it is calculated an amount of water of around 30 liters per day per person for agriculture. In the present case, it is equal to 90,000 liter per day for the entire village.

The total water flow rate that needs to be extracted is therefore calculated:

$$Q_{tot} = Q_{living} + Q_{agriculture} = 300{,}000 + 90{,}000 = 390{,}000 \frac{l}{day} = 0.0045 \frac{m^3}{s} \quad (3.1)$$

The power needed for the extraction is therefore calculated according to the formula:

$$P = Q \cdot \rho \cdot g \cdot H[W] \quad (3.2)$$

In the equation, H is defined as:

$$H = dh + h_l[m] \quad (3.3)$$

Where:

- dh is the actual depth of the wall, equal to 40 m;
- h_l is the head loss, considered as the 10% of the total head.

The average power for such daily flowrate is, then, 1.5 kW.

Small office The small office and plant coordination center is considered as equipped with three 170 W computers [63], three 25 W LED lamps [62] and an 10 W internet connection [64].

3.4.3 Load profiles

Load profiles are evaluated individually and summed up hourly.

Water well daily load The extraction rate is thought to be variable throughout the day, with differences between day and night extraction. Being the population mostly rural, the eight night hours are set from 21:00 to 5:00, time during which the extraction rate, and therefore the power, is one third of the average one. In order to obtain the same daily energy consumption as in the case of constant extraction, the daily hours extraction rate, and power, are set at four thirds of the average one, during 16 hours per day. Table 3.8 reports the explained behaviour in details. Fig.3.9 reports the water well's consumption profile.

Load	Power [kW]	Schedule	No. hours
Day extraction	2.60	05:00-21:00	16
Night extraction	0.65	21:00-05:00	8

Table 3.8: Water well daily consumption

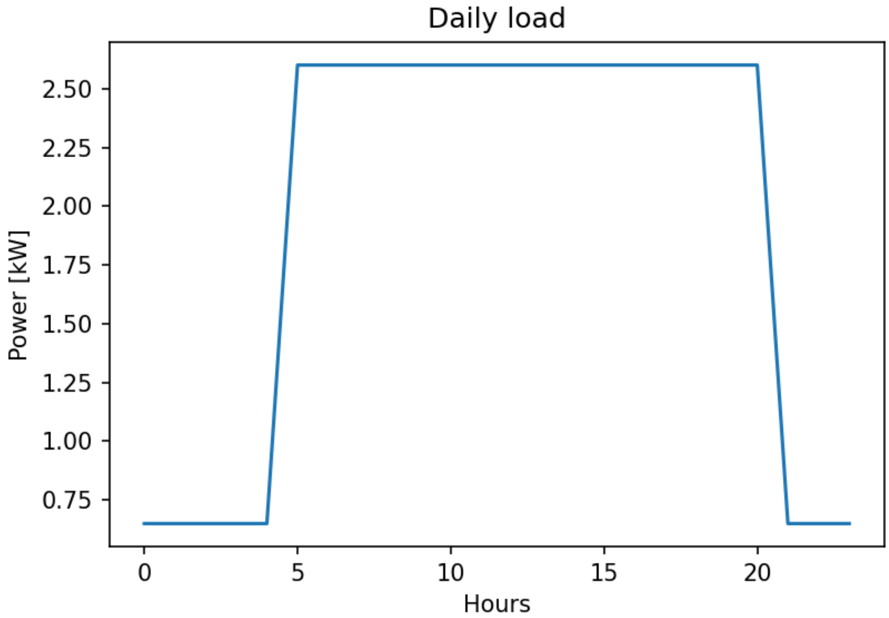


Figure 3.9: Daily water well load profile

Office daily load All the appliances are considered to be switched on during 11 hours, from 08:00 to 19:00. Their consumption and schedule are reported in Tab. 3.9 and the daily profile is shown in Fig. 3.10

Load	Power [kW]	Schedule	No. hours
3 PCs	0.51	08:00-19:00	11
3 LED lights	0.075	08:00-19:00	11
Internet connection	0.10	08:00-19:00	11

Table 3.9: Small office daily consumption

Total daily load The total daily load is computed by the sum, hour by hour, the two profiles, as reported in Fig. 3.11.

Weekly and yearly load As for the second case study, the load is considered to be constant for every day and season of the year, leading on a profile that is nothing other that the recurrence of the daily one for 365 times.

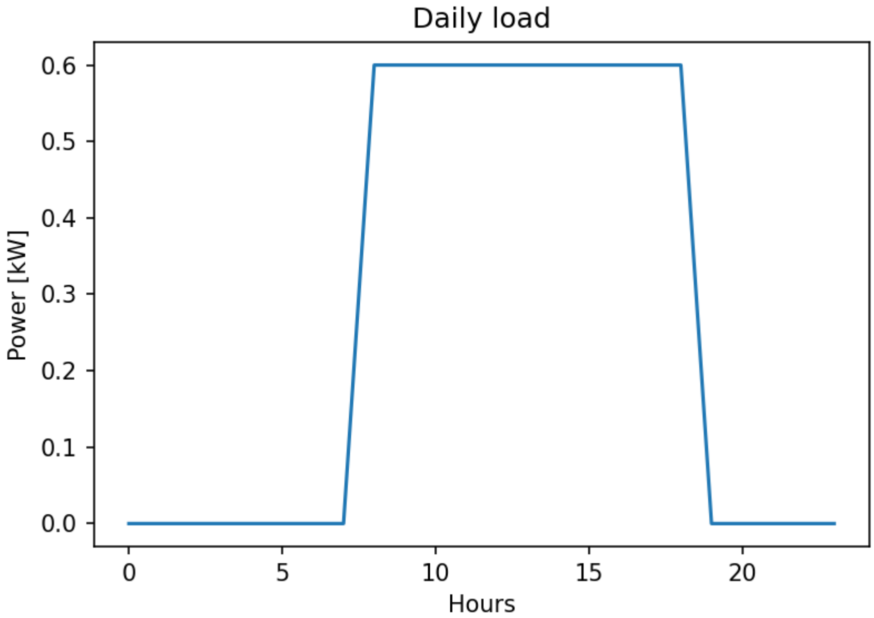


Figure 3.10: Small office daily load profile

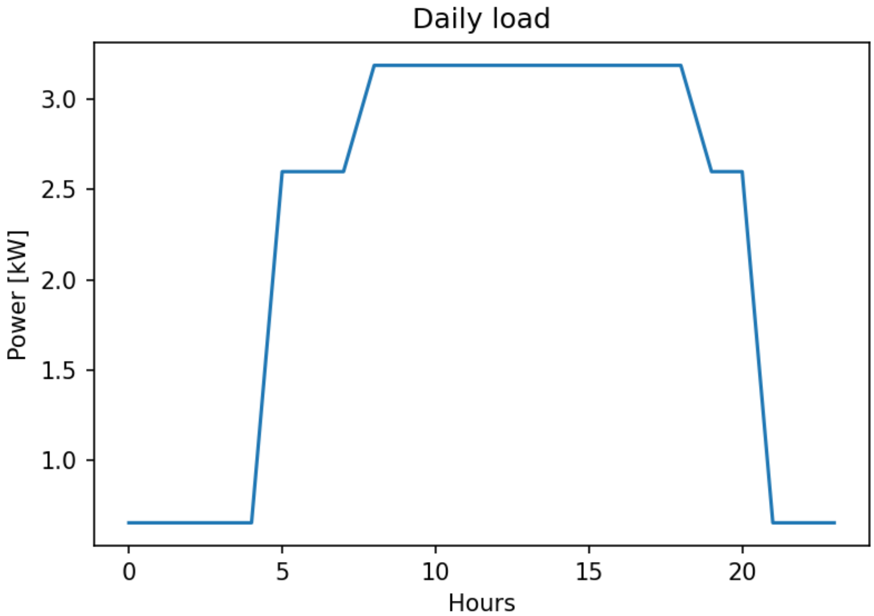


Figure 3.11: Total daily load profile

3.5 Comparison of the case studies

The purpose of this part of the study was to effectively align the real needs of the population with the necessity of providing an analysis of disparate cases, thereby validating the proposed methodology.

The cases analyzed in this study are sufficiently diversified so as to effectively cover various types of energy plants. This research, in fact, provides a comprehensive analysis of plants that employ diverse energy production technologies. Furthermore it shows different approaches towards energy production, with one plant being connected to the grid and the other two designed with a storage system. Additionally, the cases vary significantly in terms of their purpose, size, and load profiles. The variability in their purpose highlights the diverse energy needs that exist, while differences in size and load profiles provide insights into how energy demands can be met with tailored solutions.

Chapter 4

Technologies pricing

When it comes to implementing new technologies and infrastructures, it is important to carefully consider the associated costs. These costs include the upfront expenses of purchasing and installing the technology or infrastructure, as well as the ongoing costs such as maintenance and operational expenses and the costs for running the plants. The present chapter focuses on the establishment of capital, operational and marginal costs for the power systems implemented in the case studies addressed in Chapter 3.

Following an overview of all the technologies and their associated costs, the chapter moves on to a literary review of some reports addressing those prices on a global and local scale. Afterwards, prices for each technology involved are computed.

In some cases, the figures were not directly available for the countries involved in this work; therefore, their values had to be adjusted in order to fit the specific case. In fact, finding relevant information about the countries studied in this work was a challenging task. It was not easy to come across reliable data, and the process involved sifting through multiple sources and verifying their accuracy to ensure the reliability of the gathered information. To arrive at a comprehensive understanding, it was necessary to compare various sources and types of data. Ultimately, approximations had to be made based on the available information to form a complete picture.

All of the costs reported and estimated in this chapter are going to be used in Chapter 5 in the process of optimizing each plant.

To ensure that the analysis of costs would not be impacted by the onset of the COVID-19 pandemic, the costs were calculated using 2019 as a pre-pandemic baseline. As a result, the cost analysis was stronger because it was not impacted by the pandemic shock.

4.1 Overview of the involved costs

Considering the kinds of technologies and infrastructures involved, as established in the previous chapter, the following costs need to be studied.

Capital costs The capital cost, also known as CapEX, is the total cost of acquiring or constructing an asset. All the capital expenses involved in this work are listed below:

- CapEX of non-utility ground-mounted PV panels;
- CapEX of agrivoltaic systems;
- CapEX of non-utility wind turbines;
- CapEX of Li-ion storage systems;
- CapEX of electric grid expansion.

Operation and maintenance costs Operation and maintenance costs, also called OpEX and abbreviated as O&M, are the ongoing expenses associated with running and maintaining a system over its operational lifetime. These costs occur every year and are listed below:

- O&M cost of running a PV plant;
- O&M cost of running a wind plant;
- O&M cost of Li-ion storage systems;
- O&M cost of electric distribution grid.

Marginal cost The marginal cost is the additional cost incurred by producing one more unit of a product or service. Among all the case studies, the only marginal cost is the cost of purchasing a unit of electricity from the national grid.

4.2 Literary review of costs

In order to evaluate the technologies' costs, reports and articles were analyzed.

The IRENA report *Solar PV in Africa: Costs and Markets* provides insights into the costs and market trends for solar PV technology in Africa [73]. It is though important to consider the time frame of the report and its potential impact on the accuracy of the results. In fact, as the report is dated 2016, the prices presented may not be accurate due to the significant drop in renewable technology prices in recent years. Despite this limitation, the report is still useful for providing a general overview of prices in the African continent and for comparing with other works. Other works by IRENA were used: *Renewable Power Generation Costs in 2019* and *Renewable Power Generation Costs in 2021*. These last two works report costs for renewable energy technologies across the world in two different years. Other sources of data were used, such as the National Renewable Energy Laboratory (NREL) [74] and the Global Petrol Prices database [75].

In regard to the costs for agrivoltaic systems, data were taken by combining information from *pv magazine* [76] and from three articles: *Environmental and economic performance assessment of integrated conventional solar photovoltaic and agrophotovoltaic systems* [77], *Techno Economic Modeling for Agrivoltaics: Can Agrivoltaics Be More Profitable Than Ground Mounted PV?* [78] and *Renewable and Sustainable Energy Reviews* [79].

Official costs for electric distribution grid expansion and maintenance in Uganda were gathered from the Electricity Regulatory Authority (ERA) [80] and from the Uganda Electricity Transmission Company Limited (UETCL) [81].

4.3 Tailoring of the costs for specific cases

The final section of this chapter focuses on the computation of the costs of the technologies based on the information gathered from the documents cited in the preceding one. The prices are adjusted to the specific situations of the case studies. The currency used to report all the final costs is euros.

4.3.1 Solar PV

Information for solar photovoltaic plants is not always updated, in particular when it concerns the installation costs. Accurate data for photovoltaic plants in African countries are available only for the year 2016 [73], but it was necessary to find a way to report these figures with more recent values that are consistent with current trends. In order to do this, global trends were analyzed, in line with the IRENA report about power generation costs [82].

CapEX In the 2016 IRENA report, the plants are categorized based on their size and whether they were on- or off-grid.

All plants considered in this thesis are larger than kilowatt size and, since storage costs are here accounted for separately, only the costs for on-grid systems were taken into consideration. The installed cost for these kind of plants was around 2,400 €/kW [73].

To report the value to current ones, an approximate 50% reduction in LCOE, module costs, and CapEX was calculated on average from 2016 to 2021 [82].

By combining the previous pieces of information, it was determined that the current cost for solar panels installation in Uganda and Malawi is roughly 1,200 euros per kilowatt of installed power.

OpEX According to a case study report by *GET.invest* about a solar PV system in Uganda [83] the yearly operational cost is 1.5% of the capital cost. This means that, for a 1,200 €/kW investment, every year, the OpEX is going to be 18 €/kW.

A similar value was found in the NREL database, reporting 17.9 €/kW as operation and maintenance cost for commercial scale PV systems in 2021 [74]. Although NREL calculates costs mainly for the United States, the fact that renewable energy prices in Uganda are similar to those in the United States suggests that the lower labor cost in Uganda is compensated by higher material cost.

4.3.2 AgroPV

In regard to agrivoltaic systems, it is important to take into account that their expenses are greater in comparison to PV installations mounted on the ground. This is due to the structures that support the panels at a particular height from the ground, allowing vegetation to grow beneath them. va

CapEX According to the paper *Economic feasibility of agrivoltaics compared to separate systems for farming and solar energy production in arid regions* [79] an increment of about 10-20% can be detected when considering the installation cost of agrivoltaic systems compared to traditional ones.

Applying an increment of 20% to the 1,200 €/kW cost considered for photovoltaic systems in Uganda and Malawi, a value of around 1,450 €/kW was obtained.

OpEX Operation and maintenance costs are taken to be the same as ground mounted commercial PV panels, that is 18 €/kW per year.

4.3.3 Wind

The IRENA report *Renewable Power Generation Costs in 2021* provides punctual data about costs for wind power plants [82].

CapEX The report gives information about installation costs of wind turbines subdividing them by size and by continent. Comparing the total installed cost, it was evaluated that African prices experience an increment of about 40% compared to the average worldwide prices. The same increment was applied to the prices of turbines of size below one megawatt of installed power, as follows. This figure is equal to 1.74 USD/W at global level that means 2.44 USD/W for the African continent. The value is taken for the two nations and it results in 2,300 euros per kilowatt of installed power.

OpEX The report does not specify which is the relationship among the operational costs for wind turbines in Africa and in the rest of the world. Due to the lack of precise information and the fact that the NREL data for solar PV were comparable to other data gathered from different sources, it was chosen to consider the value from NREL also for wind plants. This value is around 32 €/kW per year.

The merit of this number is reinforced by the fact that it represents 1.4% of the overall installation cost, a figure comparable with 1.5% used for solar applications.

4.3.4 Batteries

As for the technologies themselves, also the storage cost for renewables dropped in recent years.

CapEX In order to understand the installation cost of Li-ion batteries, the IRENA report about prices of solar energy in Africa [73] was consulted. The same decrease in prices applied to solar panels is applied to batteries too. Therefore, the value of 2.7 USD/W dating back to 2016 is decreased by 50% to match current trends. Converting it into euros, the final value used in this work as storage CapEX is 1,300 euros per kilowatt.

OpEX Once again, NREL dataset was used to evaluate the operation and maintenance cost. In the case of batteries it results in about 42 €/kW per year.

4.3.5 National grid

When building a new power plant in an area where the national grid does not yet exist, it becomes necessary to expand the grid to connect the plant to it. This involves the construction of new transmission lines, transformers, and other infrastructure necessary to bring electricity to consumers. However, grid expansion is a costly process, both in terms of construction and maintenance expenses. These data are needed for the sole case study that involves a grid connection, which is the one located in the refugee camp of Bidibidi, in Uganda.

CapEX For what concerns the construction of a new line, ERA made available a report for the calculation of its costs. Information is provided for construction materials and labour costs.

The choice between ABC (Aerial Bundled Cable) and bare conductor connections was possible, and the first was chosen because it requires less maintenance.

Costs for single-pole construction are provided and multiplied by the number of poles needed to cover the distance of 3 km to the main grid. The number of needed poles was calculated by dividing the total distance by the average distance between poles in rural areas, which is 90 m, resulting in 34 poles. Wood poles of a height of 10 m were considered.

The total capital cost calculated according to this method is €18,680.

OpEX According to UETCL, the Ugandan energy transmission company, the yearly operational cost is about 1.5 percent of the total investment cost [81]. Given the investment price, the operation and maintenance cost is around 280 euros per year.

Marginal cost As already said, the marginal cost refers to the expense incurred in procuring one unit of electricity from the national grid. It is, therefore, necessary to acquire information about the price of electricity from the national grid in the country. The most recent available data dates back to June 2022 and is 0.154 €/kWh [75].

Chapter 5

Optimal sizing and profile loads

This chapter is aimed at the establishment of the optimal size of each plant.

When planning an energy plant, two approaches are commonly used: long-term and short-term planning. The long term approach is generally preferred for renewable energy projects since it mitigates the impact of the intermittency that is typical of the variable renewables. In fact, it allows the use of the typical meteorological year evaluated over a long period instead of a specific time frame [84]. However, its assumptions are rough and it does not allow to have hourly profiles. Short term analysis, on its part, allows a more accurate dimensioning of each component of the plant and to obtain hourly profiles.

With the aim of this work, short term analysis is the best choice for two main reasons. Firstly, the estimation of the loads was done hour by hour and, secondly, the sizing of each component is needed in order to estimate its related costs. For this reason it was choosen to implement the analysis through the open source toolbox PyPSA (Python for Power System Analysis) available in the Python environment. It helps model the operation and planning of electrical energy systems, including the generation, storage, transmission, and distribution of electricity. The tool allows for the optimization of the power system under different aspects, such as economic dispatch, integration of renewable energies, capacity expansion, and power flow. Inside the tool, the network is defined by adding the system components and their connections. For each system it is required the definition of the load, of the generators, of the connection buses and of an eventual storage system.

The chapter is structured as follows. The first section aims to explain the essential elements used in the PyPSA environment. Following this, the chapter developes into the specifics of each case study, presenting the details of the code implementation for each. This section enables to understand how the system can be tailored to different use cases and scenarios. Finally, the chapter concludes with a dedicated section that presents and analyses the results of the simulation, essential in evaluating the feasibility of each plant.

5.1 Definition of system's components in PyPSA

Each element of the power system is defined by a piece of code. A brief description of the components is reported here; for more information, the PyPSA User's Guide [85] is available online.

Buses The bus is the fundamental node of the network, to which every electrical component is connected. It ensures energy conservation for every element that feeds into and out of it. For simple networks, it is sufficient to define a single bus to which all the components are connected.

Loads The load is the power-consuming element. It is attached to a single bus. As an input parameter, a vector of 8,760 elements containing the power consumption of the system for every hour of the year has to be provided. As the default setting, the load is expressed in megawatts (MW).

Generators A generator is a component that feeds power into the bus. This definition can be used both for actual generators and for grid connections, just varying some parameters such as the type of control.

In the case of a renewable power supplier, photovoltaic or wind, the control type is set to PV. As input parameters an initial value for the nominal power and the hourly capacity factor for the renewable source involved have to be provided.

The capital cost is supplied too, quantified as euro per megawatt (€/MW) on a yearly basis. To the CapEX, expressed in annuities through the actualization factor it is added the yearly OpEX. The actualization factor takes into account the estimated life of the system and an inflation parameter, the discount rate. It is calculated as:

$$annual_n = \frac{(1+t)^n - 1}{t \cdot (1+t)^n} \tag{5.1}$$

Where:

- n is the estimated life span, 25 years in the cases of variable renewable generators [86];
- t is the discount rate, set as 4% [87].

The annualization factor results equal to 15.6.

In the case of a grid connection, instead, the component is defined through the control strategy *Slack*. Using slack control strategy in PyPSA is a common method for simulating a grid connection. It involves fixing the voltage and phase angle at one or more nodes in the network, which represents the grid connection point. No capacity factor needs to be provided. The annual cost is computer in the same way as before, but considering a time span of 35 years [88], which leads to an annual factor equal to 18.7.

In the end, information about the marginal cost is added. As mentioned in Chapter 4, this figure is defined as the cost of supplying one megawatt of energy from the national grid.

Storage The storage system is defined through the PyPSA component *Storage Unit*. Some additional attributes are introduced in this element regarding the characteristics of Li-ion batteries. In particular, some losses and efficiencies are introduced: standing losses, dispatch efficiency, and store efficiency. The standing losses, also called idle losses or standby losses, are the losses that occur when the battery is idle and not in use due to a variety of factors, such as self-discharge, leakages, and internal resistance. This value is assumed as 0.3% during 24 hours. The dispatch and store efficiencies represent the amount of energy that is lost or wasted during the processes of discharging and charging the battery, respectively. A typical value for lithium-ion batteries is 94.87% [89], assuming that the battery is discharged slowly and at a shallow depth of discharge, which can help to minimize losses and maintain high efficiency.

Another required input parameter is the energy-to-power ratio. The energy-to-power ratio is an important parameter that represents the maximum duration for which a battery can continuously supply power at its full output capacity before reaching its minimum state of charge. For the present study, the energy-to-power ratio is set to 2 hours, which will be verified and analyzed in Section 5.3 after presenting the simulation results.

Constraints are imposed on the minimum and the maximum state of charge, limiting it in a range between 10 and 90%. This constraint serves to protect the battery from damage caused by overcharging or over-discharging, as well as to ensure its optimal performance without being subjected to excessive stress or damage.

The capital cost annuity is calculated by considering the life span of the battery, the discount rate, and the initial capital cost. In this case, a 15-year life span is considered, which is a common value for Li-ion batteries [90]. The discount rate is kept at 4%. The annuity results in 11.1.

5.2 Tailoring of the analysis to each case study

This section is dedicated to explaining how the analysis was carried out for each case study, including the components involved and the input variables required. Input variables were essential in the analysis as they provided the necessary data to model different scenarios and explore potential outcomes. These inputs were specific to each case study and included information about the capacity factors, the loads and the prices.

The yearly capacity factors and loads were provided as *csv* files on an hourly basis. The information about the capacity factors is acquired through the *PVGIS* [91] and *Renewables.ninja* [92] tools, for sun and wind, respectively. In order to ensure coherence with the cost analysis conducted for the year 2019, the capacity factors for that year were chosen as a reference point. The loads in input are, instead, the ones resulting from the analysis carried out in Chapter 3.

Prices for the technologies, CapEX and OpEX, and marginal costs have to be furnished too. Those values refer to the of Chapter 4 outcomes. For sake of understanding, the costs are expressed in euros per kilowatt, even though they have to be converted into euros per megawatt to be inserted into the code.

5.2.1 Case study 1 - Plant scheme and input data

The plant implemented on the Ugandan island of Nainaivi is realized through the connection of the load, the solar generator, and a storage system to a single node, as shown in the simplified scheme in Fig. 5.1.

Information about the solar capacity factor and the school load are given as input data for the Pypsa code as well as the costs.

Concerning the prices of the technologies, they are listed in Tab. 5.1, according to the estimations made in Chapter 4.

In regard to the capacity factor, it can be noticed by the yearly profile in Fig.

Component	**CapEX [€/kW]**	**OpEX [€/kW/y]**	**Life span [y]**
PV generator	1,200	18	25
Li-ion storage	1,300	42	15

Table 5.1: Technology prices for Nainaivi plant

5.2 that it does not experience huge variations during the year. Its average value is equal to 19.1%.

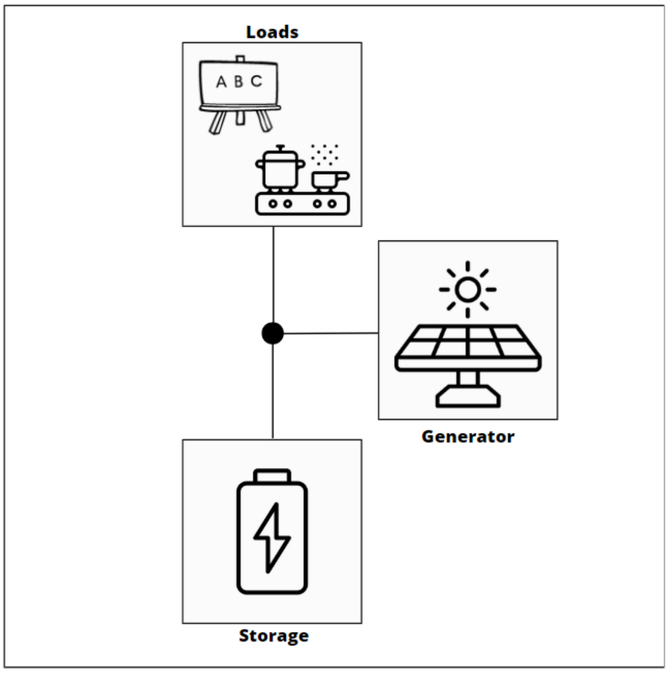


Figure 5.1: Simplified scheme of Nainaivi plant

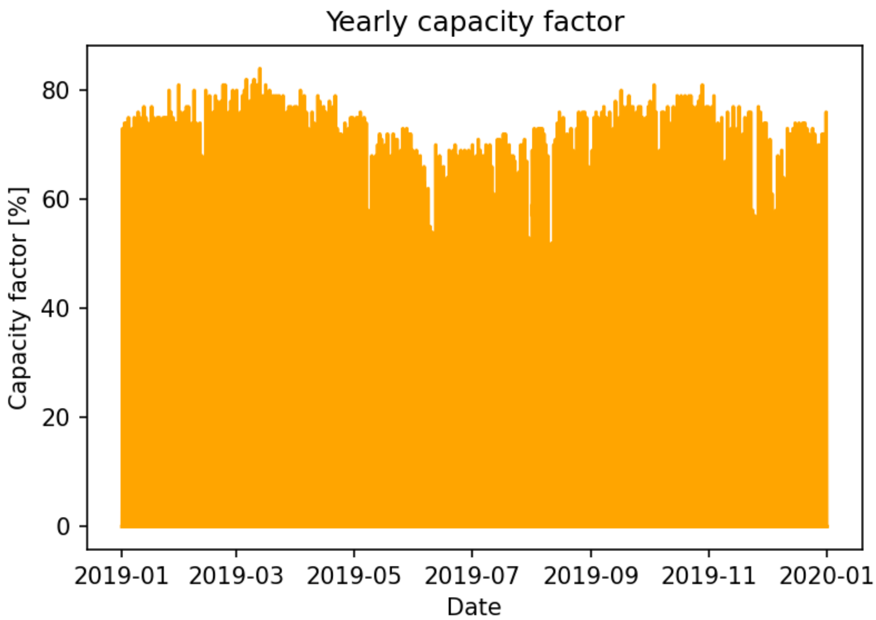


Figure 5.2: Nainaivi yearly sun capacity factor

5.2.2 Case study 2 - Plant scheme and input data

The plant of the second case study is powered by a photovoltaic and an eolic generator. A storage system and a grid connection are implemented too, as shown in figure 5.3.

Costs are listed in Table 5.2. A distinction in costs evaluation is made between

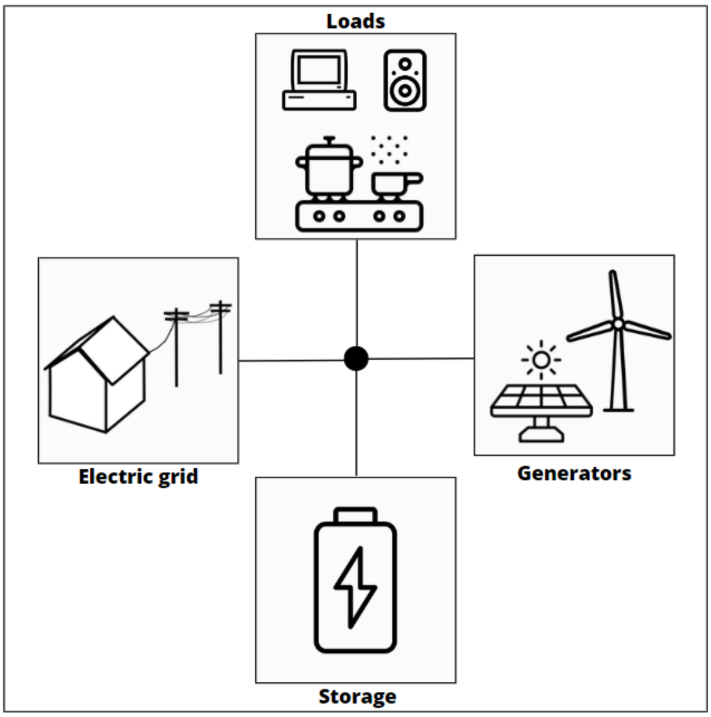


Figure 5.3: Simplified scheme of Bidibidi plant

generators and storage systems and the electric grid. Specifically, the capital cost of the electric grid is largely determined by its extension, rather than the amount of power transmitted. The operational cost of the grid is also influenced by fixed costs defined by contract. These costs are typically borne by grid operators and are often spread across the entire grid, regardless of the amount of power transmitted.

Sun and wind capacity factors are reported in Fig. 5.4. Comparing sun and wind as sources, it can be seen how the first is much more stable and constant during the year than the second. The average values are, respectively, 18.2% and 8.1%.

Component	CapEX [€/kW]	CapEX [€]	OpEX [€/kW/y]	OpEX [€/y]	Marginal cost[€/kWh]	Life span [y]
PV generator	1,200	-	18	-	-	25
Wind generator	2,300	-	32	-	-	25
Li-ion storage	1,300	-	42	-	-	15
Distribution grid	-	18,800	-	27,000	0.154	35

Table 5.2: Technology prices for Bidibidi plant

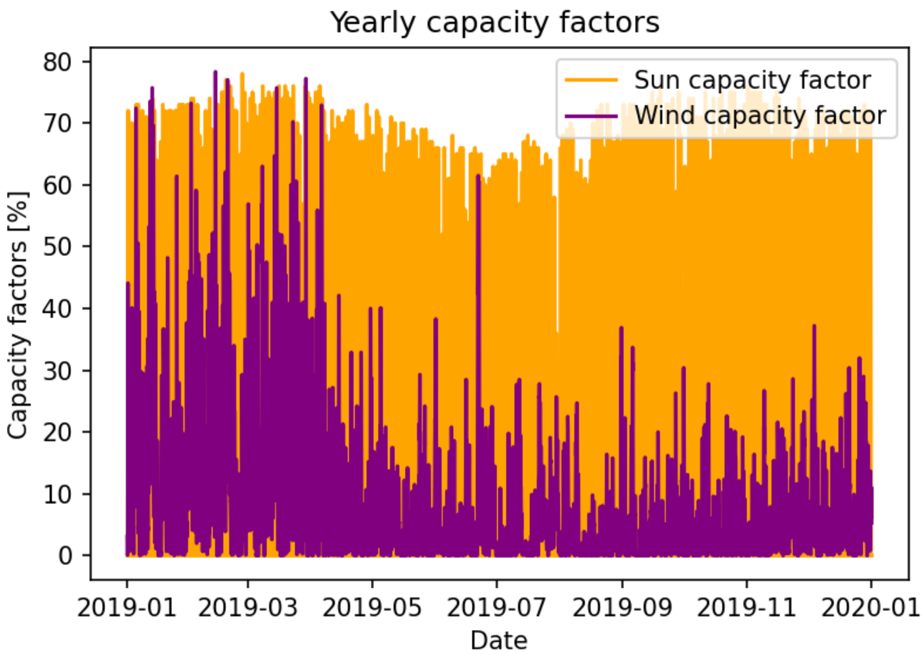


Figure 5.4: Bidibidi yearly sun and wind capacity factors

5.2.3 Case study 3 - Plant scheme and input data

The third case study utilizes a combination of agro PV and wind generators as its primary power sources. Additionally, the plant is equipped with a storage system that enables the storage and use of excess energy generated by the system.

The simplified plant scheme is shown in Fig. 5.5.
Table 5.3 reports the costs of installation and maintenance of the components.

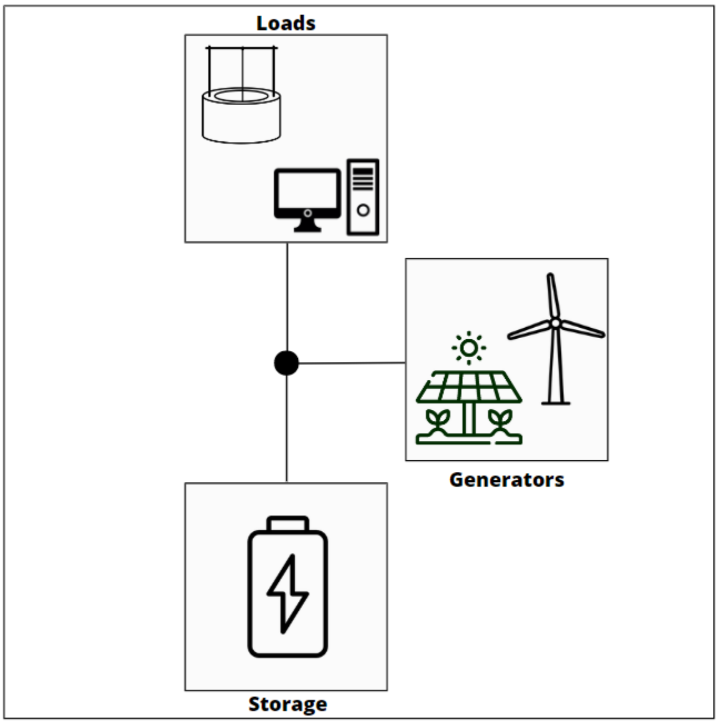


Figure 5.5: Simplified scheme of Champira plant

Component	CapEX [€/kW]	OpEX [€/kW/y]	Life span [y]
AgroPV generator	1,450	18	25
Wind generator	2,300	32	25
Li-ion storage	1,300	42	15

Table 5.3: Technology prices for Champira plant

Fig. 5.6 depicts the capacity factors of solar and wind energy sources. The average capacity factor for solar energy is 18.8%, while the average for wind energy is 18.7%.

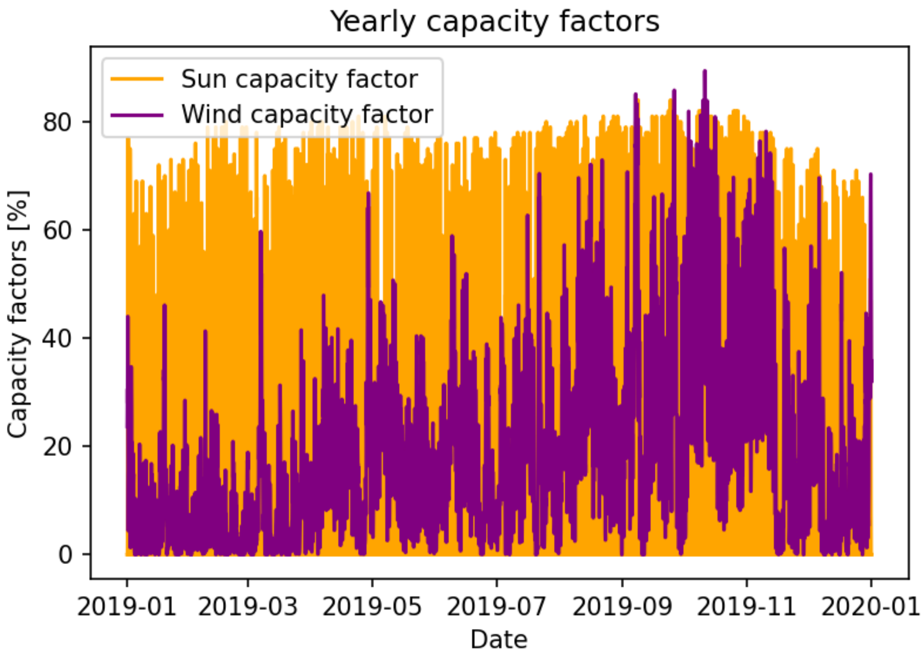


Figure 5.6: Champira yearly sun and wind capacity factors

5.3 Simulation results

This section provides an analysis of the results obtained from the PyPSA simulation for each case study. The PyPSA tool gives information about the optimal installed power for renewable generation and the optimal installed power and capacity of the battery to match the energy demand. In the presence of a grid connection, it evaluates whether or not it is worth it to install a storage system. It also provides hourly profiles. In the process of optimizing the power system, PyPSA takes into account the required power and the input prices for each technology. The tool uses this information to identify the most cost-effective solutions for meeting the energy needs of the system.

The results of every case study are here being analyzed and reported in terms of optimal power values and graphical representations of daily and yearly trends.

5.3.1 Case study 1 - Results

The results of the first case study show a required installed power of photovoltaic generation equal to 6 kW and a required storage capacity of 23 kWh.

Yearly trend By plotting the trend of the photovoltaic power generation in the Nainaivi Island Plant, Fig. 5.7, it can be noticed how it follows the pattern defined by the periods opening and closures of the school.

Because the plant is not connected to the power grid, no production is detected

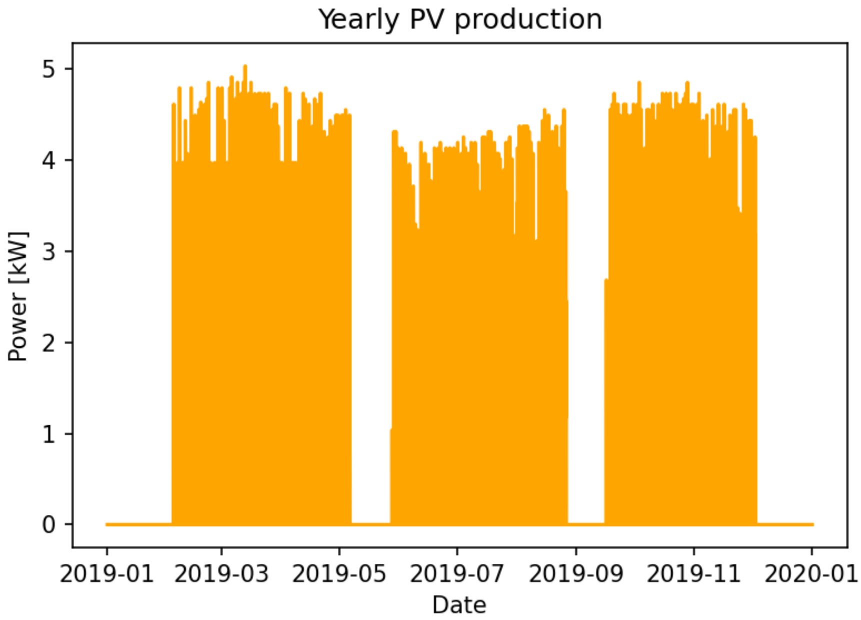


Figure 5.7: Nainaivi yearly PV generation

during school closure periods due to the absence of a load.

Also the state of charge of the battery varies according to the load shape on a yearly basis. By extrapolating the maximum state of charge from the yearly variation, it is possible to calculate the overall battery capacity. This is because the maximum state of charge is limited to a specific value, which in this case is equivalent to 90% of the total capacity of the battery. Such value is equal to 20.7 kWh, that corresponds to the 90% of 23 kWh.

The *Storage Unit component* in PyPSA allows to get the nominal installed power of the battery, equal to 11.5 kW. This data confirms that, by dividing the storage capacity by its nominal power, the energy-to-power ratio is equal to 2 hours.

Concurrently with the presentation of the previous image, it is essential to make a significant notation concerning batteries and their charge-discharge cycles. The analysis conducted has certain limitations as network stability requirements were not taken into account, leading to infrequent use of energy storage. In fact, a check on the battery state of charge would be needed to assess whether the energy from the photovoltaic system has to feed directly the load or the battery

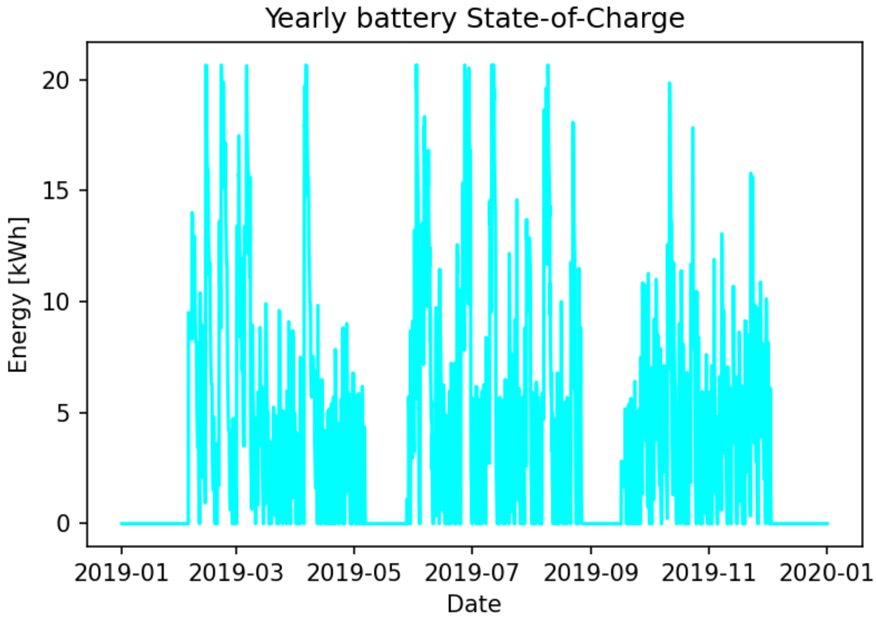


Figure 5.8: Nainaivi yearly battery state of charge

instead, not to affect the system's stability. Without this control, the number of cycles of the battery results extremely low, thus not reliable, during the year. However, this is a broad-spectrum analysis whose focus is on providing a rough estimation of the system's size and capacity, without getting into the details of the underlying components and their performance. This approach is appropriate for a high-level analysis where the goal is to obtain a general understanding of the system's capabilities and limitations.

Daily trend In order to gain a better understanding of the actual behavior of the system, a decision was made to plot its average daily behavior. This involved taking the values of production, percentage state of charge, and load and averaging them on a daily basis. The resulting values were then plotted on a single graph, allowing for easy comparison of the different factors over the course of a typical day.

What can be noticed is that the peak of consumption occurs in the same hours of the peak of generation. During the morning hours, when there is a surplus in generation, the electricity produced by the solar panels serves both to supply the load and to charge the battery, while in the afternoon hours, when solar production decreases, the battery state of charge gradually decreases as well as its energy is used to feed the system. During the night hours, when the PV production is zero, the battery energy is used to cover the load due to appliances turned on all day, such as the WiFi router, and to system losses.

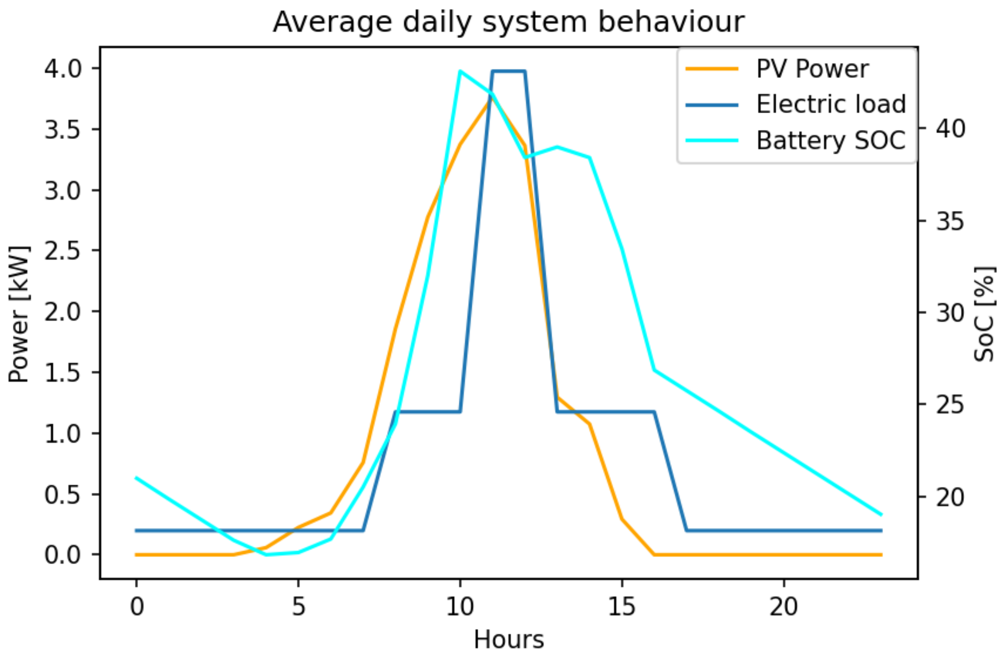


Figure 5.9: Nainaivi daily system behaviour

5.3.2 Case study 2 - Results

The second case study's results indicate the need for installation of 31 kW of photovoltaic power only.

Despite the inclusion of a wind generator in the simulation, it was excluded from the optimization process by the tool, likely because of its lower generation capacity and higher cost compared to photovoltaic panels. This information suggests that photovoltaic panels are a more efficient and cost-effective energy source for the given situation.

The storage system, implemented in the code, was excluded from the analysis as well, most likely because the system is grid-connected since the grid can supply the deficit when generation falls short of demand. Therefore, the optimization tool may have excluded the storage system as it was not deemed essential to the grid-connected system.

The plant scheme that results from the optimization process is reported in Figure 5.10.

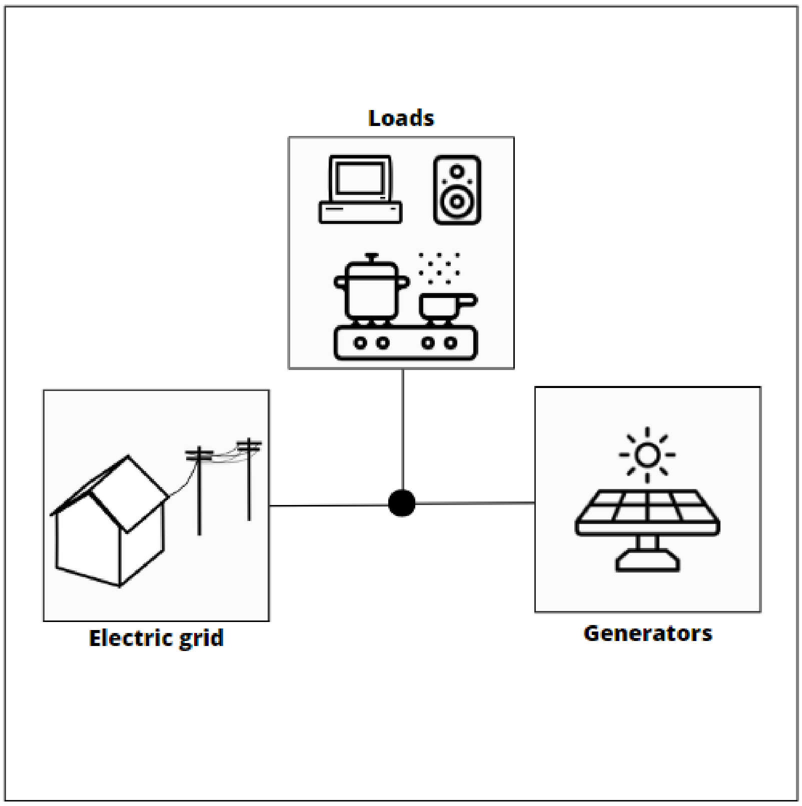


Figure 5.10: Optimized simplified scheme of Bidibidi plant

Yearly trend The photovoltaic production is quite constant during the year, with only minor variations due to seasonal changes and weather conditions. Therefore, since the yearly variation is not significant, it is not necessary to report a plot of the production over the entire year. Instead, the maximum and mean production values are reported, which are 18.7 kW and 3.5 kW, respectively.

Daily trend The system's daily behavior was evaluated and plotted in Figure 5.11. The photovoltaic and grid power contributions were averaged over a year on a daily basis.

The analysis reveals that the system is capable of covering the three peaks of the load using both photovoltaic production and energy from the national grid. The morning peak sees a higher share of grid power than photovoltaic power. The midday peak coincides with the hours of highest production, and therefore it is mostly satisfied by photovoltaic energy, leading to a higher self-consumption. The evening-night peak is fully covered by power from the national grid since the solar production is null in those hours.

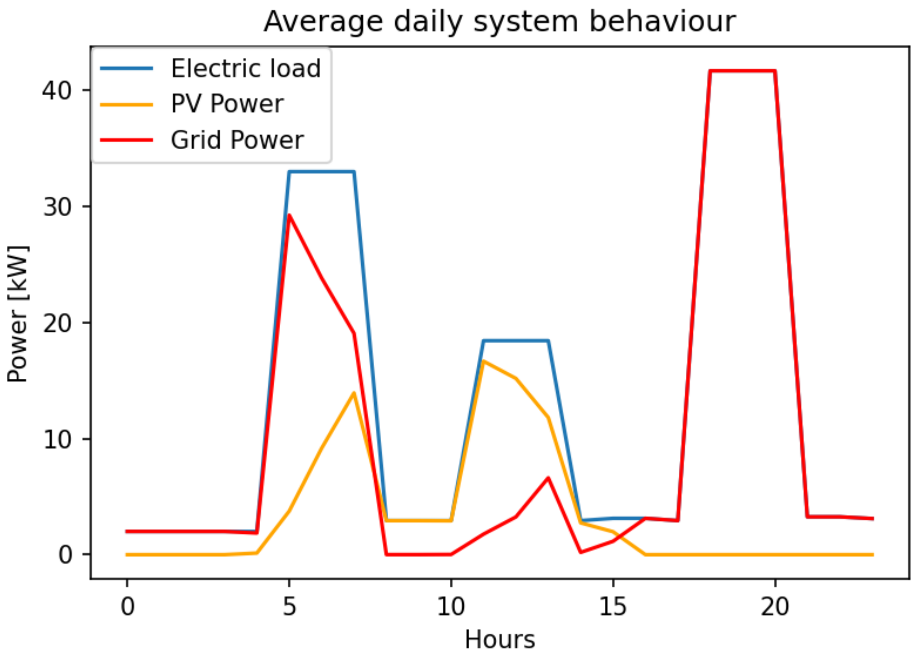


Figure 5.11: Bidibidi daily system behaviour

5.3.3 Case study 3 - Results

The third case study examined the potential benefits of integrating photovoltaic and wind power technologies in a hybrid energy system. The results of the study indicated that a system comprising both technologies would require an installed power capacity of 17.8 kW for photovoltaic and 6.2 kW for wind energy. Additionally, a storage capacity of 56.9 kWh would be needed to maintain a consistent energy supply. The integration of multiple renewable energy sources can provide a more reliable and stable energy supply compared to a system relying on a single energy source.

It is necessary to make a remark regarding wind installed power. As a first attempt, the outcome for the optimum installed power was around 3 kW. This result was obtained by using as an input the capacity factor of the *Enercon E-40/6.44* turbine, found on *Renewable.ninja* which has a nominal power of 600 kW. However, because this nominal power value was much different than the obtained value, a second step was taken.

Actual wind speeds were downloaded from *Renewable.ninja* and turbines with nominal power values close to the optimum were chosen from *wind-turbine-models.com* [93]. Only turbines with available power curves were selected to ensure accurate data. Their capacity factors were then interpolated with the actual wind speed values and used as input values in the PyPSA component to obtain more reliable data.

The wind turbines involved in this process have nominal powers ranging from 3 to 20 kW and are the following:

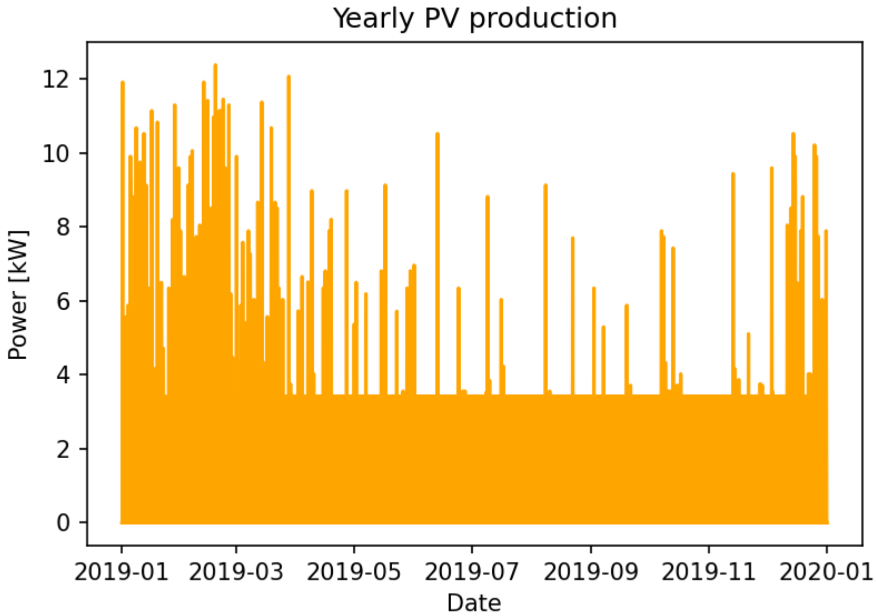
- Aeolos Aeolos-H 3kW: P_n=3.00 kW;
- Aventa AV-7: P_n=6.00 kW;
- Windspot 7.5Kw: P_n=7.50 kW;
- Hummer H8.16-10KW: P_n=10.00 kW;
- MAN Aeroman 11/11: P_n=11.00 kW;
- Hummer H13.2-20KW: P_n=20.00 kW.

Running the simulation for all the given power curves, the resulting optimal installed power is around 6.2 kW.

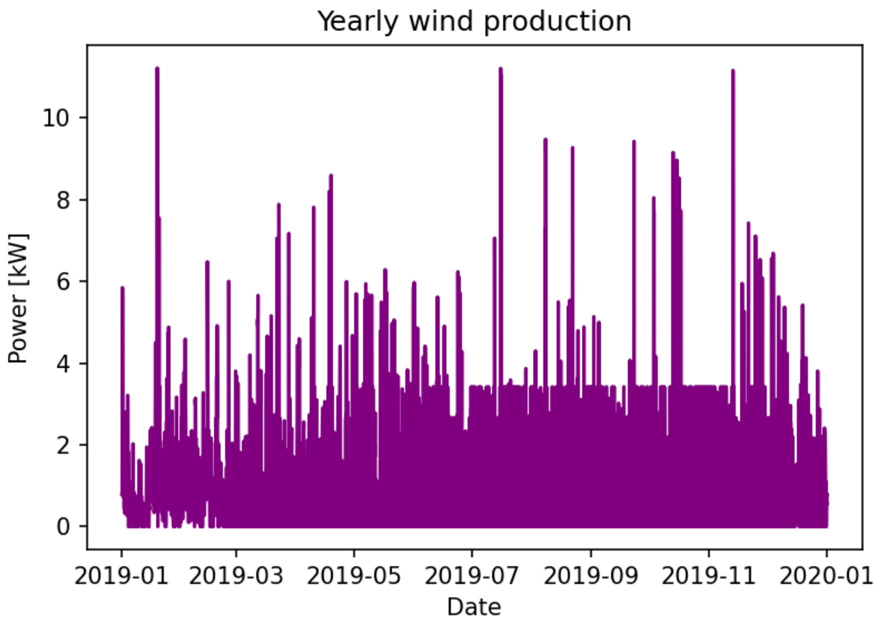
After determining the optimum power installed, the performance of the system can be analyzed, as in the previous case studies.

Yearly trend Figure 5.12 shows the yearly variation of photovoltaic and wind production. What can be observed in the two graphs is that the production path is irregular, with a constant base production and some peaks through the whole year. This behaviour deviates from the trend of the capacity factor, reported in Fig. 5.6, where it is possible to observe the seasonality of the capacity factor. The reason for this difference is that, in the optimization process, PyPSA operates a curtailment of the production in order to valorize the technology that best suits the needs of the plant for every time frame.

Figure 5.13 shows the state of charge. Also in this case, the maximum state of charge imposed on the battery is 90% of the maximum capacity, which is around 51.2 kWh. As a result, the value corresponding to one hundred percent is 56.9 kWh. The corresponding nominal power is 25.6 kW, having the battery a maximum energy-to-power ratio of 2 hours.



(a) Photovoltaic generation



(b) Wind generation

Figure 5.12: Champira yearly solar and wind generations

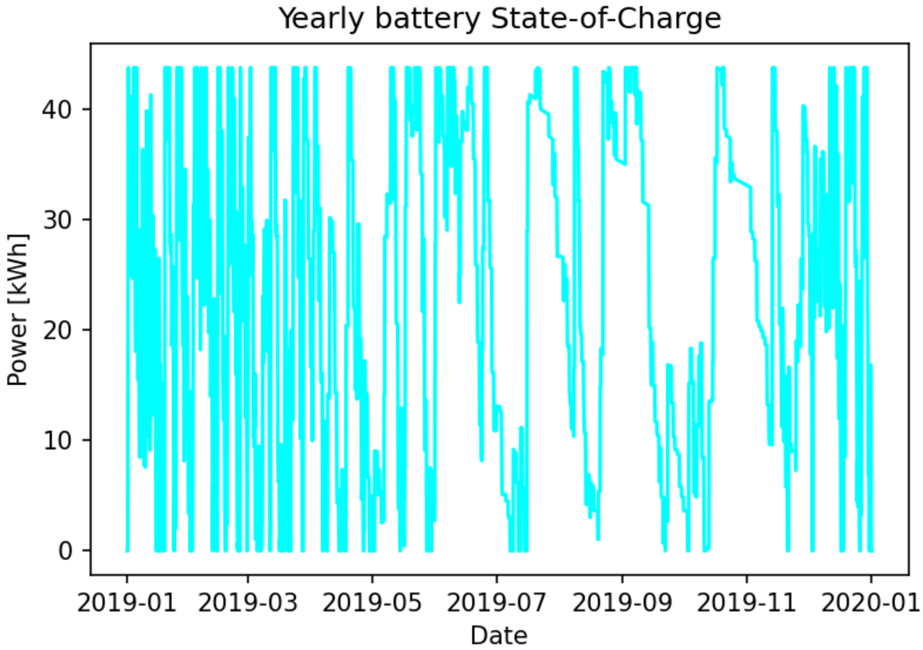


Figure 5.13: Champira yearly battery state of charge

Similarly to the first case study, the stability requirements for the system are not taken into consideration, resulting in a very low number of yearly cycles. Hence, this number should not be considered since it is not reliable.

Daily trend The average daily system behavior is plotted in Fig. 5.14. Yearly data for production and storage are averaged on a daily basis.

In contrast to the previous case studies, substantial energy consumption - in reference to the maximum one - occurs during the night hours. As there is no photovoltaic production during this time, this demand is fulfilled by the wind energy production and energy from the battery storage system.

During periods of active photovoltaic production, the generated energy is used to both power the load and charge the battery. When, instead, photovoltaic production is null, the battery is gradually depleted until the night hours.

During night hours, when the consumption is at its minimum, the generated wind energy exceeds the load requirement and this excess is used to recharge the battery.

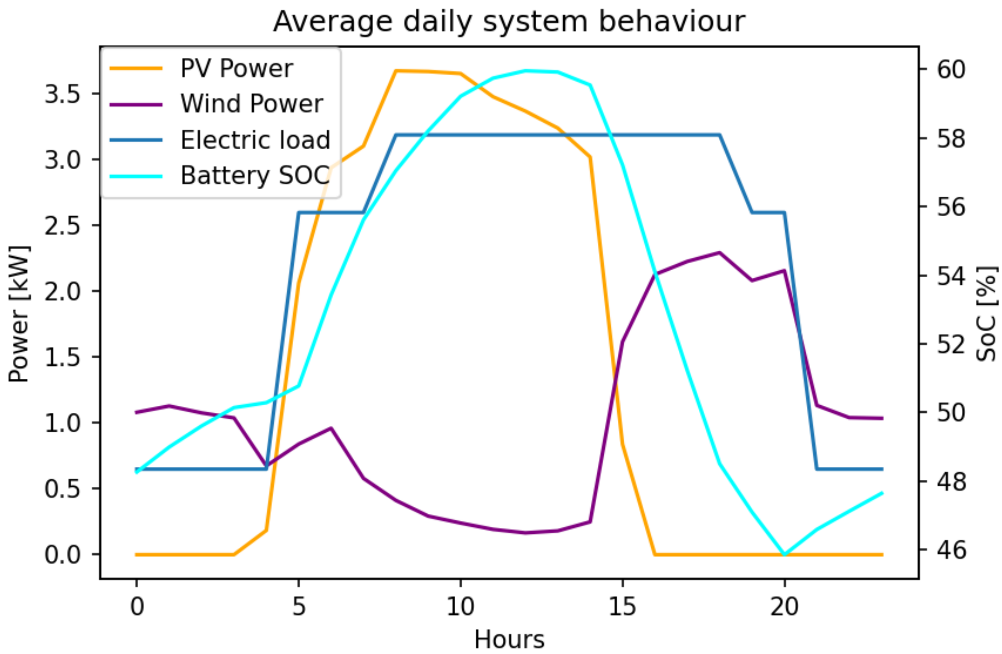


Figure 5.14: Champira daily system behaviour

Chapter 6

Financial sustainability

The last chapter of this thesis is dedicated to the calculation of the final costs of each case study, both in terms of CapEX and OpEX. The total yearly costs and LCOEs are then computed and compared. Afterwards, additional expenses are considered in the total cost of the new projects. The final section of the chapter is then going to be focused on identifying methods to fund the projects.

6.1 Technologies' costs and LCOE comparison

This section calculates the overall expenses for installation, operation, and maintenance by multiplying the total installed power by the corresponding specific costs. Both the total installed cost and the annual cost are computed.

6.1.1 Case study 1 - CapEX and OpEX

The results of the first case study show an installed power equal to 6 kW of PV panels and 11.5 kW of Li-ion storage (Sec. 5.3.1) at specific costs of, respectively, 1,200 and 1,300 €/kW (Sec. 4.3.1 and 4.3.4). The overnight installation costs are reported in Tab. 6.1.

Technology	**Installed capacity [kW]**	**CapEX [€]**
Solar PV	6.00	7,200.00
Li-ion Storage	11.50	14,950.00

Table 6.1: Nainaivi total installed capacities and costs

The total installed cost is €22,150.00.

Afterwards, the yearly expenses are reported, in terms of annualized CapEX and OpEX. The yearly capital expenses are calculated by dividing the total installed cost by the annualization factor, as in Section 5.1. OpEX is calculated by multiplying the installed power by 18 €/kW/y for solar PV (Sec. 4.3.1) and 42 €/kW/y for storage systems (Sec. 4.3.4). Yearly costs are reported in Tab. 6.2

Technology	**CapEX** [€/y]	**OpEX** [€/y]
Solar PV	460.90	108.00
Li-ion Storage	1,344.60	483.00

Table 6.2: Nainaivi yearly costs

The total yearly cost for the first case study is €2,396.50.

6.1.2 Case study 2 - CapEX and OpEX

The results of the second case study show an installed power equal to 31.2 kW of PV panels (Sec. 5.3.2) at specific costs of 1,200 €/kW (Sec. 4.3.1) and the need for a grid expansion. The overnight installation costs are reported in Tab. 6.3.

Technology	**Installed capacity** [kW]	**CapEX** [€]
Solar PV	31.20	37,440.00
Electric grid	-	18,680.00

Table 6.3: Bidibidi total installed capacities and costs

The total cost of installation is €54,440.00.

Yearly expenses are reported in Tab. 6.4. Yearly capital expenses are calculated by dividing the total installed cost by the annualization factor. OpEX is calculated by multiplying the installed power by 18 €/kW/y in the case of PV panels (Sec. 4.3.1). Concerning the OpEX of the distribution grid, the value computed at Section 4.3.5 is taken. When energy is bought from the distribution grid, a new figure, called variable cost, should be considered. It is computed as the multiplication of the marginal cost by the total energy purchased from the grid in one year. As assessed in Section 4.3.5, the marginal cost is equal to 0.154 €/kWh. The total energy purchased annually is calculated by summing up the hourly values for grid power injection given by the PyPSA analysis; it is 86,392.00 kWh.

Technology	**CapEX** [**€/y**]	**OpEX** [**€/y**]	**Variable cost** [**€/y**]
Solar PV	2,396.60	561.60	-
Electric grid	1,000.80	285.00	13,304.36

Table 6.4: Bidibidi yearly costs

The total yearly cost for the second case study is, then, €17,548.40.

6.1.3 Case study 3 - CapEX and OpEX

Finally, results of the third case study are reported. Installed powers equal to 17.8 kW of agroPV panels, 6.2 kW of wind turbines and 25.6 kW of Li-ion storage were computed in Section 5.3.3. Those values are multiplied by the specific costs of, respectively, 1,450, 2,300 and 1,300 €/kW (Sec. 4.3.2, 4.3.3 and 4.3.4). The overnight installation costs are reported in Tab. 6.5.

Technology	**Installed capacity** [**kW**]	**CapEX** [**€**]
Solar PV	17.80	44,500.00
Wind turbine	6.20	14,260.00
Li-ion Storage	25.60	33,280.00

Table 6.5: Champira total installed capacities and costs

The total installed cost is €92,040.00.

Yearly expenses are reported, in terms of annualized CapEX and OpEX, in Tab. 6.6. The yearly capital expenses are calculated by dividing the total installed cost by the annualization factor, as in Section 5.1. The OpEX is calculated by multiplying the installed power by 18 €/kW/y for solar PV (Sec. 4.3.1), 32 €/kW/y (Sec. 4.3.3) for wind and 42 €/kW/y for the storage system (Sec. 4.3.4).

Technology	**CapEX** [€/y]	**OpEX** [€/y]
Solar PV	2,848.50	391.60
Wind turbine	912.80	198.40
Li-ion Storage	2,993.20	1,075.20

Table 6.6: Champira yearly costs

The total yearly cost for the third case study is €8,419.80.

6.1.4 LCOE comparison

LCOE stands for Levelized Cost of Energy, which measures the average cost of generating a unit of electricity over a power plant's lifetime, including construction, operation, and electricity production costs.

In this case, since yearly value for expenses and power production are available, a yearly LCOE is computed as follows:

$$LCOE_t = \frac{\sum_{t=1}^{n} \frac{TC_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} = \frac{\sum_{t=1}^{n} \frac{C_t+O_t+V_t}{(1+r)^t}}{\sum_{t=1}^{n} E_t} \left[\frac{€}{kWh \cdot y}\right] \tag{6.1}$$

Where:

- TC_t is the total cost at the year t, given by the sum of:
  - C_t, the CapEX;
  - O_t, the OpEX;
  - V_t, the variable cost.
- E_t is the total energy required at the year t;
- r is the discount rate, the measure of the time value of money.

The total yearly costs have been already calculated for each case study in the previous sections. What is missing to be calculated for the computation of the Levelized Cost of Energy is the total energy consumed annually. This is done by summing up the hourly consumption reported in Sections 3.2.3, 3.3.3 and 3.4.3 occurring over an entire year. Table 6.7 reports the total yearly costs, energy consumption and LCOE for every case study on a yearly basis.

From the table, it can be observed that the case study number two, situated in

Case study	**Total yearly cost** [**€**]	**Total yearly energy consumption** [**kWh**]	**LCOE** [**€/kWh/y**]
# 1 Nainaivi	2,396.50	4,249.50	0.564
# 2 Bidibidi	17,565.50	116,777.00	0.150
# 3 Champira	8,419.80	20,889.60	0.403

Table 6.7: LCOE computation

the Bidibidi refugee camp in Uganda, has the highest yearly cost when compared to the other two case studies. However, it is interesting to note that the energy consumption in this case study is also significantly higher than the other two, which results in a much lower LCOE. This suggests that although the initial investment and yearly cost for the system in Bidibidi are higher, the high energy consumption makes it more cost-effective in the long run. The first0 case study, situated on the Ugandan island of Nainaivi, has the highest LCOE among the three case studies. Although its installation cost is relatively low, its energy consumption is also quite low due to the frequent school closures throughout the year. As a result, the plant has a lower energy production output, leading to a higher LCOE if compared to plants running all year.

6.2 Other costs

While the Levelized Cost of Energy is a useful metric for estimating the total cost of producing electricity from a power plant over its lifetime, it is important to remember that there may be other costs associated with the project that are not included in the LCOE. These costs can include expenses such as taxes, other constructions costs and appliances purchasing.

Purchasing of electric cookers The World Future Council's report *Beyond Fire* provides valuable insights into the pricing of efficient electric cookers. According to the report, cookers with power ranges between 800 and 2,300 W can be purchased at prices ranging from €5.00 to €100.00 [94]. To better understand the pricing of efficient electric cookers in Uganda, the prices found in the report were compared to actual market prices in the country. The results showed that double electric hotplates can cost around €40, while 4-plate electric cookers can cost around €100.

Grid connection fee When a new plant is connected to the main electric distribution grid, a connection fee is typically required to be paid. In Uganda, it is about USH470,000 (Ugandan Shilling), which correspond to €120 [95].

Purchasing of desktop computers According to research conducted by consulting websites of companies that sell computers in Sub-Saharan Africa, specifically South Africa, it has been found that the average price for a desktop computer in the area is approximately €500, which includes the monitor and keyboard. These companies offer both new and refurbished computers, and the price can vary depending on the brand, specifications, and country of origin.

Well drilling In regards to water wells drilling and pumps installation, data from the Groundwater Governance [96] and the Wiley article *Rural boreholes and wells in Africa-economics of construction in hard rock terrain* [97] were combined. From the Wiley's article, it was possible to get the average cost per meter for rural African wells. This figure is equal to $280 per meter of excavation, taking into account the excavation itself and the associated cost of labor, material transport, regulatory fees. Considering a depth of 30 m, the total cost for building the well is around $8,400. To the previous one, is added the cost of purchasing an electric pump. According to the article *How Much To Build A Water Well In Africa?* by Groundwater Governance, a pump may cost around $400.

To summarize the costs incurred so far, the total expense amounts to $8,800. When converted to euros, this translates to approximately €8,300.

6.3 Total costs

After computing all the additional costs associated with the case studies, it is possible to determine the total costs for each case. These costs are added to the installation costs in order to evaluate the magnitude of the initial investment.

6.3.1 Case study 1 - Total cost

The project developed for the school on Nainaivi Island, Uganda, incurred additional costs due to the purchase of three computers and two electric 4-plate cookers. The total cost of these items resulted in an additional expense of €1,700.00.

The inclusion of this extra cost, along with the initial investment required for constructing the power plant, leads to a total expenditure of €23,850.00.

6.3.2 Case study 2 - Total cost

The Bidibidi refugee camp case study incurs an extra cost of €1,120.00. This is due to the acquisition of twenty-five double electric plates, which were purchased at a cost of 40 euros each, and a one-time €120 connection fee paid to the national grid.

As a result, the total cost increases to €57,240.00 when the additional expense is combined with the previous one.

6.3.3 Case study 3 - Total cost

In the village of Champira, Malawi, the project faced extra expenses of over 8,000 euros for drilling and constructing a water well, and €1,500 for purchasing three desktop computers priced at €500 each. The total additional cost amounts to €9,800.00.

When combined with the initial investment for constructing the power plant, the total expenditure amounts to €101,840.00.

The following table provides a comprehensive breakdown of the initial costs incurred in each case study, separately reporting the expenses associated with the power plant and equipment purchases. Additionally, it presents a summary of the total initial expenditure, combining both plant and equipment costs.

Case study	**Power plant cost** [**€**]	**Equipment and appliances cost** [**€**]	**Total cost** [**€**]
# 1 Nainaivi	22,150.00	1,700.00	23,850.00
# 2 Bidibidi	56,120.00	1,120.00	57,240.00
# 3 Champira	92,040.00	8,900.00	101,840.00

Table 6.8: Total costs summary

Upon analyzing the data presented in the table, it is evident that the first case study is the least expensive, while the third case study remains the most expensive. The lowest price associated to the first case study is due to its smaller size and to the lowest price that the installation of solar panels only involves, compared to the installation of both solar panels and wind turbines. The second case study, from its perspective, incurs relatively low costs in proportion to its size. This is primarily due to the lower expenses associated with the power plant, which does not require a large storage system but involves only the costs of procuring solar panels and expanding the national grid.

6.4 Projects' financing

The final section of this work focuses on identifying viable financing options for the projects under consideration, exploring a range of potential financing models. The ultimate goal is to ensure that the projects are financially sustainable in the long run and capable of delivering reliable and affordable electricity to the communities they serve.

The potential solutions are evaluated on a case-by-case basis, taking into account factors such as the financial resources of the energy-consuming community, the type of power generation facility - including whether it is connected to the grid - and the potential availability of government subsidies or assistance from local non-governmental organizations.

6.4.1 Case study 1 - financing

When considering the first case study, it should be taken into account that a primary school in a remote island may have limited financial resources. As it is a public school, there are no private energy sellers or purchasers involved. The only private entity involved would be the company responsible for installing and maintaining the plant. Moreover, being the project stand-alone, no incentives can be applied for surplus energy selling, since there is no grid or other users to sell the energy to.

According to UNDP, the Ugandan government offers subsidies for renewable energy projects through the Rural Electrification Agency to which the school could apply, reducing significantly the project's expense. In fact, those subsidies are meant to cover up to the 40% of the project, with a price cap of USH 50 million (€ 12,650.00), for projects corresponding to certain criteria such as being located in rural areas or having a social impact [98]. Since the project's initial cost is, all included, €23,850.00 its forty percent, corresponding to €9,540.00, could be covered by the government's capital grant.

The remaining part could be covered through agreements with local ESCOs. The acronym stands for Energy Service Companies, which are entities that provide energy-related services and equipment aiming to reduce energy consumption and costs. Those entities offer services such as design and installation of energy efficient equipment and their maintenance. ESCOs are capable of recovering their costs by sharing the costs savings with the costumer [99]. In this specific case, the school is currently supposed to be powered by a diesel generator, typically unreliable and costly. The savings are, therefore, the reduced expenses of running a photovoltaic plant compared to a diesel generator.

6.4.2 Case study 2 - financing

In regards to the financing of the project located in the Bidibidi refugee camp in Uganda, some additional considerations other than the simple financing of the plant have to be done. As per the stakeholders who were interviewed, there exists a law that mandates that thirty percent of the aid or support provided to refugees must also benefit the Ugandan population living in that region. Nevertheless, there are often frictions between the two communities. For this reason, it is recommended to rely on NGOs that work on the territory to guarantee a certain social acceptance of the projects and prevent thefts and damages to the plants equipment. This because no one has the intention of creating hostilities with them. Moreover, if the NGOs are well established on the territory they have knowledge and experience in managing different kinds of projects.

The possibility of a monetary contribution from the local community is excluded because both the camp community and the Ugandan population of the north-west of the country are extremely poor. Moreover, asking for an economic contribution to the Ugandan population may exacerbate the already existent frictions.

Taking in consideration the previous statement, it can be then analyzed the best financing strategy for the plant.

Since the plant is grid-connected, the combination of net metering with a FiT or a PPA scheme, can provide high benefits. Support from NGOs may be exploited for the purchasing of equipment and to guarantee the projects' social acceptance, while the government can be involved in its financial support through a Feed-in-Tariff scheme, already consolidated in the country, being active since 2007.

6.4.3 Case study 3 - financing

The third case study, the hybrid project located in Champira village, Malawi, is the one with the highest cost of installation but it is also the one with the largest community involved, meaning that its price can be split up among multiple contributors. Asking local communities a contribution is not just a way of financing but can also help foster a sense of belonging and build support for the project. Computing an estimation of the personal yearly expenditure by considering the plant installation and maintenance and the cost for the well drilling, it is assessed that the cost per person to maintain the plant is less than €3 per year. However, given that Malawian per capita income is less than six hundred euros and the project is being developed in a poor rural area where household members, such as children, do not contribute to the household income, the sustainability of such cost is not a foregone conclusion. Therefore, to explore options for financial support for renewable energy and water projects, research was conducted on the various funding opportunities available from the Malawian government and other entities.

As mentioned in Section 1.3.9, in 2018 the government of Malawi launched the National Renewable Energy Policy in the context of the Action Agenda for Malawi's Sustainable Energy Development, aiming at accelerating the country's development and increasing access to clean energy. The Malawi Energy Regulatory Authority (MERA) established Renewable Energy Fund to provide financial support to renewable energy projects in the form of grants, concession loans and equity investments in particular in rural areas. It is not possible to determine the entity of financial support in advance, though, as each project is evaluated on a case-by-case basis by a special committee.

The Government has also established a financial support program for water projects, which can provide additional funding. A dedicated fund, set up in 2013, provides affordable loans to local authorities, private sector actors and community groups. In addition, Malawi has some development partners such as the World Bank, the African Development Bank and the European Union, which can provide financial support.

6.5 Results comparison

A significant deduction that can be made from this chapter is that a low initial investment does not necessarily make an project more convenient in absolute terms. This is evidenced by the Levelized Cost of Energy, that underlines that an effective use of the energy is key to lower the costs. In fact, the project that here has the lowest capital expense, happens to be the one with the highest LCOE. To make the investment more profitable, some strategies may be actuated for a more efficient exploitment of the plant.

In regard to the selection of the financing methods it is important to consider the characteristics of each project and the stakeholders involved. Although some financing schemes are transversal and applicable to different countries, a lot depends on the kind of policies implemented by the government of the nation in which the project is built.

In the case of a small project with a strong social impact, it is possible to access multiple kinds of funding mechanisms. Having a relatively limited initial investment prevents exceeding eventual cost ceilings that may be imposed on the funding.

If the project is, instead, located in an area characterized by social tensions, it is highly recommended to couple the financing strategies with the activity of Non-Governmental Organizations in order to ensure the safety of the facility.

To avoid burdening the extremely impoverished areas, it is advisable not to impose a monetary charge on the population. In contrast, in other regions, involving the population at a monetary level through contributions is encouraged to cultivate a sense of ownership and promote development.

When a single project combines multiple necessities it may be evaluated the feasibility of accessing different kinds of national and international fundings to reduce as much as possible the actual cost.

Conclusions

The present research has shed light on the relationship between the energy and the financial situation in developing nations with the aim of providing a comprehensive understanding of renewable projects and aiding decision-making processes. A multilateral approach has been developed to address the challenge of access to clean energy in achieving sustainable development. This approach recognizes the interplay of technical, social, and economic aspects in achieving universal clean energy access. The technical aspect involves the development and deployment of clean energy technologies, while the social aspect addresses community engagement and participation. The economic aspect focuses on ensuring the affordability and financial sustainability of clean energy projects. By adopting this holistic approach, policymakers and stakeholders can create effective strategies to achieve clean energy access for all. In a context of constantly increasing energy demand it is mandatory to ensure access to clean energies in the effort of counteracting climate change.

This methodology is addressed to developing countries, which often struggle with ensuring reliable energy, in particular in regions like Sub-Saharan Africa, where the electrification rate is less than 50%. It is proven how access to electricity supports development, education, and health. Therefore, this multilateral approach is essential in addressing the issue of clean energy access in developing countries, where it can have a significant impact on their socio-economic development.

Economic schemes and policies have been analyzed. Among those are feed-in tariffs, auction systems, power purchase agreements, net metering, and other measures such as the implementation of a carbon market. For each of them, strengths and weaknesses have been highlighted. It was assessed how they can encourage and attract investors if properly managed and if adequate support is provided by the governments. In fact, among the issues encountered in third-world nations are the social and political instabilities and the lack of expertise and finance. Through an analysis of financial schemes actuated in different countries, it was shown how the reliance on international stakeholders, such as banks and companies, is crucial to ensuring a higher probability of success for the implemented measures. Involving the population is, instead, a way of increasing the social acceptance and, thus, promoting the development of a higher number of projects.

After a country-by-country analysis, the work went on with the implementation of an area selection method. The method consists of the evaluation of five parameters - solar irradiation, wind capacity factor, terrain slope, population density, and extension of the distribution grid - to which scores have been assigned in order to indicate the suitability of each area of the country under a specific condition. Afterwards, scores were computed for every site to identify the suitable technology for installation, as well as whether on-grid or off-grid plants were feasible. Only the locations with the highest overall scores were considered for selecting the final areas where case studies would be conducted. The technological options explored are solar PV plants and hybrid plants powered by both sun and wind energy.

The method has been applied to two countries in sub-Saharan Africa, Uganda and Malawi, for which information was gathered from various sources: the Global Solar Atlas, the Global Wind Atlas, the Southampton University's research group WorldPop, and the open data platform Energydata.info. All data were analyzed and manipulated through the open-source software QGIS.

The most appropriate areas for each type of plant in both countries were identified, and this was complemented with insights from local stakeholders gathered through interviews. By doing so, a more realistic understanding of the necessities of the local communities was gained, and specific locations with unique needs were identified.

Three locations were then selected for the implementation of the case studies. Two of those are in Uganda, respectively on the island of Nainaivi in Victoria Lake and in the Bidibidi refugee camp in the north-west of the country, and one is in a village in the middle of Malawi. The social and geographical contexts were analyzed, and loads were estimated. The availability of renewable sources was evaluated by collecting data from the PVGIS and Renewable.ninja tools. For each technology involved, its price was estimated for the countries in question in terms of capital, operational, and marginal costs. All those pieces of information were then used as inputs in a PyPSA optimization analysis whose purpose was to establish the power installed for each technology.

Next, the information regarding the installed power was utilized to estimate the overall expenses for each element of the plants, including capital and operational costs. A schematic summary of the features and the total costs of each case study is reported in the following lines.

The first case study is characterized by the installation of 6 kW of solar panels and 23 kWh of Li-ion battery storage to cover a yearly energy need slightly higher than 4 thousand kilowatt-hours with an installation cost of €22,150 and a total yearly cost of €2,400.

The second case study sees the sole installation of 31.2 kW of solar photovoltaic panels and requires an expansion of the national distribution grid along 3 km. The yearly consumption is almost 120 thousand kilowatt-hours, while the installation cost and the total yearly cost are, respectively, €54,440 and €17,550.

The third case study is both an energy and a water project that sees the construction of an electric water well together with the installation of 17.80 kW of agri-voltaic and 6.20 kW of wind power and of a 57 kWh storage system. The project's energy request is above 20 thousand kilowatt-hours per year. The capital expenditure is €92,040 for the energy equipment and €8,300 for building the well. The yearly cost of the energy plant comes to €8,420.

The levelized cost of energy has been computed afterwards for each case study in order to have a comparative figure. The results show that, despite the first case study having the lowest capital expenditure, it exhibits the highest LCOE due to irregular power consumption throughout the year. On the other hand, the second case study, although incurring significant annual expenses, consumes enough energy to offset the costs, resulting in the lowest LCOE.

The methodology ends with the research on financing methods for each case study. The assessments carried out in the first chapter have been considered and integrated with more specific information regarding the kinds of projects implemented in order to draw tailored solutions for the single cases.

Some considerations can finally be drawn about further steps to take in order to make the methodology comprehensive of more aspects. In regard to the selection of suitable areas carried out in Chapter 2, two improvements can be made. To begin with, it may be useful to analyze national and regional protected areas to ensure that power plants do not interfere with natural reserves. Secondly, if detailed information is available, the potential future expansion of the national grid should be evaluated. By doing this, it would ensure the deployment of off-grid systems only in locations where it is certain that the national grid is not likely to reach in the near future because, if it does, it will render the built system obsolete. Another improvement to the analysis can be made by submitting surveys directly to the local population for a better understanding of daily consumption habits and the readiness to embrace novel technologies in everyday life.

Additionally, measures for a more effective exploiting of the energy should be included. Let us consider the first case study, the one located on the Ugandan island with the purpose of powering a school. Its LCOE is quite high compared to the other two because of the intermittent use of power during the year due to the school closures. This clearly represents an inefficient use of resources, particularly in an area without access to the national grid, where the construction of new power plants is challenging due to the scarcity of capital and resources. For this reason, a strategy for a better use of energy should be evaluated, for example by giving the local population the possibility to access the school's services during the periods of closure, in order to offset the costs. Another solution could be the construction of a mini-grid in the area that allows the plant to fulfill multiple purposes.

This work allowed for a comprehensive overview of the works present in literature about energy policies and projects actuated all over the world. By integrating insights from various scenarios, it became feasible to draw solutions with a broader outlook and a wider knowledge. The focus was not on finding the most profitable investment overall but on identifying the best way to fund a particular investment. The choice of multiple case studies, diversified among themselves, instead of just one, allowed for validation of the methodology. In fact, this proved its effectiveness in different contexts, both from a technical and an economic perspective.

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