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Sylvain RENÉ

HAITI POWER BALANCE AND ENERGY TRANSITION: EXPANDING ACCESS TO ELECTRICITY THROUGH MICROGRIDS.

Santa Maria, RS
2022

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Disertation submitted to PostGraduation Program in Electrical Engineering Post-Graduation Program, Area of Concentration in Energy Processing, of Federal University of Santa Maria (UFSM), to obtain the **Master's Degree in Electrical Engineering Post-Graduation Program**.

Advisor: Prof. Dr. Gustavo Marchesan
Co-Advisor: Prof. Dr. Mauricio Sperandio

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Endereço: Rua Augusta, Nº 57, Camobi, Santa Maria, RS, Brasil, CEP: 97105-115.
Endereço Eletrônico: sylvainrene04@gmail.com

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Approved on August 29,2022:

Gustavo Marchesan, Dr. (UFSM)
(President/Advisor)

Mauricio Sperandio, Dr. (UFSM)
(Co-Advisor)

Jocemar Biasi Parizzi, Dr. (UNIPAMPA)

Fernando Guilherme Kaehler Guarda, Dr. (UFSM)

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ABSTRACT

HAITI POWER BALANCE AND ENERGY TRANSITION: EXPANDING ACCESS TO ELECTRICITY THROUGH MICROGRIDS

Author: Sylvain RENÉ
Advisor: Gustavo Marchesan
Coadvisor: Mauricio Sperandio

Electricity represents an essential vector towards economic, industrial and social development; the inaccessibility to electricity in a country already constitutes a precondition towards underdevelopment and poverty. Haiti is a developing country that suffers from several problems in its energy matrix. The majority of the Haitian population does not have access to electricity, especially the remote rural areas that are the main energy exclusions; the cost of extending the urban electricity network to rural areas remains prohibitive and unrealistic by 2030, as the network suffers from recurrent breakdowns and is unable to meet the consumption needs of these consumers. This lack of electricity constitutes a brake on the country's economic and social growth. Nevertheless, due to its geographical position, Haiti benefits from several renewable energy sources that constitute today a sustainable and ecologically reliable alternative, allowing to increase the access to electricity in the isolated rural areas of Haiti, while reducing the production of carbon dioxide in our atmosphere. The objective of this dissertation is to make a comprehensive assessment of the Haitian energy matrix and then develop sustainable energy solution approaches that can increase access to energy in remote rural areas of Haiti, where no electrical systems exist. Two solution approaches have been proposed in this work, firstly to facilitate access to electrical energy, via individual isolated micro-systems, that can reach households in rural areas that are economically unable to be connected to the interconnected system. Secondly, to develop a hybrid photovoltaic (PV)/Diesel system which constitutes an increasingly interesting alternative to the traditional solutions.

Keywords: Haiti electric system, rural electrification, renewable energy, photovoltaic microgrid, solar energy.

RESUMO

EQUILÍBRIO DE ENERGIA HAITIANA E TRANSIÇÃO DE ENERGIA : EXPANDINDO O ACESSO À ELETRICIDADE ATRAVÉS DE MICRORREDE.

Autor: Sylvain RENÉ
Orientador: Gustavo Marchesan
Coorientador: Mauricio Sperandio

A eletricidade representa um vetor essencial para o desenvolvimento econômico, industrial e social; a inacessibilidade à eletricidade contribui para o subdesenvolvimento e a pobreza. O Haiti é um país em desenvolvimento que sofre de vários problemas em sua matriz energética. A maioria da população haitiana não tem acesso à eletricidade, especialmente as áreas rurais remotas que são as principais exclusões energéticas. O custo de estender a rede elétrica urbana às áreas rurais permanece proibitivo e irrealista até 2030, já que a rede sofre com falhas recorrentes e é incapaz de atender às necessidades de consumo desses consumidores. Esta falta de eletricidade constitui um empecilho para o crescimento econômico e social do país. Entretanto, devido a sua posição geográfica, o Haiti se beneficia de várias fontes de energia renovável que constituem hoje uma alternativa sustentável e ecologicamente confiável, permitindo aumentar o acesso à eletricidade nas áreas rurais isoladas do Haiti, ao mesmo tempo em que reduz a produção de dióxido de carbono em nossa atmosfera. O objetivo desta dissertação é fazer uma avaliação abrangente da matriz energética haitiana e depois desenvolver abordagens de soluções energéticas sustentáveis que possam aumentar o acesso à energia em áreas rurais remotas do Haiti, onde não existem sistemas elétricos. Duas abordagens de soluções foram propostas neste trabalho: Primeira para facilitar o acesso à energia elétrica, através de micro-sistemas individuais isolados, que podem chegar a residências em áreas rurais economicamente incapazes de serem conectadas ao sistema interconectado. Segundo: para desenvolver um sistema híbrido fotovoltaico (PV)/Diesel que constitui uma alternativa cada vez mais interessante às soluções tradicionais.

Palavras-chave: sistema elétrico do Haiti, eletrificação rural, energia renovável, micro-rede fotovoltaica, energia solar.

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"Comes Lord Jesus !".

LIST OF ACRONYM AND ABBREVIATIONS

EDH	Electricité d'Haiti
LDC	Least Developed Countries
MTPTC	Ministère des Travaux Publics, Transports et Communications
UN	United Nations
SDG	Sustainable Development Goals
PV	Photovoltaic
BMEJ	Bureau des Mines et de l'Energie
UNDP	United Nations Development Programme
GDP	Gross Domestic Product
PREPOC	Plan de Relance Economique Post-Covid-19
MSME	Micro, Small and Medium Enterprises
PHARES	Programme Haïtien d'Accès des Communautés Rurales à l'Énergie Solaire
HDI	Human Development Index
ECVMAS	Enquête sur les Conditions de Vie des Ménages après le Séisme
ONPES	Observatoire National de la Pauvreté et de l'Exclusion Sociale
GW	Giga Watt
GWh	Giga Watt hour
TW	TeraWatt
TWh	TeraWatt hour
EJ	Exajoule
UNCED	United Nations Conference on Environment and Developmen
IePF	Institut de l'Energie et de l'environnement de la Francophonie
IEA	International Energy Agency
AIEA	International Atomic Energy Agency
CO^2	Carbon Dioxyde
NOAA	National Oceanic and Atmospheric Administration
RAEW	Rural Electrification and Empowerment of Women
LCOE	Levelised Cost Of the generated Electricity
OECD	Organisation for Economic Co-operation and Development
WHO	World Health Organization
UNFCCC	United Nations Framework Convention on Climate Change
IRENA	International Renewable Energy Agency
IMF	nternational Monetary Fund

MPPT	Maximum Power Point Tracking
TPES	Total primary energy supply
MEF	Ministere de l'Economie et des Finances
OECD	Organisation for Economic Co-operation and Development
LNG	liquefied natural gas
PPSELD	Project for Sustainable Electricity Distribution
NRECA	National Rural Electric Cooperative Association
PSDH	Strategic Development Plan of Haiti
RAEW	Rural Electrification and Empowerment of Women
ANARSE	Autorité Nationale de Régulation du Secteur de l'Energie (ANARSE)
ESMAP	Energy Sector Management Assistance Program
GWEC	global renewable energy community
OLADE	Latin American Energy Organization
PWM	Pulse Width Modulation
REN21	Renewable Energy Policy Network for 21st Century
LNG	Liquefied Natural Gas
PPA	Power Purchase Agreements
BRH	Banque de la République d'Haïti
IDB	Inter-American Development Bank
LDC	Least Advanced Countries
GWEC	Global Wind Energy Council
NGO	Non Governmental Organization
Gt	Giga Tons

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1 INTRODUCTION GENERAL

In 1882, after the inauguration of the first electric factories for the production of direct current, built by Thomas Edison in London (Holborn Viaduct) and New York (Pearl Street), it became impossible to conceive of any pole of development and economic growth without first thinking of electricity, as this became a daily necessity in our lives. Electricity may be considered as one symbol of modernity and of a certain industrial revolution that brings a type of technical and economic progress. Nowadays, electrical energy represents a consumer good in its own right and has become greatly indispensable for its contributions in changing daily habits and improving the people life quality. The functioning of all public and private bodies are totally dependent on electrical energy; To this effect, the slightest electrical failure has considerable economic and social consequences, since electrical energy is essential for the functioning of industries, transportation, heating, lighting, hospitals, stores, banks, etc.). Taking into account the usefulness of electrical energy, there are valid reasons to consider electricity as the essential vector of economic and industrial development. The existence of the electricity in a country is already an asset towards the growth of the economy and attracts investment; conversely, a deficiency in electrical energy is an indicator that repels investment and discourages potential investors from undertaking productive activities that can contribute to the development of local industries, businesses, schools, health centers, etc. As mentioned above, it has played a preponderant and crucial role in the creation of wealth in the major industrialized countries of the world such as the USA, China, Japan, France, Canada, Brazil, Mexico, etc. Also in the progress of the least developed countries (LDCs) and developing countries, located in Africa, South America, including the Caribbean. It is even possible to state that life without electricity is impracticable, especially in the more modern and sophisticated cities. Specifically, Haiti is a country in great economic difficulty and in serious energy crisis, where the lack of energy is a major obstacle to its economic and social development. The problem of electricity is recurrent in the country, while having serious consequences on the material conditions of existence of the Haitian population, increasing a very high unemployment rate in the country. The shortage of electricity and repeated power failures are among the scourges that undermine Haiti, slow down its development and fuel the riots that regularly shake the country (FLOIRAC, 2020). It is an anomaly that in the 21^{st} century, more than eight million people in Haiti do not have access to electricity. Haiti is the only country in the Caribbean with an electrification rate of less than 47% and the only state and territory in the Americas with the lowest per capita electricity consumption in 2020 (ATLASOCIO, 2019) [see table 2.10]. Also, is the country using the highest rate of biomass as energy source of the American continent (PAUYO, 2017) The little electrical infrastructure that exists is mostly found in urban centers where there is a large concentration of services; While remote rural areas are left out. If nothing is done to improve the quality of electricity production and distribution, Haiti will have difficulty reaching the United Nations Sustainable Development Goals by 2030. The objective can be reached by exploiting renewable energy sources in Haiti (wind, solar, hydro, biomass and geothermal), which can help increase the accessibility of energy throughout the country, particularly in rural areas that are completely without electricity infrastructure. In order to reduce the chronic blackout that plagues the country, multiple large public energy development projects have been implemented by the Haitian State during the last decade. These projects aimed to diversify and increase energy production capacity, renovating the existing power plants, developing the energy mix from hybrid micro-grids based on renewable energies, improving the supply and distribution of electricity in the country, while reducing the costs related to production, etc.

Despite all this, the problem remains, even to get worse, because Haiti remains until now the only country in the Americas with a low rate of access to energy. According to data from the World Bank, about 57% of the population, or more than 6 million people in Haiti have no access to electricity. The part of the population that does have access to electricity lives in urban areas and receives this electricity intermittently, as the availability of electricity is highly fluctuating energy may only be available for a few hours a day even in the largest cities. There are many neighborhoods in the urban area that can go for days or even weeks without energy.

This lack of electrical energy is a major obstacle to the socioeconomic development of the country and of Electricité d'Haïti (EDH), a company on the verge of bankruptcy. It is now necessary to analyze the context of evolution and the global dependence of electrical energy, which is unquestionable for the well-being of humanity and its importance in the economic and social development of a country. Taking into account the importance of energy to the socioeconomic recovery of a country, it is therefore extremely important to study this subject and to see the global context with regard to energy production and global climate data in the first place; secondly, to analyze the current and evolving context of energy production in Haiti in specific context: the Sustainable Development Goals of the United Nations (SDG7) for 2030. These document makes the analysis of the energy balance of the country, to identify the energy resources, the sectors of consumption as well as of the national energy potential, determination of the profile of Haiti's load, and finally to determine the best alternatives for the energy production in Haiti.

1.1 GENERAL OBJECTIVE

The general objective of this dissertation is to discuss viable and sustainable solutions based on the exploitation of renewable energies. The solution should propose the access to electrical energy to the most isolated people; to optimize production while guaranteeing the quality of the energy produced; It should also contribute to reduce public expenditure in terms of importing fuels on the international market, while moving towards a form of energy that is without impact on the ecology of the country.

1.2 SPECIFIC OBJECTIVE

- Analyze the Haitian national energy policies;
- Elaborate a scientific document that can serve as a reference for students, researchers and all those involved in the Haitian electrical network;
- Promote the use of renewable energies as a sustainable solution in the energy matrix of Haiti;
- To allow an easy understanding of the EDH problem in order to solve it easily;
- To encourage discussion on Haiti's energy difficulties in order to seek the best solution;
- To propose a sustainable and reliable solution to solve the blackout in the city of Abricots area.

1.3 MOTIVATION

Haiti is a developing country which suffers from several problems in its energy matrix. Most of the Haitian population does not have access to electricity and even those that do have it suffer from recurrent blackouts. Nevertheless, due to its geographical position, Haiti enjoys several renewable energy sources, such as solar and wind. Thus, a comprehensive study of the Haitian energy matrix and the proposal of appropriate solutions to the particularities of this country is essential. This work should propose solutions for increasing access to electricity in Haiti as well as mitigating blackouts.

1.4 METHODOLOGY

This document is a scientific and technical research paper presenting a synthesis made through the sources of documentation that are already available; also, by analyzing existing data through Internet sites providing reliable data. Many documents consulted in this work provide information on the state of operation of the Haitian electrical system, including economic and social characteristics. The global diagnosis of electricity has been analyzed and presented in this paper, as well as its impacts on the socioeconomic and developmental conditions of Haiti; I have proposed types of photovoltaic microgrids as a reliable and sustainable alternative, which can increase access to electricity in rural areas, while reducing production costs. In this case, in this paper, we studied the different characteristics of microgrids that can promote access through isolated house areas and in urban communities of the country.

1.5 MASTER THESIS ORGANIZATION

- In the first chapter of the document, there is a general introduction of the themes studied in the document; the general and specific objectives, the motivation and the methodology
- In chapter II: a review of the global situation of Haiti on the geographical and territorial, demographic, economic and social levels; including a global diagnosis of the current energy production in the country.
- In chapter III: we made an analysis of the potential renewable energies in Haiti; we made a review of these different renewable energy sectors and their level of contribution to the global energy matrix of the country.
- In chapter IV: we emphasized mainly on the electrification of the rural regions of Haiti; we made alternative proposals and undertake a feasibility study of a hybrid micro-grid that can contribute to increase the electrical energy in rural areas of Haiti, taking the community of Abricots as a pilot project.
- In chapter V: the conclusion; In this chapter, the sustainable energy solutions were proposed that could contribute to the improvement of electricity production in Haiti.

2 GLOBAL SITUATION OF HAITI

2.0.1 Review of literature

The history reveals that Haiti is the first Caribbean country, in which is located the first electrified city of the Caribbean region; and this, well before the existence of many of the countries of the world. In fact, since 1895, 13 years after the creation of the first electric network in New York by Thomas Edison (in September 1882), in the city of Jacmel (southern region of Haiti), a mini electric power station (Jedo) was installed, which operated with natural coal from France. In January 1896 this mini electric power station already had more than three hundred (300) subscribers (BIJOUX et al., 2021). From 1911 - 1914, which coincided with the First World War, under the initiative of Narbal Boucard, decided to stop importing coal from France to operate the power plant, and transformed the Jedo plant into a private hydroelectric plant (1914).

A little later, in August 1909, the decree authorizing the formation of the Compagnie d'Eclairage Électrique, which supplied the inhabitants of Port-au-Prince and Cap-Haïtien, was issued in the West (BIJOUX et al., 2021).

The first generator was introduced in Haiti in Jacmel in 1895, it could provide a power of 1 270 kW. In 1910, the city of Port-au-Prince began to enjoy the benefits of electricity. The production of electrical energy was carried out by private companies until it was taken over by the Haitian state with the commissioning of the Péligre hydroelectric power station in 1971 and the creation of the autonomous body called Electricité d'Haïti (BME, 1989). When making the energy assessment of Haiti, it's necessary to make the history of energy in Haiti, by consulting the documents that have been written. It is necessary to review the country's energy literature, as well as Haitian legislation, in order to better diagnose and identify the problem.

In the document : Haiti Sustainable Energy Roadmap by world Institute, Haiti electricity projections assume an annual growth in electricity demand of 9% from 2012 to 2020, and of 13.4% from 2021 to 2030, to reach a total of 6 500 GWh by 2030 (WORLDWATCH-INSTITUTE, 2014). Based on this annual demand, peak demand is estimated to exceed 1 GW by 2030, indicating that Haiti will need to add significant new capacity in order to secure demand at peak times of the day over the next 20 years (WORLDWATCH-INSTITUTE, 2014).

The experts of the study recommend the installation of 604 MW additional renewable energy, composed of 27% hydroelectricity and 14% solar and wind energy. The study that renewable energy will certainly be able to meet more than 90% of Haiti's electricity demand while reducing energy costs and with less than USD 7 billion of investment between 2013 to 2030 (UNDP, 2019).

In this section, is presented a general diagnosis of the Haitian energy system; To begin, a presentation of the socioeconomic conditions of Haiti is essential in the analysis, in order to better understand the context in which the country evolves, namely the territorial occupation of the country (territorial division, urbanization, geo-economic conditions of the citizens, etc.). Then, a review of Haitian energy, population evolution and the macroeconomic situation is presented.

2.1 GEO-LOCALISATION

Haiti is a Caribbean country which has an extent of (27 750 km^2); It is located in the western part in the Northern Hemisphere. Its territory is geographically divided today into 10 departments and 145 communes, 571 communal sections (rural areas), and 64 neighborhoods (HAITIREFERENCE, 2001). This figure (2.1) represents all departments and the territorial administrative division of Haiti.

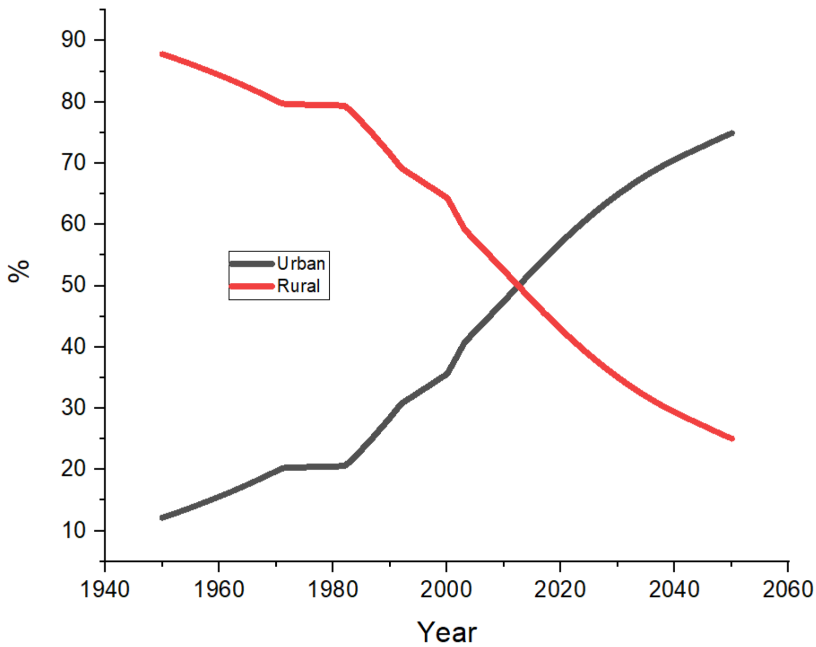
Figure 2.1 – Map of Haiti departments

Source: (MONTELEONE; BONACCORSO; MARTINA, 2020)

2.1.1 Demographic factors of Haiti

According the Population Division of the Department of Economic and Social Affairs of the United Nations, urbanization is defined as a complex socioeconomic (figure 2.2) process that transforms the built environment, converting formerly rural into urban settlements, while also shifting the spatial distribution of a population from rural to urban areas (POPULATION.DIVISION, 2019). Urbanization also designates the historical phenomenon of the transformation of society which manifests itself by an increasing concentration of the population in urban agglomerations. It is measured by the number of inhabitants in cities in relation to the total population, the population density, the territorial extension of cities and its consequences on the way of life (ORSENNA, 2017). With regard to urbanization, until 1950, 12.17% (or 392 000 people) of the Haitian population lived in urban areas and 87.83% (2 829 000 people) in rural areas (UN-WU, 2018):

Figure 2.2 – Movement of the Haitian population during a centennial (1950 - 2050)



Source: (UN-WU, 2018)

From that same year, Haiti began to register a vertiginous demographic increase and an impressive displacement of population, moving from rural areas to urban areas, especially to the country's capital, which concentrates the main economic and political activities. No region of Haiti is unaffected by the mass exodus of the population, motivated by the search for employment and better living conditions. Depending on the curve (figure 2.2), it is expected that by 2050, approximately 74.93% (10 520 000) of the population will live in urban areas at the expense of the rural population which will decrease to a percentage of 25.17% (or 3 521 000).

The figure (2.2) shows the growth and internal migration of the Haitian population from rural to urban areas. In fact the exodus of the population is mainly to the capital of Port-au-Prince, which is now a highly overpopulated city. In an interval of 70 years, the urban population has overtaken the rural population. In 2020, the urban population was 57.09% (or 6 492 000 people) and the rural population was 42.91% (or 4 880 000 people). According to the world bank report, each year, as many as 133 000 Haitians are becoming city dwellers (W.BANK/IBRD, 2017); Mass migration from rural to urban areas can be interpreted as follows:

- Rapid growth of the urban population;
- Lack of basic social services in rural areas, such as electricity, drinking water, etc.
- Underdevelopment of rural areas
- Centralization of services and a concentration of all institutions in the metropolitan area.

2.1.2 Urbanization of Haiti

With respect to land use planning, Haitian cities today are overpopulated and suffer from significant deficits in infrastructure and in services ; It develops without coordination or regulation, which increases to their exposure to the risks of natural disasters (W.BANK/IBRD, 2017). In the last few years, we have witnessed the anarchic expansion of Port-au-Prince of which has become a set of very unhealthy slum areas because almost all of the beautiful neighborhoods are crowned with slum areas, this is the degradation of the way of life of the inhabitants. Haiti is the third country with the highest urbanization rate in the Latin America and the Caribbean, behind Trinidad & Tobago and Mexico (W.BANK/IBRD, 2017). The table (2.1) shows the territorial distribution across the ten departments, by population and size of the territory in the year 2020 : The most urbanized regions of Haiti are the West area at 87%, the North area at 66%, the Artibonite area at 57%. In 2020, Port-au-Prince accounts for 24.53% of the total population of Haiti (WORLD-POPULATION, 2022). Most of the country's public investment and basic infrastructure are located more than 35% of primary and secondary schools, nearly 75% of colleges and universities, more than 50% of hospitals, more than two-thirds of banks, 80% of electrical capacity, and more than 70% of manufacturing industries (BERNADIN, 1999).

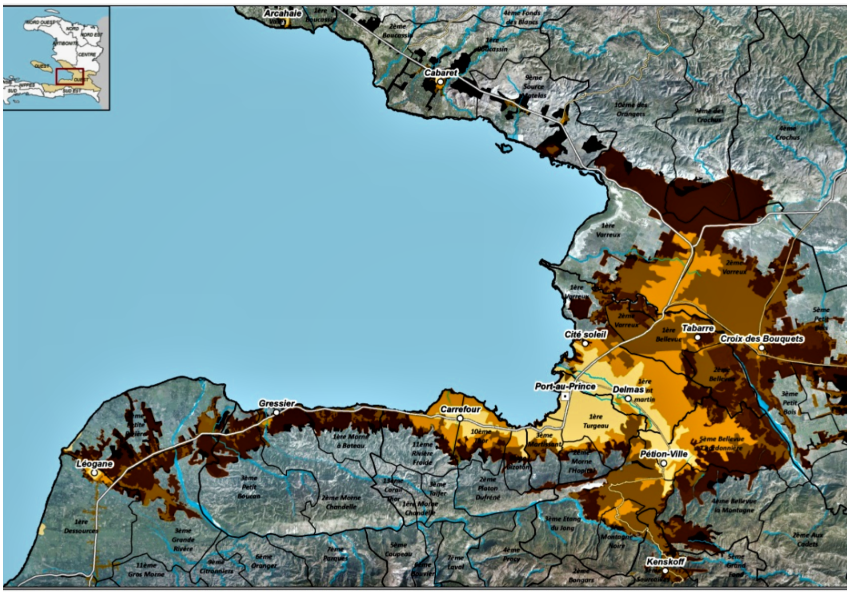
Table 2.1 – People by region in Haiti

Classification	Department	Area km²	Population
1	West	4 983	4 029 705
2	Centre	3 487	746 236
3	Artibonite	4 887	1 727 524
4	North-East	1 268	342 525
5	South	2 654	774 976
6	North	2 115	1 067 177
7	North-West	2 103	728 807
8	South-East	2 034	632 601
9	Grand'Anse	1 912	468 301
10	Nippes	1 268	342 525

2.1.3 Overview of Haiti's urban areas and main challenges

Port-au-Prince is the main center of all the country's economic activities, since it is where almost all the main public and private institutions, such as airports, ports, industries, commercial centers, etc. It houses almost all of the country's institutions : hospitals, two-thirds of the banks and 3/4 of higher education, and 80% of the energy consumed in the country (J.M.THEODAT, 2020).

Figure 2.3 – Development of the urban area of Port-au-Prince between 1980 and 2016

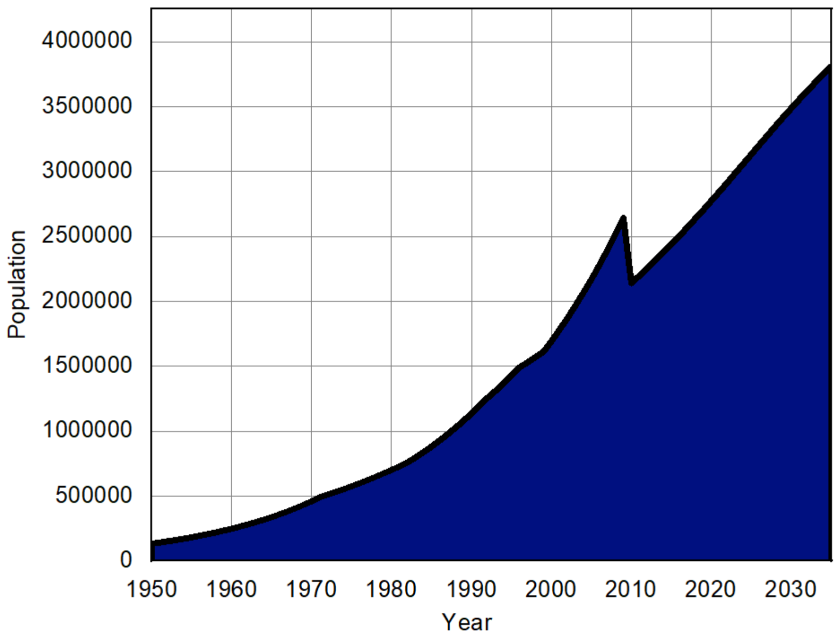


Source: (URBAYITI, 2018)

It is until now the main destination of migration and rural exodus and faces many challenges that penalize its economic development and make the living conditions of its inhabitants extremely difficult(URBAYITI, 2018).

In figure (2.3) present par (TAMRU; MILIAN, 2018), one can easily notice a high concentration of the population in the urban areas, while the rural areas are almost empty; Port-au-Prince was built in 1749 on an area of 36.04 km^2; From 9 400 inhabitants in 1789, the city's population grew to 60 000 inhabitants in 1927, then to 136 000 inhabitants in 1950, 2 million in 2003 inhabitants and approximately 2 915 276 inhabitants in 2022 (THEODAT, 2022). Despite the lack of energy, drinking water, and other basic infrastructure and social services, in 2022, the city of Port-au-Prince ranks 169^{th} among 1 187 most populated cities in the world, with a growth of 2.51% over the year 2021 (WP, 2022). Being already greatly overpopulated, the increase in population coincides with slumming and an increase in the need for basic social services, notably electrical energy.

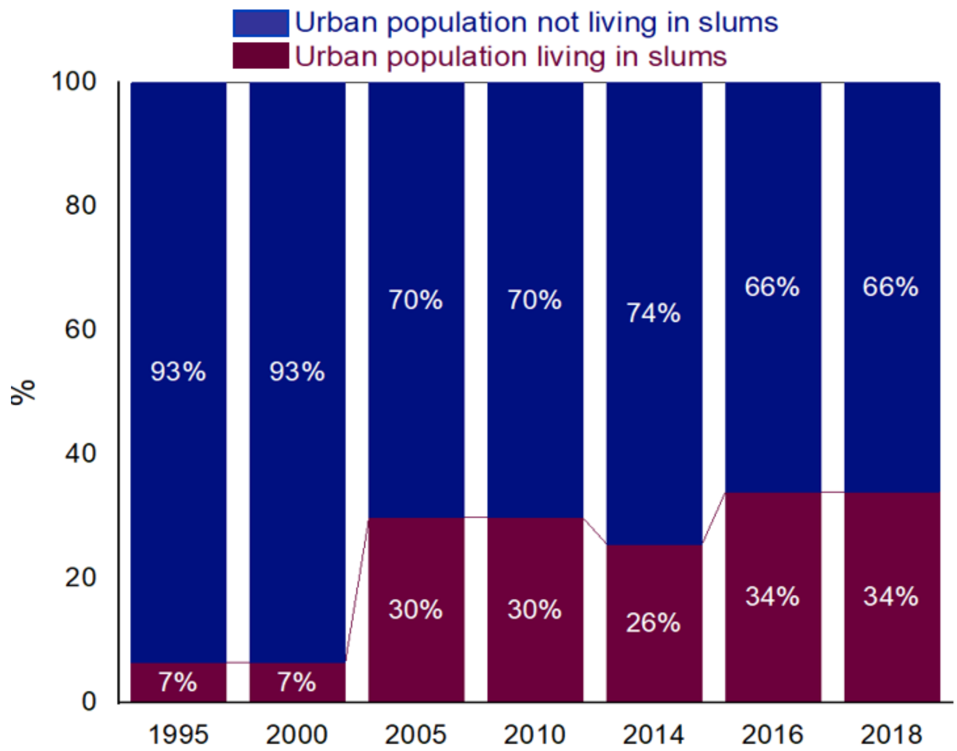
Figure 2.4 – Population forecast of the urban area of Port-au-Prince between 2000 to 2035



Source: (WORLDPOPULATION, 2022)

In the figure (2.4), it is easy to see that a population decline occurred during the year 2010 when a devastating earthquake of magnitude 7 and 7.3 on the Richter scale caused a real disaster on January 12, 2010, destroying thousands of buildings and making, according to estimates, more than 220 000 people dead, more than 300 000 were injured and more than 600 000 people left the disaster area to seek refuge elsewhere in the country (GOYET; SARMIENTO; GRUNEWALD, 2011). However, the population starts to increase again in Port-au-Prince from this year or a few months after. With a variable growth rate per year, the population projection of Port-au-Prince until 2034 is projected to 3 809 537 inhabitants as figure (2.4) (WP, 2022). Therefore, the problem of urbanization, overpopulation and rural exodus are real problems that cause the expansion of slums, with many precarious neighborhoods, with a very unhealthy environment; In this case, the penetration of basic services are difficult to access. According to statistics, throughout the urban areas of Haiti, the majority of the population is still living in slums, in precarious neighborhoods; According the (figure 2.5), it can be said that the population increases, the number of inhabitants increases proportionally through the slums.

Figure 2.5 – Urban population living in slum or not households

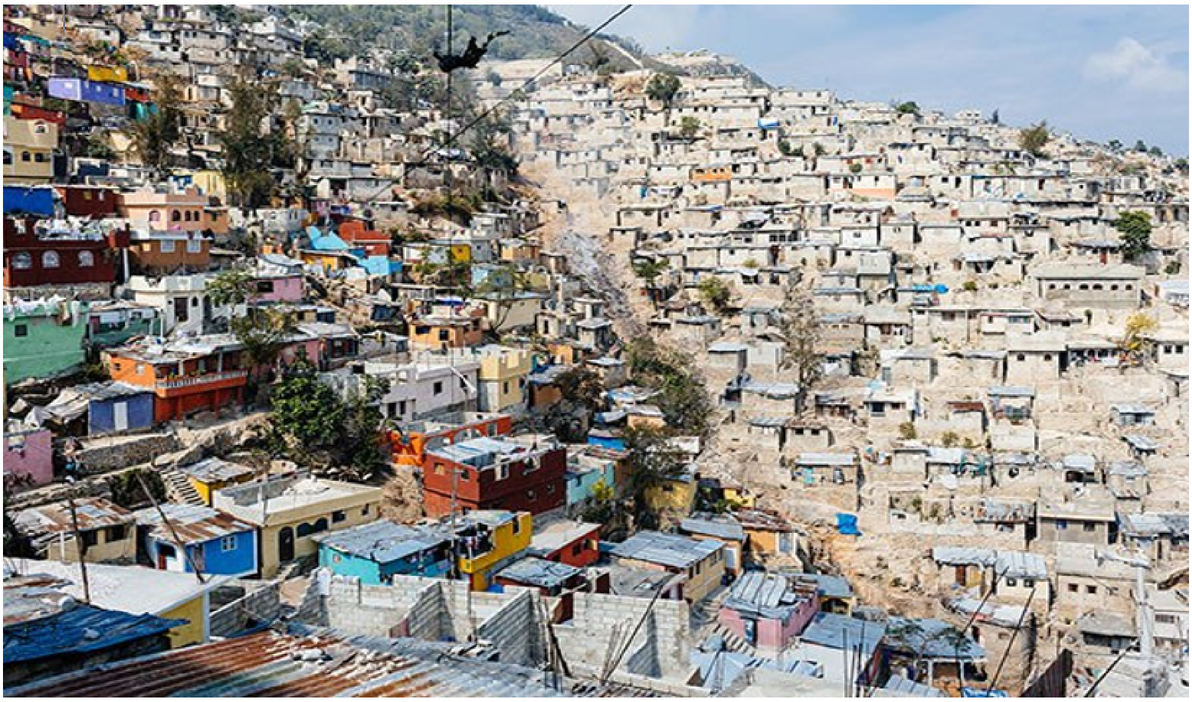


Source: (OURWORLDINDATA, 2022)

The norms of constructions are not respected at all; Moreover, the houses are built in inappropriate places, and very near from each other; which makes difficult the penetration of the electric energy in the slims areas. The urban area of Port-au-Prince presented the following characteristics (URBAYITI, 2018):

- Development of informal settlements : (more than 60% of the inhabitants of the urban area occupy areas unsuitable for urbanization and risky such as slopes of the hills;
- Generalized under-equipment in terms of infrastructure: difficult access to water, sanitation, electricity;
- Unequal distribution of services and economic activities on the territory.

Figure 2.6 – Scam construction in precarious neighborhoods in Port-au-Prince



Source: (RTBF, 2012)

The figure (2.6) shows how the environment of the capital of Port-au-Prince is notably surrounded by precarious neighborhoods with informal settlements, which are densely populated such as: Baillergeau, Fort Mercredi, Village de Dieu, Cité l'Eternel, Village de Dieu, Cité Plus, Fort National, Carrefour-Feuilles, Belair, Savane Pistache, Bois Jalousie, Cité Maria, Cité Sainte-Marie, Cité Soleil etc. In these underprivileged neighborhoods, the billing of basic services such as drinking water and electricity are not recoverable, because many people do not have conditions to pay for it.

2.1.4 Overview of Haiti's rural areas and main challenges

The rural area of Haiti is inhabited almost entirely by the poorest and most disadvantaged, both socially and economically, i.e. the peasants. It is considered as a marginalized regions, totally devoid of any infrastructure and basic services such as access to drinking water, electricity or other public services. In terms of housing, the peasants live in house that they build themselves, each on their own plots of land, using mostly dry straw for construction, as well as sheet metal, wood or plastic. Until now (2022), rural households have had only kerosene, candles and, in some businesses, diesel-powered generators to meet their lighting and electricity needs. Indeed, 91% of rural households and 75% of the urban poor do not have electricity (PREPOC, 2020). Two problems remain and prevent the penetration of energy in rural areas of Haiti:

- The majority of houses are not suitable for electrical installation due to their fragility.
- Because of their totally precarious socioeconomic conditions, the peasants are in great difficulty to pay their consumption bills. This being said, we must implement reliable energy solutions, facilitating the integration and access to all to electrical energy in accordance with the (SDG7), 7^{th} goal of Sustainable Development Goals by the UN (United Nations), ensure universal access to affordable, reliable and modern energy services (UN, 2018); Which is also adapted to the economic situation of people in very precarious living conditions throughout the rural areas of Haiti. The figure (2.7) shows the types of house hat are predominantly found throughout rural Haiti:

Figure 2.7 – Two types of Rural House

House made of dry straw in rural Haiti

Widely isolated house in rural Haiti

2.1.5 Electrification plan for Haiti

The damage and losses causes by the earthquake (2010) are estimated at nearly 7.9 billion US dollars, which is equivalent to just over 120% of the country's gross domestic product in 2009, according to the assessment of losses and damages produced (GOVERNMENT, 2010). About 1.5 million people, representing 15% of the national population, were directly affected (GOVERNMENT, 2010). As part of a vision and guidelines for the post earthquake rebuilding of Haiti, the Head of State at the time defined a long-term vision for the development of Haiti, with a view to rebuilding the Haitian Nation by transforming the disaster of January 12, 2010 into an opportunity for Haiti to become an emerging country by 2030 (GOVERNMENT, 2010). In this document entitled : Plan d'action pour le relèvement et le développement national d'Haïti, les grands chantiers pour l'avenir (Action Plan for National Recovery and Development of Haiti, major projects for the future), it was inserted a policy along 3 axes, and access to energy and priority one of the pillars that at first glance can allow the country to achieve these objectives (GOVERNMENT, 2010):

- Economic reconstruction: revival of national production, restoration of economic and financial circuits, access to electricity.
- Social rebuilding: health - food security - nutrition - water - sanitation, labor-intensive activities.
- Institutional rebuilding: democratic institutions, restarting the administration, justice and security.

According to the Energy Sector Development Plan 2007 - 2017 (PLAN, 2006), drafted jointly by EDH, Bureau des Mines, with technical assistance from the International Atomic Energy Agency (IAEA), with regard to the energy sector; the Haitian government's objectives are defined as follows:

- To support the recapitalization of companies in difficulty (the case of EDH for example);
- Improve and modernize the management of public enterprises in key sectors, including EDH;
- Improve the production and distribution of electricity in the country;
- Strengthen the state's standardization role in key sectors of the economy, including energy;
- Prepare and implement the reforms required to create an enabling environment for local and foreign investment;
- Prioritize a significant improvement in the country's electricity supply;
- Promote alternatives to wood energy and encourage the development of renewable energy including energy forests and other biomass sources.

With respect to the electricity sub-sector, the Government of Haiti has established the following priority objectives for Electricité d'Haiti, an important public utility the following priority objectives for Electricité d'Haïti, an important public utility (PLAN, 2006):

- A management contract with clear performance criteria for the company;

- The provision of electrical service for at least 12 hours a day in the Port-au-Prince metropolitan area and in the rest of the country;
- The increase of the revenue from 47% to 75% for the next 15 years and the increase of the commercial profitability of the company;
- The stabilization of EDH and the establishment of the necessary conditions for its recovery;
- The improvement of the quality of electricity and service provided to customers;
- Reducing technical losses and increasing efficiency;
- Reducing fraud and theft of electricity.

In the Plan Stratégique de Développement d'Haïti (Strategic Development Plan for Haiti), the recovery of the energy sector is one of the main pillars on which the Haitian State must react in its public policy; To achieve this, the program targeting the electrification of the country therefore provides for the implementation of four sub-programs relating to (MPCE, 2012).

1. Increasing the capacity of electrical energy production;
2. Increasing the capacity of electrical energy transmission;
3. Increasing the distribution capacity of electrical energy;
4. Improving the marketing of electrical energy.

2.1.6 The existing situation and main energy challenges in Haiti

The poor access to electric energy in a developing country like Haiti is one of the major challenges to its development. In fact, the existence and the conditions of production of electric energy in Haiti are greatly precarious and alarming. Although the situation is critical, it does not cease to worsen continuously for multiple, variable, complex and recurrent reasons. From this observation, the equitable access to all to electricity is still far from being a reality in Haiti because the country is confronted with enormous electricity crises. We must also believe that the existing poverty in Haiti is also a consequence of the lack of access to energy; This being said, we must address the energy problem in order to eradicate the chronic and severe poverty that plagues Haiti. In another project document drafted by the UNDP in agreement with the Ministère des Travaux Publics, Transports et Communications (Ministry of Public Works, Transport and Communications), including the Bureau des Mines et de l'Energie (Office of Mines and Energy) in the framework of a project developed and entitled: Rural Electrification and Women's Autonomy, starting in January 2018 and ending in December 2022, they made allegations, namely that Haiti is facing a serious energy crisis, characterized by numerous factors, among others:

- The burden on the economy of importing of fuels (finished product);
- A very low per-capita consumption and a very high consumption intensity (energy consumption per GDP);
- A low rate of access to electricity;
- Non exploitation of available renewable resources.

These allegations are partially true, but do not take into account all the complexities of the problem. When one makes the global diagnosis of the Haitian electrical system, there are a lot of constant, recurrent, major and complex constraints and challenges that make it difficult the development of a stable and efficient electrical network. From the documents of evaluations of the Haitian electrical sector, the data collected prove that the rickets of the Haitian electrical network is fundamentally due to infrastructural, technical, political, financial, legal, economic and climatic constraints. How to make Haiti emergent by 2030, without a stable and efficient electrical network, where the availability of energy is perceived as a rare commodity.

In the Plan de Relance Economique Post-Covid-19 pour la période 2020 - 2023 (Post-Covid-19 Economic Recovery Plan for the period 2020 - 2023) - PREPOC 20 - 23, the Government has decided to address the energy crisis and to take the necessary measures so that the Haitian population will eventually have access to modern and affordable electricity 24 hours a day. Achieving this result requires interventions in the existing electricity networks and also off-grid interventions (PREPOC, 2020). It states that in the sparsely populated rural areas of Haiti, which should not be connected to centralized electricity production and distribution systems, decentralized systems will have to be implemented through the development of micro-grids and the promotion of individual or collective solar systems to meet the energy needs of households and businesses located in isolated areas. In this document, mini and micro-grids operating primarily from renewable energy resources (solar, wind, hydro, biomass) are appropriate to provide not only electricity to meet domestic needs, but also to promote economic activities and foster the emergence of micro, small and medium enterprises (MSME). A major program is underway in this sense since 2019 and is financed by the IDB for an amount of USD 38 million and provides among other things, the development of decentralized mini-grids according to (PREPOC, 2020):

- The Haitian government will have to support the development of mini and micro network programs and promote the establishment of public-private partnerships between municipalities and private operators in order to support and ensure their viability in the short and medium term through incentives.

- The Government will also have to clarify and strengthen the regulatory framework for the supply and marketing of these electricity services very quickly.
- The Government should strengthen the anchoring of this approach by diligently implementing the mini-grid project within the framework of the PHARES.

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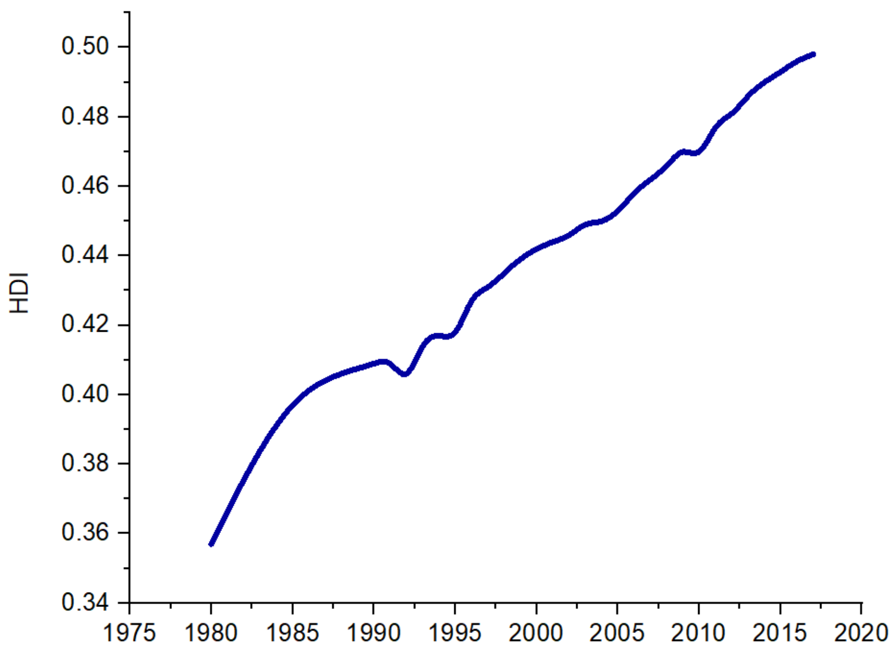
2.1.7 Socioeconomic condition of Haiti

Haiti remains the poorest country in the LAC (Latin America and the Caribbean) region and among the poorest countries in the world. In 2021, Haiti had a GDP per capita of USD 1 815, the lowest in the LAC region and less than a fifth of the LAC average of USD 15 092 (WORLD-BANK, 2022). According to the UN Human Development Index, Haiti is ranked 170 out of 189 countries in 2020, with a IDH of 0.510 (2019) less than of 6/10 (See the figure (2.8)).

Figure 2.8 – Human development Index of Haiti (1980 - 2017)



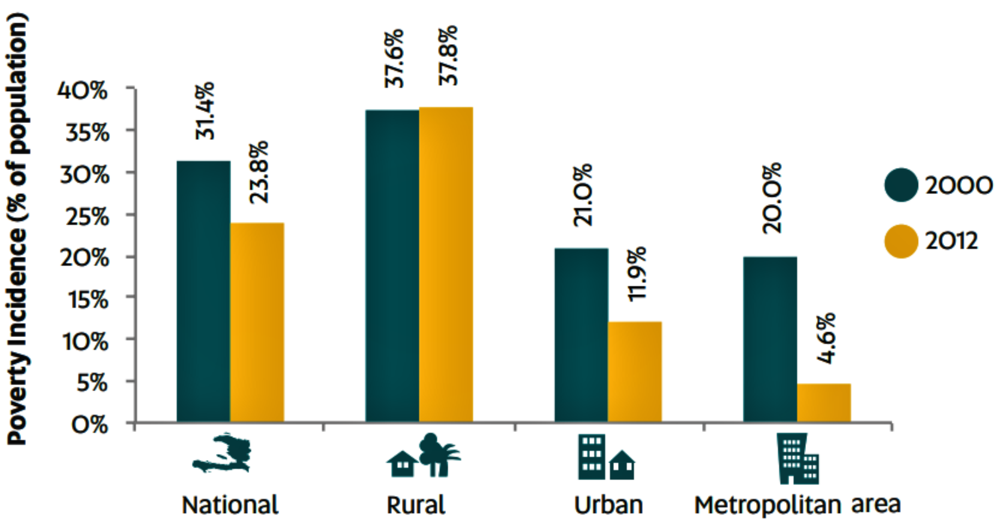
Source: (HDI, 2022)

In this regard, we must take into account the low purchasing power of the majority of the population is hit by extreme and absolute poverty, as 70% of the population lives on less than USD 2 per day (World Bank) 50% with less than USD 1 per day (AD'OCC, 2022); Underemployment affect 60% of the population. According to (HDI, 2022), the Human Development Index (HDI) of Haiti in 2019 is 0.510/1 which places the country in the lowest human development. This analysis takes into account health longevity, life expectancy at birth, knowledge or education, and standard of living. The figure (2.8) shows the annual evolution of Haiti's HDI since 1980 to 2017 according (PNUD, 2020).

2.1.8 Poverty indices in Haiti

The rural people of Haiti are characterized by extreme poverty personified, as their income is clearly below the poverty line. As main sources of income, they practice subsistence agriculture, archaically cultivating a plot of land for the cultivation of makeshift gardens, being able to ensure their survival in terms of food and send the surplus to the market in order to obtain some income. The poverty profile presented in the figure (2.9) explains the depth of it in relation to the urban, rural and metropolitan area of Port-au-Prince, using data on poverty thresholds and rates, established in 2013 from ECVMAS surveys (WORLDBANK; ONPES, 2014). According the data of the World Bank and ONPES in the (figure 2.9), at the national level, the extreme poverty rate declined from 31% to 24% between 2000 and 2012. Indeed, the extreme from 21% to 12% in urban areas and from 20% to 5% in the Metropolitan Area, while it stagnated at 38% in rural areas (WORLDBANK; ONPES, 2014).

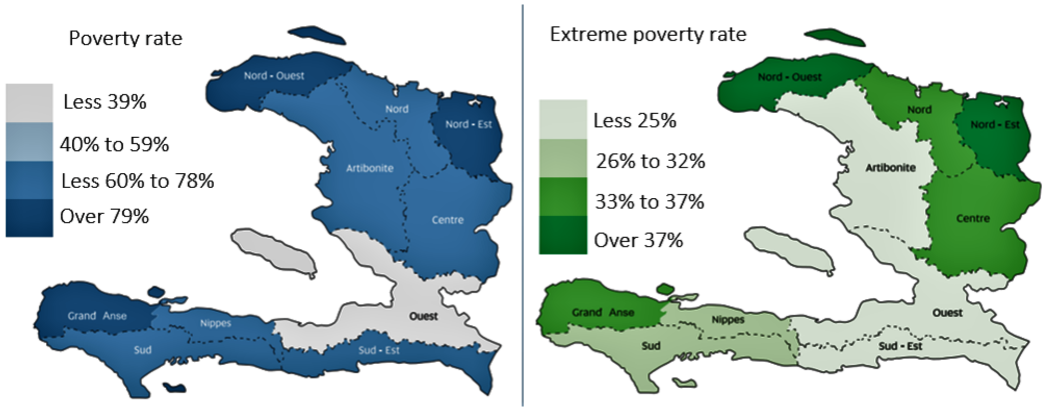
Figure 2.9 – Evolution of extreme poverty in Haiti, 2000-2012



Source: (WORLDBANK; ONPES, 2014)

In 2021, poverty likely increased to 87.6% of its population lives on less than USD 6.85 per day; And 58.7% lives on less USD 3.65 per day and 30.32% when using the extreme poverty line USD 2.15 per day (WORLD-BANK, 2022). The current situation of Haiti is particularly representative of the social, economic and energy challenges faced by the entire region. Multidimensional poverty, economic insecurity, unemployment, a very low standard of living and lack of access to electricity are national issues. According to ONPES and World Bank, the map (2.10) represents the distribution of poverty by geographic department in Haiti (WORLDBANK; ONPES, 2014):

Figure 2.10 – Poverty map of Haiti

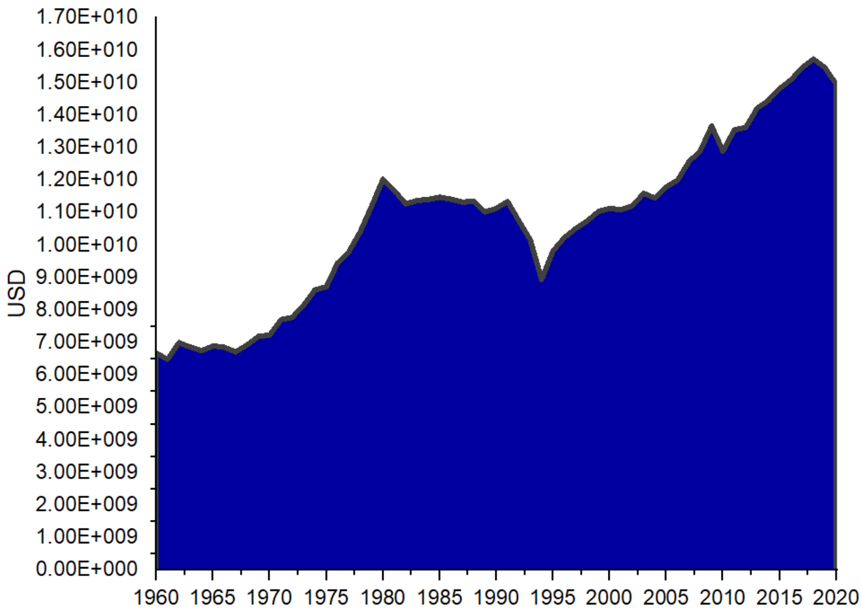


Source: (WORLDBANK; ONPES, 2014)

2.1.9 GDP of Haiti

GDP is an indicator that measures the wealth created in a country over a given period of time. It can be analyzed from three angles: production, income and demand. Haiti is one of the smaller economies and is currently ranked 115^{th}. If this is calculated per inhabitant taking into account the purchasing power parity, then Haiti is in the list of the world's richest countries in place 154^{th} and the inflation in Haiti was in 2021 at around 16.84% (WORLDDATA, 2021); It reached an all-time high of 25.2% in 2020, due to the sharp depreciation of the gourde at the beginning of the pandemic, leading to a rise in imported inflation (DGT, 2022). Indeed, the wealth created by a country is a wealth produced that allows to constitute the income that will feed the demand. According to data from (WORLDBANK.ORG, 2022), Haiti's Gross Domestic Product will grow slightly over the years 1960 - 2020:

Figure 2.11 – Haiti, GDP in billion dollars 1960 - 2020



Source: (MADDISON, 2022) Our World in Data, with all data of the World Bank and OECD

2.1.10 GDP per capita

GDP per capita is one of the key indicators of economic performance; It measures economic activity economic activity or income per person. GDP per capita is a general indicator of average living standards or economic well-being and is calculated by dividing the value of GDP by the number of people in a country (Table 2.2). GDP per capita (PPP based) is gross domestic product converted to international dollars using purchasing power parity rates and divided by total population. An international dollar has the same purchasing power over GDP as a USD (Measured in constant USD, which adjusts for inflation); In the table (2.2), we can see all GDP per capita of Haiti during the year 2016 and 2020 is very low compared with the world average (WORLDBANK.ORG, 2022):

Table 2.2 – GDP Per capita of Haiti during 2015 - 2020

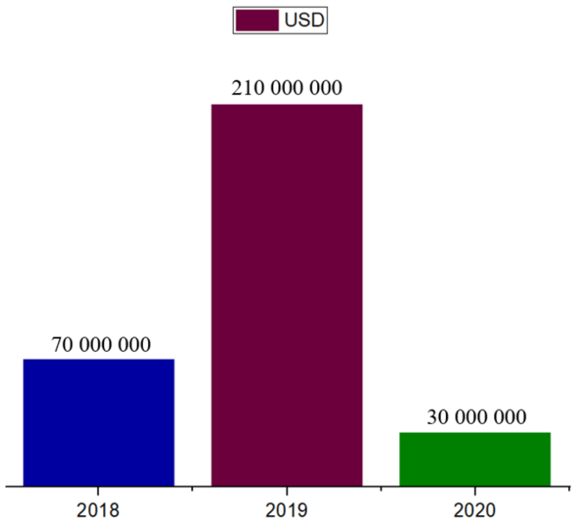
Year	GDP (USD)	GDP Per capita (USD)	World Average
2016	15 102 001 152	1 393.18	10 390.6
2017	15 481 102 336	1 409.63	10 620.97
2018	15 739 297 792	1 415.00	10 848.13
2019	15 474 153 472	1 373.88	11 012.92
2020	14 956 794 880	1 311.71	10 540.36

Source: (OURWORLDINDATA.ORG, 2022) with data of the World Bank & OECD

2.2 HAITI, OIL-BASED PRODUCT CRISIS IN THE LAST FEW YEARS

The Haitian energy crisis has been going on for a long time as a poor country and importer of petroleum products which is characterized by a great energy insecurity; Has serious consequences on the living conditions of the Haitians, also on the economic growth, the commercial development, the hospitals, the schools, etc. thus imposing to the government colossal financial efforts to restore the operating conditions of the sector (figure 2.12).

Figure 2.12 – Haiti, Fossil-fuel subsidies, 2015 - 2020



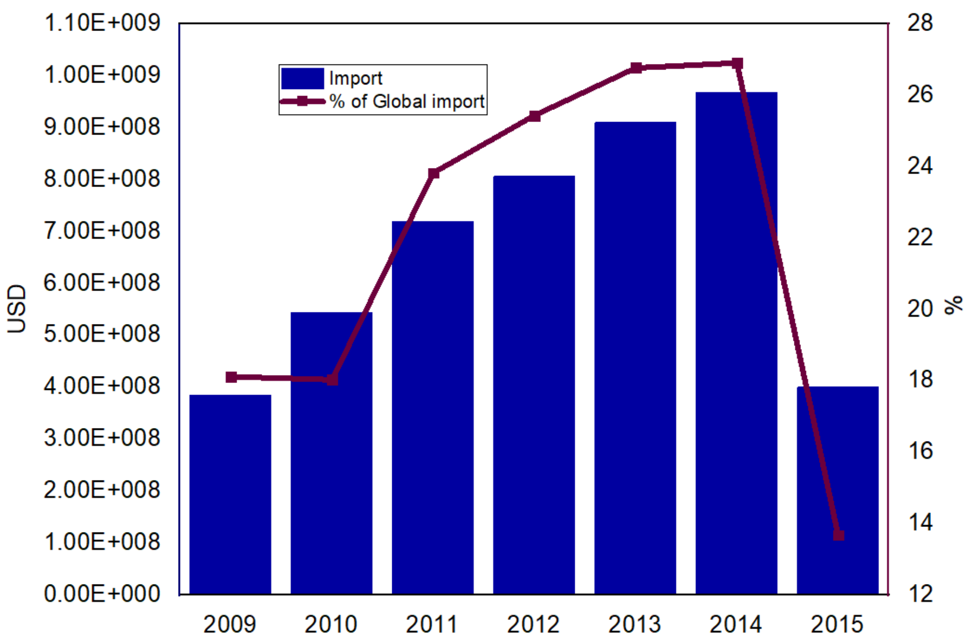
Source: (IEA-OECDI, 2022)

From a national point of view, petroleum products are a transversal and strategic product because the functioning of the public and private administration, the electric factories, the transport depend almost entirely on petroleum products. Haiti's fuel consumption needs amount to 900 000 gallons per day (equivalent to 20 000 barrels); Equivalent to 28 million gallons per month or 336 million gallons per year according to (SAINT-VIL, 2022). In fact, the variation of the costs of petroleum products on the international market has serious consequences on the level of energy production. According to figure (2.12) from, the pretax subsidy for fossil fuels by Haiti being a poor country, (measured in millions of nominal USD) amounts to USD 69.92 million in 2018; USD 205.18 million in 2019 ; And USD 31.29 million in 2020, with the objective of contributing to the reduction of greenhouse gases in our atmosphere. The figure opposite shows the amount of subsidy of petroleum products by Haiti (IEA-OECDI, 2022). The main hydraulic, solar, wind, and biomass resources that constitute the energy wealth of Haiti are so far under-exploited, which could allow the country to be self-sufficient only through renewable energies. To this end, it is obvious that the energy crisis has an immediate correlation with the existing poverty in Haiti, and which more than half of Haitians are struck by extreme and absolute poverty.

2.2.1 The dilemma of oil product supply

Haiti has no domestic production of crude oil or refining capacity. As a result, all necessary petroleum products are imported. The petroleum products sub-sector, which represents only 20% to 25% of the national energy supply, consumes more than 35% to 50% of the country's external revenues. Haiti's energy matrix is essentially composed of thermal power plants equipped with rotating machines that use diesel or fuel oil. Diesel generators represent 65% of the country's electrical production. This represents a high cost in terms of the import of fuel for the operation of thermal engines, which makes the country dependent on the import of oil for the electricity it generates (LUCKY; AUTH; OCHS, 2014). The choice of fuel and the control of the flow of supply and consumption remain a major handicap and are part of the problems that plague the growth of EDH, since the energy produced by the thermal power plants depends heavily on the oil markets and the policy of purchase prices by the importers or by the Haitian state. This being said clearly, the Haitian state was forced to finance the import of fuel, while enduring the fluctuations of prices on the international market. The figure (2.13) represents the import of oil in current USD and percent of total import of Haiti:

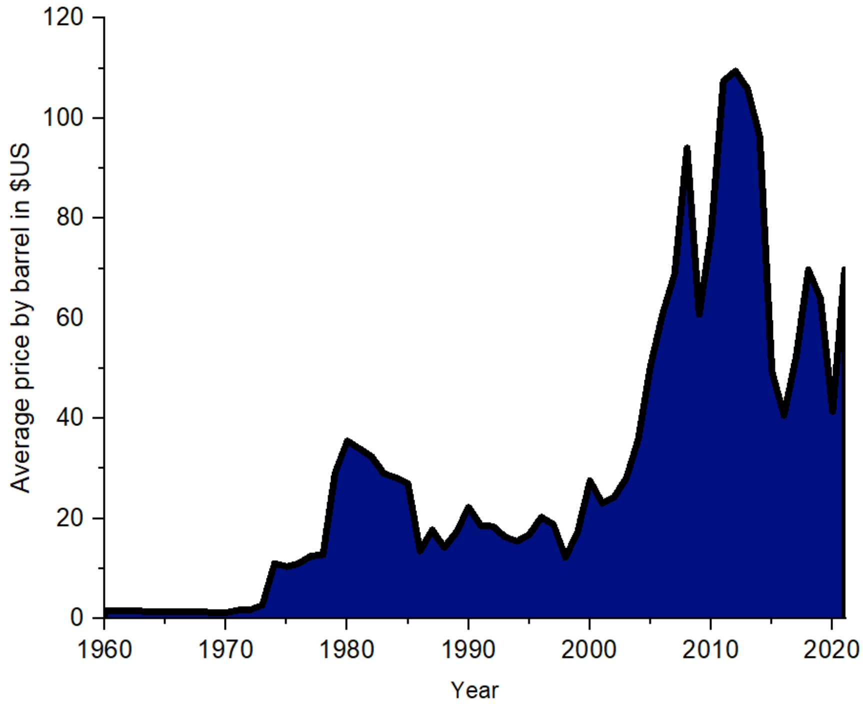
Figure 2.13 – Haiti, annual fuel import (2005 - 2015)



Source: (PERSPECTIVEMONDE, 2022)

We cannot talk about the production of electrical energy without ignoring the fuel crisis, which is a recurring, major and factual problem facing the country, because the Haitian power plants are generally thermal. Haiti is an importer of petroleum products; The fuel crisis is a major and recurring problem in Haiti. In 2006, the country joined the Petro-Caribe alliance. This is an agreement between Venezuela and the Caribbean countries, which consists of a loan in the form of oil. According to this agreement, the countries involved in the agreement will have to repay Venezuela over a period of 25 years. Thus, Venezuela is committed to supplying oil to Haiti, which will have to pay under very advantageous conditions, according (MICHEL, 2018). However, this Petro-Caribe fund has been squandered by bad governance and propels the country into a very heavy debt to Venezuela for the next few years; Moreover, because of the financial sanctions taken by the U.S administration against Venezuela, Haiti does not receive any more of its oil; Thus, the last shipment was in April 2018. After the earthquake of 2010, the Haitian state decided to freeze the prices of oil sold in Haiti; Thus, when the prices of gasoline increase on the international market, the state proposes to pay the difference, so that the prices paid at the pump remain stable. The figure (2.14) presents the variation in the average price of OPEC crude oil between 1960 to 2021. In 1960, the price of crude oil per barrel was USD 1.63; In 2012, the price per barrel was USD 109.45; While in 2021, the price per barrel was USD 69.72.

Figure 2.14 – OPEC, fuel price fluctuations (USD per barrel)



Source: (STATISTICA.COM, 2022)

Recurrently, inflation and price fluctuations on the international market cause great economic panic and episodic scarcity of fuel, for several weeks. The population being economically incapable, with a very low purchasing power is opposed to the adjustment of fuel prices; Economists as well as public transport drivers' unions, reject any possible increase in the prices of petroleum products in Haiti and force the government to subsidize petroleum products in order to keep the price stable and unchanged. Quite often, the shortage of fuel causes violent demonstrations and anger among the population, which always reacts quite violently. The (figure 2.15) were taken during a period of fuel shortage in 2022:

Figure 2.15 – Fuel shortage in Haiti

The government has finance the increases on each gallon so that the population can buy the product at the same price, taking into account that the increase in fuel prices on the local market, in this economic context could lead to serious consequences on the population, the majority of which lives in extreme and absolute poverty. However, this fuel subsidy represents a heavy burden for the public treasury, as each month costs the Haitian government more than 9 billion of Gourdes (YVES, 2022).

Since the end of the Petrocaribe program with Venezuela, Haiti has had to import fuel from other countries. In recent years, the price of fuel has risen on the world market, however, the Haitian government is tightly caught between a rock and a hard place, with a bone of contention as to whether to continue to subsidize the price of fuel, which is further impoverishing the country, or to adjust the prices at the pump. Exhausted, the Haitian government ended the subsidy during the year 2018, follows a brutal riot of July 6 and 7, 2018 caused by a sudden increase in prices of petroleum products at the pump. In turn, the country was totally paralyzed for 3 months (commonly known as Peyi lock). As a result, total paralysis of the energy sector, transportation, hospitals, factories etc. According to this source (GLOBALPETROLPRICE.COM, 2021), where the price of fuel at the pump is thus (see table 2.3):

Table 2.3 – Haiti, cost of fuel in 2022

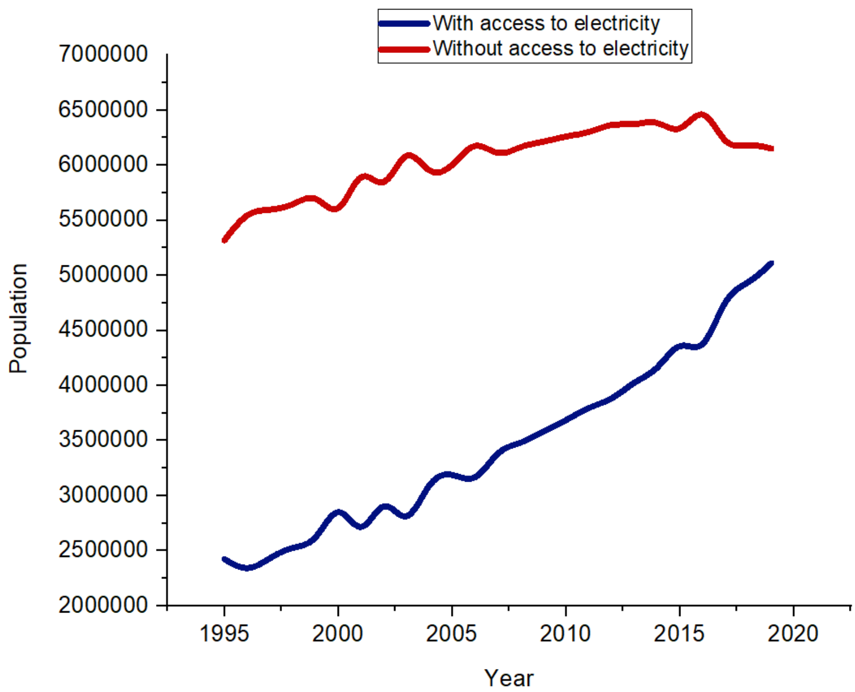
Fuels	Cost (Gourdes)	Cost (USD)
Gasoline	570	4.054
Diesel	670	4.766
Kerosene	665	4.728

Source: (GLOBALPETROLPRICE, 2022)

2.2.2 Haiti, Energy accessibility by quantity of population

Access to energy is an indispensable condition for poverty reduction in the world (KOUCOÏ, 2017); In 2019, more than half of the Haitian population no have no access to electrical energy; Haiti's electrification rate remains the lowest in the northern hemisphere and in the Latin America and Caribbean region. In this case, the number of people without access to energy has varied over the last few years. However, in recent years, the percentage of access to energy has been gradually increasing (see figure 2.16); However, the curve of people without any access to electricity tends to decrease; According this graph shows the evolution of the numbers of people without access (red curve) and with access (black curve)to electricity in Haiti from 2005 - 2019.

Figure 2.16 – Haiti, electricity access by quantity of population



Source: (UNWPP, 2019)

According all data, it increases from 26% in 1990 to 37% in 2010 and was estimated at 45% in 2018 and 46.93% in 2020 (OURWORLDINDATA, 2022). This increase in electrical coverage is mainly achieved from the implementation of a few hybrid micro-grids that are installed throughout some regions of the country. These variations suggest the combined effects of population growth and the energy production deficit. With such a rate of increase in access to electricity, Haiti should reach universal coverage after 2070 (PREPOC, 2020). However, despite the progress in terms of people having access to energy in the last few years, in 2019, the number of inhabitants with access to electricity was 5.2 million inhabitants and the number of inhabitants without access to electricity was 6.2 million inhabitants and totally outside the electrical networks (UNWPP, 2019). The situation of Haiti's energy balance shows a very low level of production in relation to the installed power, largely insufficient to meet the demand for loads; In particular in rural areas, the electrical coverage is less than 2.2% (WORLD.BANK, 2020). Barely 30% of households have access to the electricity network, often intermittently and at prohibitive rates, half of which are illegal.

At the moment, World Statistics place Haiti among the least electrified countries in the world; this is significantly behind the countries classified by the UN as Least Developed Countries, with a per-capita consumption 4 times lower than the average consumption of these countries. This situation considerably hinders the country's ability to carry out development expenditures, especially in infrastructure such as health, education and other basic needs such as access to drinking water and electrical energy. As cities grow in population, the challenge of financing inclusive and sustainable urban development becomes increasingly complex. The poor performance of the energy sector is due in part to inefficient management and the lack of a sustainable energy policy. According to data collected by the World Bank, this table shows the progression of the level of accessibility of electrical energy in Haiti from 2014 to 2019:

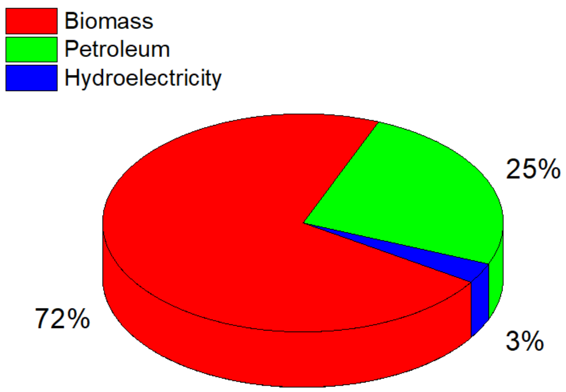
Table 2.4 – Electricity access by population in Haiti

Year	Total Population	Energy Access (%)	Rural area (%)	Urban area (%)
2014	10 549 007	39.5	2.3	74.6
2015	10 695 540	40.8	2.5	75.6
2016	10 839 976	40.4	no data	76.4
2017	10 982 367	43.3	3.1	77.9
2018	11 123 183	44.4	3.0	79.0
2019	11 263 079	45.4	2.6	80.5

2.3 GLOBAL ENERGY OFFER IN HAITI

In 2012, Haiti's overall energy supply consisted of 72% biomass (firewood and charcoal), 25% petroleum products (conventional energy resources imported, liquid and gaseous oil products and sometimes mineral coal) and 3% hydroelectricity (DELUSCA, 2020) figure (2.17).

Figure 2.17 – Haiti, Global Energy Offer (2012)



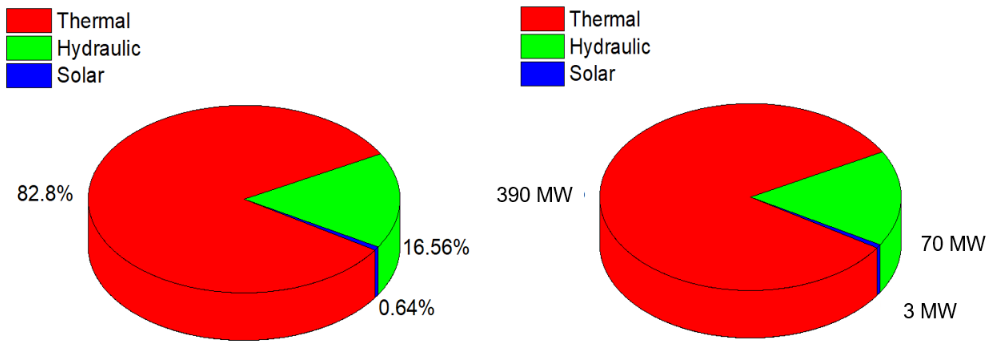
According the BME, the most important energy sources in Haiti are the Biomass, which accounted for 75% of final energy consumption for all sectors in the year 2000 (PLAN, 2006). The largest amount of wood energy and charcoal (80%) is used in the domestic sector, mainly for cooking. In fact, electricity (3%) represents a small part of Haiti's global energy offer, because in rural areas, biomass (firewood, charcoal, cane bagasse, others organic waste, ...) represents almost the only energy source, allowing rural people to cook their food, for lighting, etc.

2.3.1 Energy mix of Haiti

The energy mix of Haiti is dominated at 82.9% by thermal sources and 17.10% by renewable sources (OLADE, 2021). The figure (2.18) shows the installed power total in the country according to different sources in 2020 in Haiti:

In 2020, the installed capacity in Haiti is divided as follows: thermal 390 MW, hydroelectricity 70 MW, Solar 3 MW; While the needs for the whole country would be 800 MW (according Evenson CALIXTE, Director of ANARSE (National Authority for the Regularization of the Energy Sector)(FLOIRAC, 2020) In 2015, 89% of the production consumed in Port-au-Prince and 96% in others regions came from conventional thermal power plants (PREPOC, 2020). A slight increase in energy mix was made during the year 2020 and is represented as follows: Thermal production 82.8%; Hydroelectricity 16.56%; Solar energy 0.64% (See figure 2.18).

Figure 2.18 – Installed capacity by source in Haiti (2020)

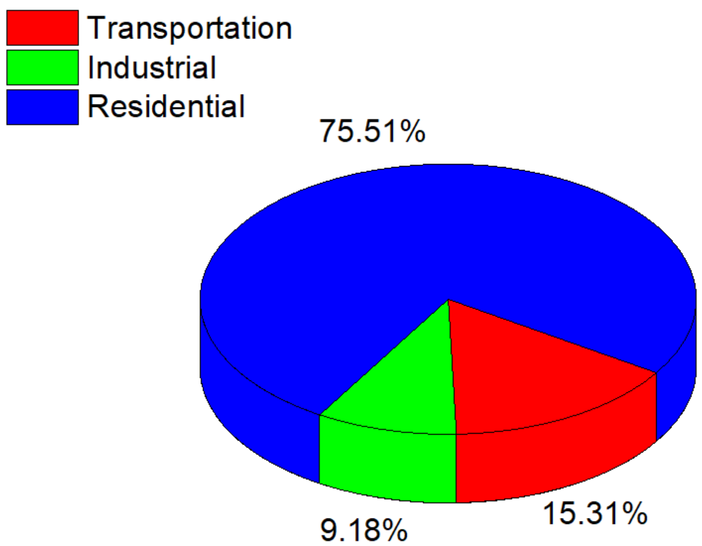


Source: (OLADE, 2021)

2.3.2 Electricity consumption in Haiti, by sector, 2011

The figure (2.19) refers to the global energy that was consumed and losses in 2020 in Haiti by sector according to data collected by (OLADE, 2021). Energy is mainly consumed through the residential sector, with the transport sector in second place and the industrial sector in third place. Note that the growing need for electrical energy for lighting, refrigeration and cooking, hospitals, etc., is not currently being met with electricity from the grid. In relation to this problem, all sectors of society are deeply affected and has serious implications on the sociological conditions of Haiti. The unmet need for electrical energy is driving investment out of the country, being a prerequisite for attracting investment; The consequences of this are unemployment and poverty.

Figure 2.19 – Electricity Consumption in Haiti, by Sector, 2020

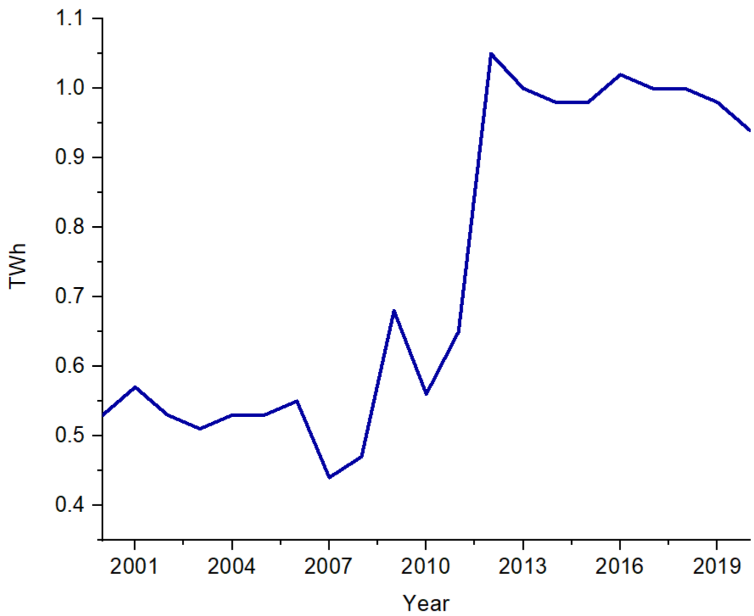


Source: (OLADE, 2021)

2.3.3 Evolution of the electric generation by year in Haiti

Electricity generation (figure 2.20) is entirely insufficient to meet demand over the last few decades in Haiti; This being said, it does not take into account population growth and new commercial investments:

Figure 2.20 – Haiti, electricity demand evolution (2000 - 2020)



Source: (BP-OWID, 2022)

In the figure (2.20), we can see the annual variation in electricity production with its highs and lows of production, depending on the political situation, the availability of fuels, etc. The study projects that the gap between supply and demand will gradually narrow, with generation increasing by 7.9% to 2 782 GWh in 2028 (WORLDWATCH, 2014).

2.3.4 Power generation by source in Haiti (2020)

Electricity production in Haiti is predominantly provided by thermal power stations, hydraulic energy, and solar energy. The evolution of the country's production capacity is estimated approximately at 1 059 TWh in 2020, distributed in this way: Thermal 970 GWh, Hydraulic 88 GWh, solar 1 GWh (table 2.5).
However, until the year 2020, despite a slight increase, the electric system cannot fully satisfy a demand of 1 000 GWh; to achieve this, the existing production should be doubled

Table 2.5 – Power generation capacity by source in Haiti (2020)

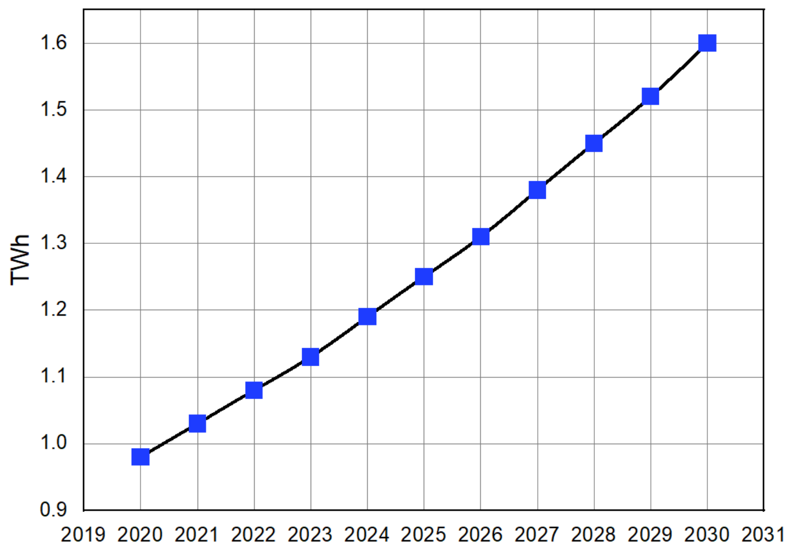
Energy Source	GWh	%
Thermal	970	91.59 %
Hydraulic	88	8.33 %
Solar	1	0.08 %
Total	1059	100%

Source: (OLADE, 2021)

for the next 6 years, providing a stable and affordable energy for people with low purchasing power.

The figure (3.6) shows the total energy production of Haiti from the year 2000 to 2020. In 2012, Haiti's total energy production experienced the highest level of consumption (1.05 TWh); However, from that date on, consumption decreases (see figure 3.6) and during the year 2019 and 2020, the total energy consumption was 1 TWh.

Figure 2.21 – Electricity demand forecast (2020 - 2030)



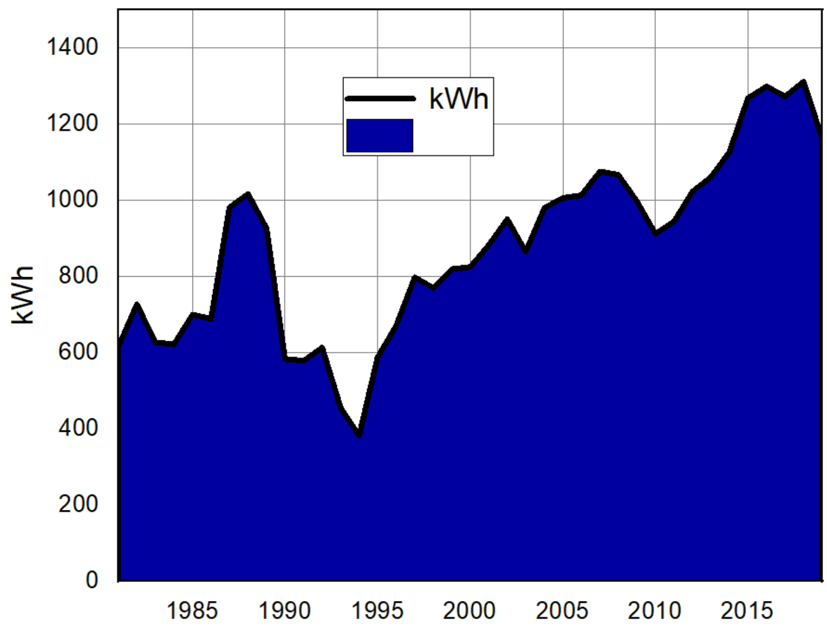
The demand is increasing due to the galloping demography and rapid urbanization, as cities are developing in an anarchic way and increase the pressure on the EDH (PAUYO, 2017); By 2030, in a positive scenario electricity consumption will increase as a result of population growth and new demand from industry and other sectors in a positive scenario. Based on existing demand, a projection of demand for 2030 can be made, using the 5% per year growth rate usually used by EDH in projections.

It should be noted that this projection does not take into account future installations and needs; this scenario is based on the energy that is currently available; with such a production rate, the electrical consumption will not exceed 1.60 TWh in 2030, according to the availability of consumption 1 TWh in 2020, although the need will be greater to meet all the needs of the country (figure 2.21).

2.3.5 Energy consumption per-capita (without electricity)

Approximately, 80% of Haiti's energy needs are met by local resources (firewood and charcoal 71%, bagasse 4% and hydroenergy 5%) according to the Bureau des Mines et de l'Energie (BME). Petroleum products contribute the remaining 20 percent of the annual demand for fuel. To meet this demand, between 12 and 30 million trees are cut down each year, which is equivalent to a consumption of between 3.4 and 3.7 million tons of fuel-wood (1.6 million to 1.8 million tons of oil equivalent)(BME, 1989). In the figure (2.22), we can see the level of consumption for each person varies from one decade to another; This can be explained by the availability of energy in the country; Also by an increase in population across the country. The energy used per person in Haiti during 2019 is 1 164 kWh, significantly lower than the world average is 21 154 kWh; The figure (2.22) shows the the energy consumption per person in Haiti: (BP-SRW, 2022):

Figure 2.22 – Haiti, energy consumption per-capita from the year (without electricity)



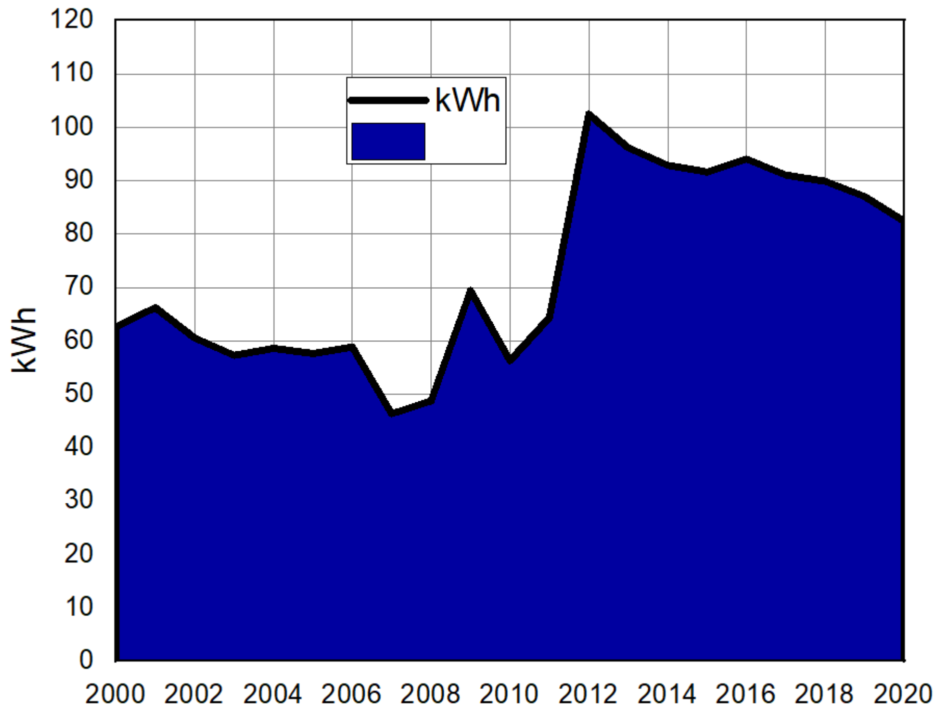
Source: (BP-SRW, 2022)

2.3.6 Haiti, Per capita electricity generation

Haiti is among the countries with a very low level of per-capita consumption; In 2014, it was ranked last (142^{th}) in the ranking of the world's states by electricity consumption per-capita out of 142 countries. In the world ranking, Haiti is ranked among the countries with the lowest rate of electricity consumption per capita in the world. The electricity used per person in Haiti during 2020 is 83 kWh, significantly lower than the world average is 3 429 kWh.

According the figure (2.23), we can see the energy precariousness exists among the most vulnerable people that exist in the country, because this level of consumption is not distributed in an equitable way to all (OWID, 2022):

Figure 2.23 – Haiti, energy use per-capita from the year 2000 - 2020



Source: (OWID, 2022)

2.3.7 Installed power capacity by department in Haiti

According to the data made available, in 2019, the total installed capacity in Haiti is 413.52 MW. Table (2.6) shows the level of production available in each of Haiti's departments, in relation to regional electricity coverage and the size of the population.

Table 2.6 – Distribution of electricity production throughout the national territory

Classification	Region	MW	Surface	Population	%
1	West	269.07	4 983	4 029 705	65.02
2	Centre	54	3 487	746 236	13.1
3	Artibonite	19.47	4 887	1 727 524	4.7
4	North-East	18.45	1 268	342 525	4.5
5	South	15	2 654	774 976	3.6
6	North	15	2 115	1 067 177	3.5
7	North-West	8.38	2 103	728 807	2.0
8	South-East	6.25	2 034	632 601	1.5
9	Grand'Anse	6	1 912	468 301	1.4
10	Nippes	1.9	1 268	342 525	0.5

2.4 GENERAL CONSTRAINT OF ELECTRIC SYSTEM OF HAITI

From an review of literature on the energy sector of Haiti, the data collected prove that the rickets of the Haitian electrical network is fundamentally due to constraints of energy, infrastructural, technical, political, financial, legal, economic and climatic orders. The accumulation of facts prove that the EDH is a totally precarious company from the following constraints:

2.4.1 Constraint of the non-availability of energy

The accessibility of energy in rural areas is regressing [(See table 2.4)]. Furthermore, even in regions where there is a presence of electrical networks electrical energy is not always available to meet the needs of users. The instability of the grid and the fluctuating prices of fuel (oil) on the international and local markets to run thermal engines causes incessant blackouts.

2.4.2 Constraints of Inter-connectivity of the grid

There is no national electricity transmission power grid, as there is no interconnection between the central power grid and the regional power grid. The electricity system is made up of separate mini-networks, scattered throughout the country. With the exception of Peligre, which is a large hydropower station, Haiti's generating fleet is made up mainly of a variety of thermal generation facilities, each with its own characteristics, which does not facilitate management of the power system. The physical structure of the network is equally vulnerable; The electric cables and poles used in the transfer of power have sometimes fall, due to lack of maintenance.

2.4.3 Technical constraints, losses and recovery

The quality of service provided by EDH is deplorable because of daily rationing and untimely cuts. Breakdowns are common, due to broken conductors and exploding distribution transformers as a result of overloads caused by network non-technical losses (PAUYO, 2017). On the other hand, the cost of production is expensive and technical losses on the network are enormous due over current caused by the clandestine connections on the distribution lines (PAUYO, 2017). EDH's network has significant transmission and distribution losses. The total loss rate is estimated at 70% according HaitiPriorise (BELT et al., 2017). This number is extremely high by international standards; Approximately 30% of electricity losses in Haiti are technical and result from the inefficiency and overloading of the national grid (WORLDWATCH, 2014). The remainder of Haiti's transmission and distribution losses are non-technical, resulting from illegal connections and EDH's inability to collect tariffs from some customers. See table 2.7 (BELT et al., 2017).

Table 2.7 – Electric losses by power grid in geographic region

Region	Total Losses in (%)
Jeremie (Grand'Anse)	17.7
Cayes (South)	33.5
Petit-Goâve (West)	57.8
Jacmel (South-East)	6.9
Port-au-Prince (West)	59
Saint-Marc -Gonaives (Artibonite)	74.2
Mirebalais-Hinche (Centre)	49.6
Fort-Liberté (North-East)	16.8
Cap-Haitien (North)	63.6
Port-de-Paix (North-West)	21.3

Source: (BELT et al., 2017)

The table (2.7) contains the loss rate revealed during the study across the ten independent and unrelated EDH distribution networks, which experience average technical and recovery services losses. It was reported that several power plants are at a standstill, others are vandalized and in Peligre only one of the three turbines is working. The public company is unable to obtain fuel for the operation of several diesel engines. In some cases, the equipment is old and spare parts are no longer produced for these engines. In order to alleviate this problem October 2010 to September 2011, the total energy produced in, switching to prepaid meters is a must because EDH must stop selling on credit (ALPHONSE, 2022). In Haiti was approximately 875 GWh. The table (2.8) shows the distribution of energy during this period (W.BANK, 2012).

Table 2.8 – Losses and recovery

Distribution	GWh
Technical losses	175
Commercial losses	425
Energy billed but uncollected bills	83
Bills collected	193
Total	875

Source: (W.BANK, 2012)

2.4.4 Political and financial Constraints

1. Absence of continuity in the government's decisions on development of the sector and lack of transparency in the governance of the sector;
2. The absence of a sustainable energy policy, focused on the exploitation of renewable energy sources in the production of green electricity, such as solar, wind, biomass and hydraulic; EDH, as a public institution that manages the production, distribution and billing of electricity is a company on the verge of bankruptcy (ALTERPRESSE, 2011). EDH's revenue is close to USD 6 million per month while expenses hover around USD 17 million per month, which represents close to USD 11 million in (monthly) deficits for the company according (ALTERPRESSE, 2011). Generally it is the public treasury that allows EDH to absorb its losses (ALTERPRESSE, 2011). In this case, until now, EDH represents a heavy financial burden for the Haitian economy; In the 2020 - 2021 budget, the country is forced to fund 16 billions of Gourdes annually. (NOUVELLISTE, 2019); The subvention of EDH is larger than the budget allocations of the Ministries of Agriculture, Environment, Tourism, and Social Affairs combined (NOUVELLISTE, 2019). This situation has greatly ruined the country's economy.

2.4.5 Constraints of law

Non strict application of Article 70 of the decree of February 3, 2016 (MONITEUR, 2016) governing the electric energy sector in Haiti regarding the theft of electricity, stipulating as follows: Any person who connects directly to a public or private electricity network without a contract with the holder of a license or right of operation will be prosecuted and sentenced to a prison term of 6 to 12 months and to pay damages claimed by the operator concerned.

Figure 2.24 – Clandestine connection on the EDH network

Source: (HAITILIBRE, 2018)

This law is not being enforced to the full extent of the law, as electricity theft and clandestine connections continue on the EDH network (2.24). This situation discourages private investors from investing in the production of electrical energy in the country.

2.4.6 Social Constraints

Poverty is also a factor in holding back (PAUYO, 2017). Due to the high level of poverty in the country, estimated at nearly 60% (2020) (WORLDBANK, 2007), most of the population is vulnerable and cannot pay their electricity bill, especially those living in the slums where there is a large concentration of the population. Also rural population, the majority of whom are vulnerable, with their low incomes, prefer not to be supplied with electricity in order to avoid the monthly energy costs.

2.4.7 Constraints of climatic vulnerability

Cyclical problems arise and also seriously affect the functioning of the Haitian electrical system. Globally, Haiti is the third most affected country by climatic events, according to the Global Climate Change Index published in 2016 by German-watch. Of all the Caribbean countries, Haiti suffers the most disasters per square kilometer. The table (2.9) contains some of the great natural disasters that have totally destroyed the region :

Table 2.9 – Natural disaster of which Abricots is a victim

Date	Disaster events names (Hurricanes)
October 11, 1954	Hazel
October 4, 1963	Flora
September 29, 1966	Ines
August 5,1980	Allen
September 11, 1988	Gilbert
November 12/13, 1994	Gordon
August 26, 2008	Gustav
November 4, 2010	Thomas
October 24/25, 2012	Sandy
October 4/5, 2016	Matthew
January 12, 2010	(Earthquake) magnitude 7.3
August 14, 2021	(Earthquake) magnitude 7.2

In fact, Haiti has been the victim of several successive natural disasters, namely the two most devastating such as an earthquake of magnitude 7.3 on the Richter scale of (January 12, 2010) and Hurricane Matthew on October 4, 2016, have successively resulted in damage and losses related to the country's electrical infrastructure. Post-disaster studies revealed that more than half of the population (53.2%) did not have direct access to electricity after the earthquake. As for the hurricane, micro-grids in many departments were totally destroyed. Haiti has the highest hurricane vulnerability index in the small island states region island states : 12.9 on a range of 13, (BIT et al., 2017). Between 1971 and 2014, it has been affected by 137 natural disasters. Following Hurricane Matthew (2016), which totally devastated the southern region of Haiti, leaving a toll of 546 dead, 2.1 million affected, with an effect of 25% on the GDP (MARCELIN; CELA, 2017).

On August 14, 2021, a powerful earthquake of magnitude 7.2 on the Richter scale to cause damage and losses in the country, which would be valued at 1.5 billion dollars, about 10% of the gross domestic product and a human toll of 2 248 dead, 12 763 injured and 329 missing.

2.4.8 Constraint of grid productivity

Electricité D'Haiti (EDH), the national electricity company, covers only a limited number of cities and towns, forming a perimeter of 9 networks and 33 isolated and non-interconnected centers. The country's electrification rate is the lowest in the Northern Hemisphere and the Latin America and Caribbean region. It went from 26% in 1990 to

37% in 2010 and was estimated at 46.93% in 2020. With this rate of increase in access to electricity, Haiti should reach universal coverage after 2070 (PREPOC, 2020). The level of reliability of the circuits in the national grid is very low; power flow analyses show that almost all substations are saturated and the capacity of power transformers is insufficient (MTPTC et al., 2011); This obstacle prevents all circuits from being supplied simultaneously. The generation system is working mechanically until now since the system is not computerized; This being said, the power plants are not working optimally. This state of disrepair is the main cause of the poor quality of service provided to customers. The country is in the dark is the title of an article published on March 23, 2022 in the country's largest daily newspaper (FLECHER, 2022) on the state of disrepair of the national network of not being able to supply homes in the metropolitan area with electrical energy. The article mentioned that all the thermal power plants serving the metropolitan area of Port-au-Prince and managed by the State are at a standstill.

2.4.9 Constraints of the fuel supply problem

With a very low level of commercial profitability, the company is constantly unable to cover its operating expenses, including fuel and electricity purchases, due to the low rate of invoice collection. Fuel procurement is a major problem for the company, which buys fuel on credit but is unable to pay its suppliers, yet production costs are far below recovery, meaning that the company is producing at a loss. Unable to operating expenses, including fuel and electricity purchases, due in part to low payment collection rates, EDH has been dependent on transfers from the Treasury, which have averaged USD 200 million per year in recent years (or 10 percent of the national budget and 10% of the national budget and 1 - 2% of GDP) (SINGH; BARTON-DOCK, 2016).

2.4.10 Constraints of infrastructure and equipment

The lack of road infrastructure makes interconnection between communes very difficult, which completely encloses most of the country, especially the regional populations. Haitian cities are not equipped with adequate urban infrastructure and basic services, which undermines productivity and livability. In the Plan de Relance Economique Post-Covid-19 (2020 - 2023) (PREPOC, 2020). written by the Ministry of Economy and Finance and the Ministry of Planning and External Cooperation in Haiti, it was reported that investments in rural electrification in Haiti have remained scarce over the past 30 years. This statement suggests that rural Haiti has long been marginalized by the central government. since the founding of this nation, basic needs such as good schools, health centers, electricity, potable water, and recreation have never been fully met in rural Haiti. As a result, peasants are still poorly served. Providing them with affordable access to energy can have a significant impact on their standard of living, health, education, productivity, and ability to participate in modern society; The maintenance is also a fundamental problem.

2.4.11 Ranking of American States and territories by energy per-capita

According to the World Ranking of States and Territories by Electricity Consumption in kWh per capita, in 2014, Haiti is ranked last among all countries in Europe, Asia, Africa and Oceania, having the lowest level of consumption per capita in the world. According to the website (ATLASOCIO, 2019) this table relates the ranking of the States and territories of America by energy consumption per capita (See table 2.10).

Table 2.10 – Classification of America's countries by energy consumption per capita

No	Countries	2014 (kWh)	2020 (kWh)
1	Canada	15 588	17 199
2	USA	12 994	12 945
3	Trinidad & Tobago	7 093	6 457
4	Curacao	4 798	6 353
5	Chili	3 880	4 379
6	Suriname	3 597	3 938
7	Uruguay	3 085	3 714
8	Argentina	3075	3200
9	Venezuela	2 719	2 621
10	Brazil	2 620	2 923
11	Mexico	2 157	2 526
12	Panama	2 064	2 540
13	Costa-Rica	1 942	2 289
14	Dominican Republic	1 616	1578
15	Paraguay	1 552	6 918
16	Cuba	1 451	1 634
17	Peru	1 346	1 601
18	Colombia	1 332	1 549
19	Jamaican	1 051	1 358
20	Salvador	937	1 022
21	Bolivia	743	825
22	Honduras	620	1104
23	Guatemala	578	847
24	Nicaragua	568	703
24	Haiti	39	82

Source: (ATLASOCIO, 2019)

2.4.12 Classification countries by electric performance

Electrical energy being one of the essential engines of development, remains a heavy burden for the emancipation of Haiti, independent since 1804, remains until In 2022, the list of 46 LDCs (FOLIO, 2016). On the other, Haiti among the energy-deficient countries; and it seems that it will remain there for some time to come if nothing is done. In a report carried out in February 2016 by (CHOISEUL, 2016), with the objective of ranking the electrical systems of countries according to criteria of quality, availability, access, quality of the energy mix and environmental footprint, etc. This assessment was carried out according to the data collected and lists the countries in five categories : best performing countries, performing countries, intermediate countries, deficient countries and failing countries (table 2.11).

Table 2.11 – Countries Classification by energy consumption per capita

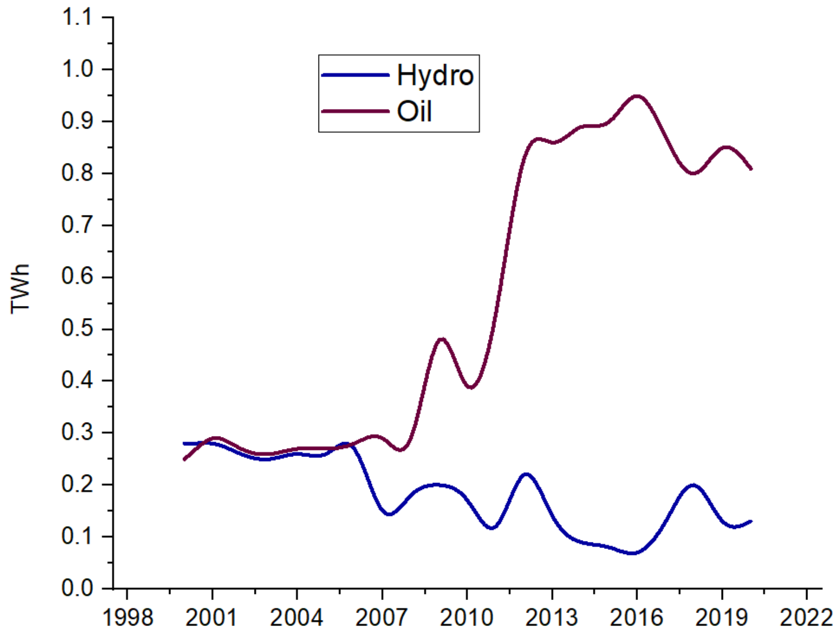
Rang 2016	Countries	Score 2016	Previous rank	Evolution
1	Norway	73.3	1	Fixed
2	Sweden	67.8	1	Fixed
3	Iceland	65.2	4	Increasing
144	Burkina-Faso	24.4	144	Fixed
144	Benin	22.2	146	Increasing
146	Haiti	20	144	Increasing

Source: Choiseul Energy Index 2016

2.4.13 Electricity generation of Haiti

According the figure (2.25), hydroelectric and thermal are the two main sources of production in the country; we can see on the figure that in the year, Haiti's energy production. In 2000, electricity generation in Haiti was 0.28 TWh based on hydroelectric energies and thermal production based on diesel or fuel oil contributed to a production of 0.25 TWh; In 2007, hydroelectricity production dropped to 0.15 TWh while thermal production was 0.30 TWh; In 2016, thermal sources dominate electricity production with 0.95 TWh against 0.07 TWh for hydraulic sources; In 2020, thermal sources contribute 0.85 TWh against 0.13 TWh for hydroelectricity (BPS, 2022).

Figure 2.25 – Energy Production by Haiti for 20 years (2000 - 2020)



Source: (BPS, 2022)

2.5 THE ENERGY INSTANCES IN HAITI

Nowadays, the electricity sector in Haiti is regulated, controlled and ensured by several public utility entities, belonging to the national government; each of which plays a role in the electricity production in Haiti:

- MTPTC
  This ministry has the mission to conceive, define and concretize the policy of the Executive Power in the fields: Public Works, Transport, Communications, Drinking Water, Electricity and in all other fields defined by the Law.

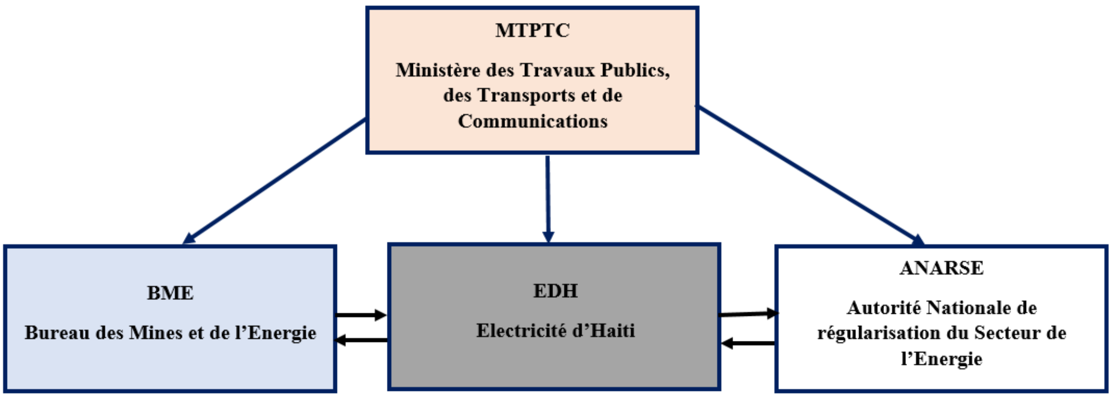
- BME
  The Bureau des Mines et de l'Energie is an autonomous organization created in 1986 and operating under the supervision of the Ministère des Travaux Publics Transports et Communications (MTPTC). Its main mission is to promote the research and exploitation of Haiti's mineral and energy resources as well as the appropriate techniques related to them.

- ANARSE
  L'Autorité Nationale de Régulation du Secteur de l'Energie was created by the decree of February 3, 2016 and is placed under the supervision of the Ministère des Travaux Publics Transports Communications (MTPTC). Its role is to ensure

the promotion and development of the energy sector by regulating the activities of production, operation, transport, distribution and marketing of electricity throughout the national territory.

- EDH
  Electricité d'Haïti, an autonomous state agency of an industrial and commercial nature, was created by the law of August 9, 1971. Currently governed by the decree of August 20, 1989, the mission of EDH is to produce, transport, distribute and market electrical energy throughout the national territory. However, the law of September 8, 2002 removes the monopoly of EDH and allows other private operators to penetrate the market; EDH is the only company that owns electrical production stations throughout the national territory of Haiti. The figure (2.26) presents the organizational chart of the energy production authorities in Haiti:

Figure 2.26 – Public authorities responsible for the energy sector in Haiti



2.6 THE OPERATORS OF ELECTRICITY IN HAITI

Electricity is produced in Haiti by different types of operators; Electricity generation in department is largely provided by independent producers, who enjoy monopoly or oligopoly situations (PAUYO, 2017) and EDH:

2.6.1 Public operator (EDH)

Electricité d'Haïti (EDH) is the public authority that produces, transports, distributes and markets electricity throughout the country; for a long time, the company alone had a monopoly on electricity throughout Haiti. Although EDH has its own network and production facilities, its production capacity is very low compared to the demand for electrical energy; In 2013, approximately 50% of the total production was purchased from independent power producers using diesel engines, consuming diesel fuel, and under very expensive PPA with an average per kWh between USD 0.24 and USD 0.38 (MTPTC, 2013). In this case, the Haitian State has become favorable to private investors to compensate for the lack of production, thus abandoning the monopoly of the exploitation of electrical energy to make way for competitiveness.

2.6.2 Independent power producers (IPP)

In the law of September 9, 2002, the state grants general guarantees to all private investors, and defines the conditions and general forms of incentives for certain types of investments that can increase the competitiveness of the electricity sectors. Under this law, private companies can invest in Haiti to produce energy. This gives rise to private companies such as SOGENER with a production capacity of 16 MW; E-Power with a production capacity of 30 MW; including the company HAYTRAC with a production capacity of 12 MW. These three private operators are essentially thermal and since 2015, 84% of the energy injected into the grid comes from these producers (PREPOC, 2020). These companies only produce the available power, which is then injected into the EDH network, without entering into commercialization; they prefer to sign a power purchase contract with the Haitian State, which pays monthly according to the amount of power supplied according to the public-private partnership model. In the departments, SOGENER signed four power purchase agreements in 2002 for a total installed capacity of 24 MW in four regions: Cap-Haitien (8 MW), Artibonite (8 MW), Petit-Goâve (4 MW) and Les Cayes (4 MW) (BME, 1989).

2.6.3 The private operators

The Private operators install their generation sources, particularly in a remote area of the country where EDH has not been able to penetrate; They also market their generation. Depending on the region, the private operators may distribute power by connecting to the main EDH grid to supply customers when the infrastructure is already in place; otherwise, they install distribution lines themselves. These operators only pay taxes to the state; SIGORA in the North-East department of Haiti is the main representative of this sector with a hybrid production, coupled renewable energy and a thermal source (diesel generator).

2.6.4 Cooperatives

The CEAC (Coopérative électrique de l'arrondissement des Côteaux) is an energy cooperative that produces energy only for its members, who pay less than the national tariff in Haiti. Consumers are provided with a prepaid smart meter; It also operates autonomously and independently in remote areas. It differs from independent operators in that it operates on a non-profit basis.

2.6.5 The Projects / Non Governmental Organization (NGO)

These are microgrids built in an isolated area, as part of the implementation of a community project, financed by a national or international institution in order to facilitate access to a community isolated or abandoned by the Haitian State; For example, the construction in 2015 of an 11 kW hydroelectric microgrid, in the locality of Capotille (North-East), as part of the implementation of the Small Grant Programme, SGP/UNDP, serving about 70 households. Once completed, this microgrid is administered by the community with a non-profit purpose. The Pilot Project for Sustainable Electricity Distribution (PPSELD), a 10 MW thermal microgrid installed in the Industrial Park of Caracol, is a USAID and NRECA International, Ltd.

2.7 CONSUMER PROFILE IN THE ELECTRICAL SYSTEM OF HAITI

In the Haitian electrical system, the profile of consumers varies considerably depending on their consumption; The categorization of consumers can first be divided into commercial customers, households or industrial companies; Secondly, the types of consumers can be categorized into legal consumers and illegal consumers and fraudsters, since their legal or illegal status determines their behavior face-to-face the network. For each type of consumer, we will identify their consumption behavior, i.e. the equipment and materials used. Therefore, it is necessary to carry out a profiling of the consumers in order to better identify the distribution of the charges to the quantities consumed by all of its customers;

- Legal consumers: are regular customers of EDH who have fulfilled their subscription contracts and pay their bills regularly. The regular consumers are most responsible consumers and use energy in a conscious way.
- Illegal consumers: are those who are clandestinely connected to the EDH grid, and who consume energy without paying. It use energy irresponsibly and do not care

about any consumption costs; Their attitude has a direct impact on the availability of scarce energy. Illegal consumers are not recognized as customers of the EDH; in recent years, fraudsters have been continuously increasing on the EDH network, consuming energy irresponsibly without paying their bills. This practice causes very high commercial losses for EDH.

- The Fraudsters: are Regular or irregular consumers who develop strategies to avoid paying for their actual consumption. The actor who intervenes at any level of the operating chain and manipulates the control elements (the energy meter) in order not to pay for what they have consumed. Customers who open their meters to change the setting in order to avoid billing their consumption normally.

- Neighborhood committees: are individuals who organize themselves as leaders in precarious localities in the metropolitan area of Haiti and in other cities; They give themselves the right to intervene and fraudulently exploit the EDH network. The committee is responsible for connecting all the houses in the neighborhood to electricity, and pays money without the knowledge of EDH. The committee is also responsible for solving the technical problems of the network, because quite often, the transformers explode due to overloads caused by the hacking of the networks. Indeed, very often, breakdowns occur and last for a long time (more than 15 days); the committee then organizes fundraising to buy a new transformer which becomes theirs. The subscribers therefore pay the neighborhood committee instead of EDH. All this contributes to increasing the rate of losses on the EDH network:

2.8 LOAD PROFILES IN THE HAITIAN ELECTRICAL SYSTEM

It corresponds to a maximum of electrical power on the power grid, and therefore to a peak of electricity consumption. Electricity consumption profiles follow an overall periodic pattern with daily, weekly or seasonal consumption. Thus, we speak of daily peak to designate the maximum power demand over a day. The level of the seasonal peak, which designates the maximum power demand over a year, allows the power of the electricity production fleet to be sized. In Haiti, the peak electricity demand also varies according to the season and holidays, with summer days being hotter and, in general, the Christmas, world cup soccer player and Carnival periods weighing on the electricity supply system. These peaks and valleys in demand are essential data for calculating and evaluating equipment needs, maintenance and upgrades. The profile of the loads in the Haitian electrical system depends on the types of consumers: according to the observations, there are large consumers, medium consumers and small consumers.

- Large consumers: Industries, manufacturing factories, hotels, etc.

- Medium consumers: Offices, shops (carpenters, cabinet makers, craftsmen using motorized machines for their work, public offices using air conditioning 8 hours per day, etc.

- Small consumers: Households using light bulbs, fan, television, iron, etc.

The numbers, the various electrical demands of customers, the efficiency and age of the equipment, as well as the type and quantity of equipment vary enormously from one region to another. Until now in Haiti, no campaign has been carried out in order to sensitize consumers to become more responsible in their consumption, since the level of education of the population does not allow them to make a rational and thoughtful management of energy, especially illegal consumers and fraudsters.

It should also be noted that the invasion of the country by electric and electronic waste that is to say, very energy consuming devices that are chased in other countries such as the USA, Canada, Dominican Republic. This products are dumped in Haiti to be resold as a quality product, and are bought unconsciously by the population. Among these old and obsolete equipment, we find refrigerators, televisions, washing machines, irons, electric ovens, dryers, electric stoves, water heaters, photocopiers etc. To is noticeable that the type of consumption in urban areas is clearly different in rural areas; The types of loads most commonly used in rural areas are very low capacity appliances; The types of electrical equipment most frequently used in the Haitian energy system in rural areas are light bulbs, FM radios, television, telephone chargers, etc.

2.9 DESCRIPTION OF THE HAITIAN POWER GRID

Haiti's electrical network is 60 Hz, with 87 km of 115 kV high voltage transmission lines, 2000 km of 65 kV medium voltage lines and 110 V low voltage (1 phase + neutral). The production centers are mainly public and private; The metropolitan area of Port-au-Prince has 65.07% of the electrical resources, since it is the main commercial stronghold of the country. Regarding the distribution of electrical energy on the Haitian territory, the electrical energy produced by the different EDH power plants passes through an Radial system grid. Each Medium Voltage line comes from a Transformer Station from which low voltage lines leave and reach the homes:

- The Port-au-Prince metropolitan network is composed of one hydroelectric power plants (Péligre) and others micro hydropower plant.

- The thermal power plants in area metropolitan (Carrefour, E-Power, Pétion and Varreux) and others thermal power in all provinces (See figure 2.27).

- Ten (10) substations or distribution stations that are currently operational in area metropolitan, namely the Varreux substation, Croix-des-Bouquets, Croix-des-Missions, Tabarre, Ancien Delmas, Canapé-Vert, Carrefour-Feuilles, Toussaint Brave, Martissant and Rivière-Froide).
- A dispatching station (Nouveau Delmas) where the network control center, the Dispatching is installed.
- And four other intelligent sub-station that are projects in perspective.

Figure 2.27 – Some power plants with conventional sources (EDH)

Petion Bolivar (thermic power plant) 34 MW | Carrefour 1 (thermic power plant) 49.5 MW | Jérémie (thermic power plant) 4.9 MW

Source: (EDH, 2022)

2.9.1 Overview of Haiti's existing Power Plant fleet

In Haiti, there is not yet an interconnected network, as each city in each region has its own installation. The largest region, Port-au-Prince, is the only one with an integrated distribution network. The figure (2.27) show some of the thermal and renewable electricity generation plants that are being installed in Haiti. The table (2.12) shows the power installed through the different electrical power grid of Haiti.

Taking into account that the evolution of demand varies according to the growth of the population, new substations will have to be built with new margins of power, in order to meet the demand for electricity and to facilitate the distribution of energy throughout the large agglomerations.

The New Delmas sub-station (table 2.18) is the convergence point of the network, which connects the hydroelectric power station of Peligre by a 115 kV line of approximately 55 km in length and to the other power stations by two lines of 69 kV not connected.

Table 2.12 – Overview of Haiti's existing Power Plant fleet Sources

Name of Unit	Location of Unit	Owner	Plant Type	Installed MW	Operating Capacity
Varreux	P-au-P	EDH	Distillate	68	34
Carrefour	P-au-P	EDH	Distillate	48	24
Péligre	P-au-P	EDH	Hydro	54	26
Sogener	P-au-P (varreux)	SOGENER	Distillate	40	20
E-Power	P-au-P	PPP	heavy fuel oil	30	30
Centrale José Marti	Cap Haïtien	PPP	heavy fuel oil	15	15
Centrale Simón Bolívar	Gonaives	PPP	heavy fuel oil	15	15
Centrale Alexandre Pétion	Carrefour	PPP	heavy fuel oil	30	30
Caracol	Caracol	PPP	heavy fuel oil	10	10
Thermal outside Area West	Provinces	-	Distillate	72	36
Hydro outside Area West	Provinces	-	Hydro	8	4
Mirebalais Hospital	Mirebalais	-	Solar	0.4	0.4

Source: Worldwatch Institute

2.9.2 Sub-Transmission lines (metropolitan area)

These transmission lines are used to transport power over distances of more than 1km or over long distances, as there is a geographical dispersion between the production sites and the consumption centers. The table (2.13) and (2.14) shows the capacity of the transmission and distribution lines in the Haitian electrical system; The majority of these lines allow the flow of power in the metropolitan areas, because in the other regions (departments), most often, the source of production is inside the city.

Table 2.13 – Sub-Transmission Line characteristics in the power system of Haiti

Area	Voltage Level(kV)	Length (km)	Characteristics
Metropolitan	115 kV	56	Sub-Transmission line
	69 kV	53	Sub-Transmission line
	7.2 / 12.47 kV	900	Distribution line
	2.4 / 4.16 kV	20	Distribution line

Table 2.14 – Some transport lines in metropolitan area of Port-au-Prince/Haiti

Area	Origin	Arrival	length(km)	Voltage(kV)
Central-West	Peligre	Nouveau-Delmas	55	115
Metroplitan	Nouveau-Delmas	Ancien-Delmas	0.5	115
Metroplitan	Nouveau-Delmas	Varreux	4	69
Metroplitan	Nouveau-Delmas	Jonction	5.6	69
Metroplitan	Jonction	Croix-des-Bouquets	5	69
Metroplitan	Jonction	Croix-des-Missions	6	69
Metroplitan	Nouveau-Delmas	Canape-vert	4.9	69
Metroplitan	Canape-vert	Carrefour-Feuilles	4.15	69
Metroplitan	Carrefour-Feuilles	Toussaint Brave	1.1	69
Metroplitan	Carrefour-Feuilles	Martissant	2.85	69
Metroplitan	Martissant	Carrefour	3.85	69
Metroplitan	Carrefour	Rivière Froide	3.4	69

2.9.3 Power system characteristics of Haiti

In each of the regions of the South, Artibonite, and the North there are isolated distribution networks, which are not connected, either within the region or between regions (BME, 1989). To achieve a national interconnected network, this requires enormous expenditures for the construction of large high-voltage transmission lines. However, the total length of the transmission and distribution lines for the whole country is 1 760.5 km (2005); For the metropolitan area, the total length of the transmission and distribution lines for the metropolitan area is about 1 029 km (BME, 1989).

2.9.3.1 Transformer sub-stations HTA/HTB

The majority of the sub-stations in the metropolitan area are supplied by the 69 kV line. Two substations are supplied with 115 kV: the Ancien Delmas substation (See figure 2.28) from two lines coming from the 115 kV bar of Nouveau Delmas and the new substation of Tabarre intercalated on the 115 kV lines, at about 3 km from Nouveau Delmas, allows us to understand the distribution of electricity production throughout the country (table 2.13); However, it is clear that Haiti is a traditionally centralized country, leaving only a small part to local communities.

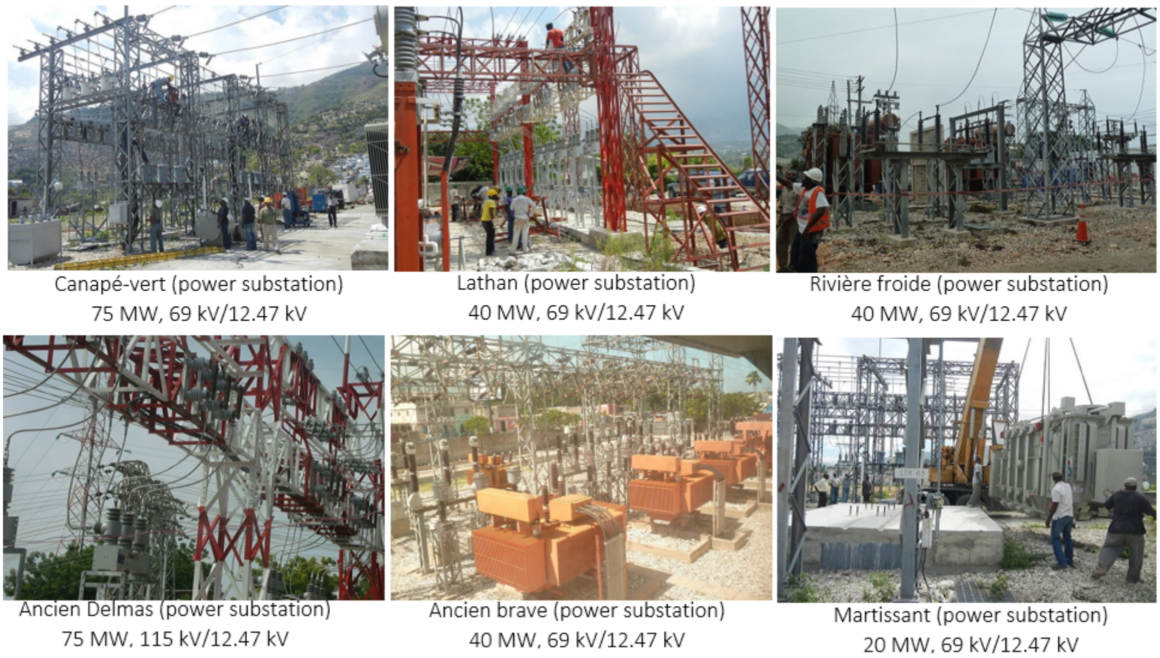
The transformer station contains high and medium voltage devices, such as power transformers, protection devices (circuit breakers, disconnect switches, etc.), measuring and control devices. In the metropolitan network of Haiti, the table (2.18) contains the transformer stations in medium voltage:

Table 2.15 – Sub-station of HTA - HTB power system of Haiti

Sub-stations	Power (MVA)	Voltage-In	Voltage-out	Departure Qty
Ancien Delmas	55	115	12,47	9
Nouveau-Delmas	45	115	69	
Canape Vert	75	69	12.47	5
Toussaint Brave	40	69	12.47	3
Carrefour-Feuilles	20	69	4.16	3
Martissant	20	69	12.47	3
Rivière-Froide	30	69	12.47	3
Croix-des-Missions	20	69	12.47	3
Croix-des-Bouquets	40	69	12.47	2
Varreux	40	69	12.47	6
Tabarre	60	115	12.47	11

Source: ANARSE

Figure 2.28 – Some sub-stations of distribution in metropolitan area



Source: (EDH, 2022)

2.10 NATIONAL INTERCONNECTION STUDY

In a study to build a National Transmission Network to interconnect regions such as Port-au-Prince, Jacmel, Jérémie, Gonaïves, Cap Haïtien, Môle Saint Nicolas, Fort-Liberté, and the Peligre power plant. It is therefore recommended the construction of approximately 1 079 km (table 2.16) of high voltage lines connecting the main cities of the country and the extension of 12 others substations and cost [table (2.18) and (2.17)] throughout the country (PAUYO, 2017):

Table 2.16 – Study of needs in transmission lines for a perspective national interconnection

High Voltage Lines	Capacity (MVA)	Load (MVA)	Length (km)
$Carrefour \rightarrow Jacmel$	2x 40 MVA	13	76
$Varreux \rightarrow Gonaives$	2x40 MVA	78	142
$Carrefour \rightarrow Petit - Goave$	2x 40 MVA	62	58
$Petit - Goave \rightarrow Cayes$	2x 40 MVA	56	125
$Cayes \rightarrow Jeremie$	2x 40 MVA	26	95
$Varreux \rightarrow Gonaives$	2x 40 MVA	78	145
$Gonaives \rightarrow Cap - Haitien$	2x 40 MVA	39	99
$Port - de - Paix \rightarrow MoleSaint - Nicolas$	2x 40 MVA	6	72
$Cap - Haitien \rightarrow Fort - Liberte$	2x 40 MVA	13	52
$Peligre \rightarrow Cap - Haitien$	2x 40 MVA	81	110
$CapHaitien \rightarrow Port - de - Paix$	2x 40 MVA	13	105

Source: (PAUYO, 2017), Haiti Priorise

Table 2.17 – Study of needs in funding for a perspective national interconnection

Components	2017 - 2021	2028 - 2032	US millions
Substations	348	189	537
Lines high voltage	1 079		1 079
Power Control Center	8	4	12
Total	1 435	193	1 628

Source: (PAUYO, 2017), Haiti Priorise

Table 2.18 – Study of needs in Sub-station for a perspective national interconnection

	2020			2032		
Substations	Qty	Power(MVA)	Load(MWA)	Qty	Power(MVA)	Load(MWA)
Carrefour	3	20	62	3	20	111
Petit Goave	2	5	6	1	5	2
Jacmel	2	10	13	1	10	23
Cayes	2	20	30	1	20	53
Jeremie	2	10	13	1	10	23
Gonaives	2	20	39	2	20	70
Varreux	3	50	116	1	50	209
Môle Saint Nicolas	2	5	6	1	5	12
Fort Liberté	2	10	13	1	10	23
Péligre	2	50	78	1	50	139
Cap Haïtien	2	50	78	1	50	139
Port de Paix	2	5	6	1	5	12

Source: (PAUYO, 2017), Haiti Priorise

2.11 COMPARATIVE ENERGY STUDY BETWEEN HAITI AND THE DOMINICAN REPUBLIC

Haiti and the Dominican Republic share the island of Hispaniola; The Dominicans inherited the eastern part of Hispaniola and Haiti the western part. For a long time, the two countries were at a comparable level of development. In the 1970, the Dominican Republic had a fairly similar rate of economic growth (NOUVELLISTE, 2019).
Over the last thirty years, the growth gap between the two countries has widened (NOUVELLISTE, 2019). The Dominican Republic has moved out of the category of poor countries and into the middle category. Haiti, on the other hand, has continued to stagnate in the group of the poorest countries and has not been able to emerge from the political, social and economic crisis (NOUVELLISTE, 2019).

According to a comparative study between energy management, there is a big difference between the two countries. In 2020, the Dominican Republic's generation fleet is made up of a diverse matrix of technologies such as combined cycle, internal combustion engines, steam and gas turbines, hydroelectric, wind and solar photovoltaic plants. The primary sources that provide energy for production are natural gas, coal, solar, wind, water, biomass and petroleum derivatives, according the (table 2.19).

Table 2.19 – Energetic matrix comparison, Haiti and Dominican Republic by source (2020)

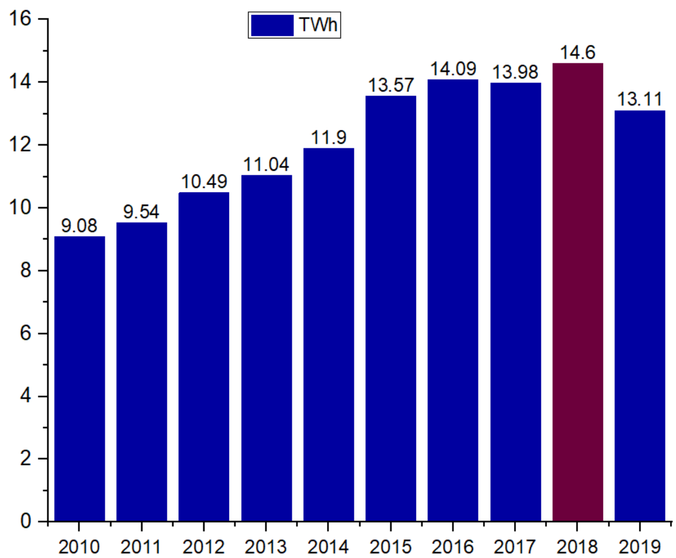
Country	Haiti		Dominican Republic	
Power generation Source	MW	%	MW	%
Hydraulic	78	16.54%	624.0	12.62%
Wind	no data	no data	366.6	7.4%
Solar	3	0.56%	163.0	3.3%
Biomass	no data	no data	30.0	0.6%
Natural Gas	no data	no data	969.0	19.60%
Fuel	390	82.90%	558.5	11.3%
Carbon	no data	no data	1 065.6	21.6%
Oil Derivatives	no data	no data	1 165.3	23.6%
TOTAL	471	100%	4 942	100%

Source: (OLADE, 2021)

2.11.1 Haiti, Primary energy

Primary energy is the energy contained in the resources drawn from nature; it comes from multiple sources: crude oil, natural gas, solid fuels (coal, biomass), solar radiation, hydropower, wind power, wave power, geothermal energy, and energy from nuclear fuels. The figure (2.29) is based on data published by IEA regarding Haiti's total primary energy supply consumption for Haiti since 2010 - 2019:

Figure 2.29 – Haiti, global supply primary energy consumption



Source: (IEA-WE, 2022) BP Statistical Review of World Energy; and EIA

Interpreting the figure (2.29), we note an increase in the consumption of primary energy in Haiti, particularly in biomass; however, we also note a decrease in the consumption of fuel and hydraulic energy; on a global level, energy consumption differs from one country to another, particularly according to the current socioeconomic situation of the country. All this to say that the consumption of primary energy in Haiti is corollary with the amount of energy available, economic growth, and population growth are important indices in the increase of energy demand and the reduction of energy consumption in the country. The table (2.20) shows all primary energy by source in Haiti since 1990 - 2019:

Table 2.20 – Total primary energy supply (TPES) by source for Haiti accordiing IEA (in Tera Joules (TJ)

Years	Bio-fuels & Waste	Oil	Coal	Wind & Solar	Hydro
1990	86 156	12 583	310	No data	1 645
1992	88 298	10 685	671	No data	1 156
1994	91 562	12 642	No data	No data	839
1996	95 367	12 597	No data	No data	879
1998	99535	17 795	No data	No data	1 102
2000	102 762	24 035	No data	No data	1019
2002	105409	23843	No data	No data	936
2004	110 506	22 036	No data	No data	936
2006	117 427	22 036	No data	No data	976
2008	122 905	23 491	No data	No data	637
2010	130 089	28 935	No data	No data	652
2012	139 195	37 408	No data	No data	736
2014	135 509	38 100	No data	4.0	324
2016	140 628	41 653	No data	7.0	256
2018	144 379	47 438	No data	12.0	710
2019	146 548	42 537	No data	12.0	720

Source: IEA

2.11.2 Regional comparative study of energy availability in the Caribbean in 2020

In a regional context, relating to the major imbalances between the structure of energy production and consumption and the capacity to exploit the energy resources available to meet the electrical energy needs of its territory.

Table 2.21 – Renewable energy generation in OLADE Countries (2020)

Country	Generation(GW)	Surface (km^2)	Population	Electrification(%)	Consumpt. per/capita
Argentina	41.95	2 780 400	45 196 000	98.79	2 755
Barbados	0.32	430	287 000	100	3 110
Belize	0.13	22 970	398 000	92.72	1 294
Bolivia	3.71	1 098 581	11 673 000	93.70	717
Brazil	179.52	8 515 759	212 559 000	99.77	2 392
Chile	26.31	756 096	19 116 000	99.70	3 731
Columbia	17.76	1 141 749	50 883 000	96.81	1 311
Costa-Rica	3.54	51 100	5 094 000	99.40	1 961
Cuba	6.66	109 884	11 327 000	99.98	1 328
Dominican Rep.	4.92	48 442	10 448 000	97.86	1 489
Ecuador	8.10	256 370	17 643 000	97.20	1 441
Grenada	0.05	340	113 000	94.70	1 734
Guatemala	4.11	108 889	16 858 000	88.95	615
Guyana	0.34	214 970	787 000	91.44	1 120
Haiti	0.47	27 750	11 403 000	46.93	83
Honduras	2.94	112 492	9 363 000	85.02	708
Jamaica	1.16	10 990	2 961 000	97.50	3 110
Mexico	83.12	1 964 375	128 933 000	99.08	2 145
Nicaragua	1.62	130 370	6 625 000	98.50	555
Panama	4.12	75 420	4 315 000	94.35	2 140
Paraguay	8.77	406 752	7 253 000	99.60	1 892
Peru	15.20	1 285 220	32 972 000	97.00	1 396
Salvador	2.36	21 040	6 321 000	97.80	947
Suriname	0.50	163 820	587 000	90.34	3 108
Trinidad & T.	2.42	5 130	1 399 000	99.60	6 047
Uruguay	4.92	176 215	3 531 000	99.90	3 214
Venezuela	30.29	912 050	28 436 000	98.94	2,917

With such a low level of consumption, Haiti is among the countries where energy consumption per capita is very low in the world and is ranked last in Latin America and the Caribbean. However, by 2030, access to reliable, affordable and good quality electricity services is fundamental to achieving growth and sustainable development goals.

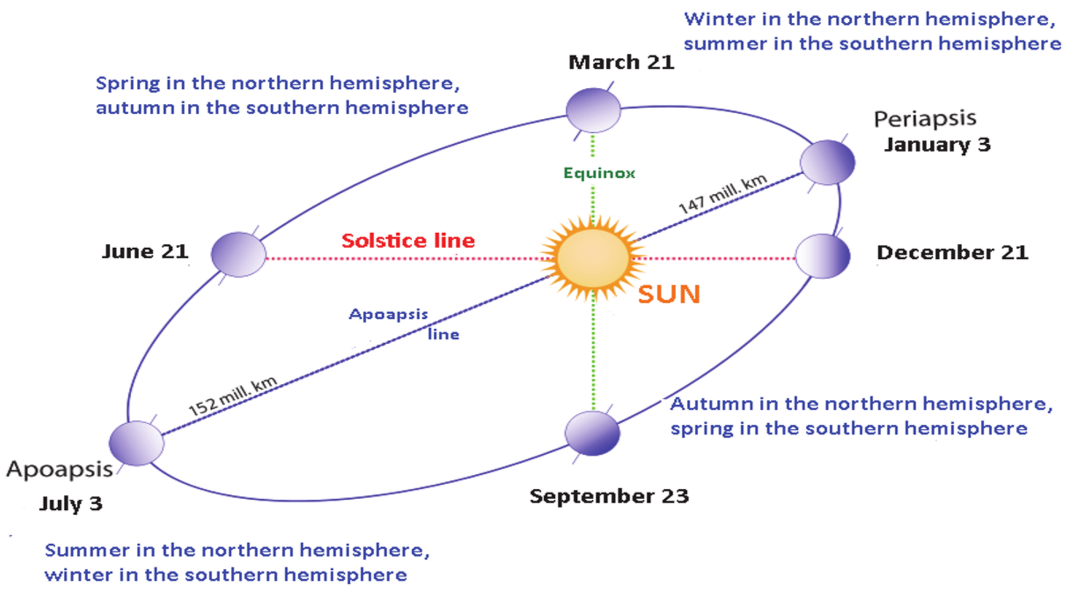
3 RENEWABLE ENERGY

Many studies have shown that Haiti has a very high potential for renewable energy; this being said, the country benefits from the availability of several sources of renewable energy such as solar, wind, biomass and hydraulic, which can constitute promising sources of energy to meet the country's energy needs. The approach to be developed in this chapter is related to a diagnosis of renewable energy in Haiti available; Methodologically, we will proceed firstly to highlight the potential of Haiti with regard to each source of renewable energy and their availability on the territory; Secondly, their contributions in the energy matrix of Haiti.

3.1 GENERAL CONSIDERATION THE SOLAR ENERGY

The sun emits a considerable amount of energy, called solar energy, or solar radiation. At any one time, the earth intercepts approximately 180.10^6 GW (WALD, 2020) On a planetary scale, solar energy is free and available everywhere in nature. This type of energy is directly transmitted by the sun in the form of light and heat since the amount of energy received by the Earth is considerable (see figure (3.1)).

Figure 3.1 – The trajectory of the Earth's movement around the Sun



Source: (MARINICĂ, 2019)

Each year, the Earth receives 1 070 000.00 petawatt-hours (PWh, or 1 015 Wh), which is more than 8 000 times the annual world energy consumption (133 PWh in 2005) (FUTURA-SCIENCES, 2008). Exploiting only 0.01% of this energy would therefore be sufficient to cover the energy needs of the planet (FUTURA-SCIENCES, 2008). Solar radiation is the Earth's main source of natural energy.

3.1.1 Photovoltaic energy production

Photovoltaic solar energy is electrical energy produced from solar radiation by means of the photovoltaic modules. It is said to be renewable because its source (the Sun) is considered inexhaustible on a human timescale. The principle of photovoltaic solar energy is to transform solar radiation into electricity using a photovoltaic cell. The PV cell converts radiative energy (radiation) into electrical energy with an efficiency ranging from 5% to 16% depending on the technology (GHEZAL, 2018). A photovoltaic cell is an electrical device that directly converts solar energy into electrical energy.

3.1.2 Modeling of a photovoltaic generator

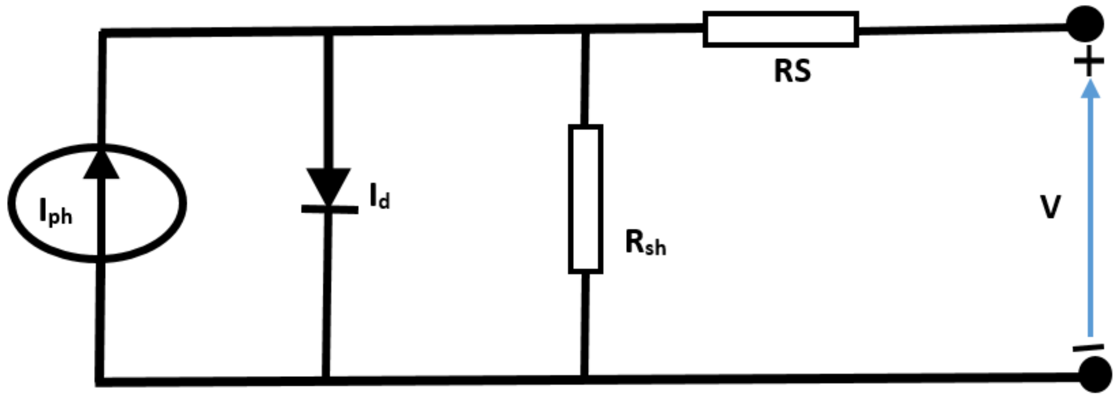
A photovoltaic panel consists of several cells connected in parallel and a series combination. The parallel combination of PV cells is responsible for increasing the current and the series connectivity is responsible for increasing the voltage of the PV generator (KHAN et al., 2013). A single PV cell can be represented by a diode connected in parallel with a current source. It also has a series and parallel resistors. The shunt resistor RSH is added due to the recombination or leakage of electrons at the diode junction and the series resistor RS is added for the compensation of the junction resistance. The equivalent electrical circuit of a photovoltaic generator is modeled (figure 3.2) from a PN junction. The current Iph, proportional to the irradiance, is added, as well as a term modeling the internal phenomena (ZAOUI, 2016). The equivalent electrical circuit of a single PV cell is shown in figure (3.2): The current I in the output of the cell is then:

$$I = I_{ph} - I_s = exp\left(\frac{(qV - R_s I) - 1}{kT}\right) - \left(\frac{U + R_S I}{R_{Sh}}\right) \tag{3.1}$$

$$\left(\frac{kT}{q}\right) = V_T \tag{3.2}$$

The equation (3.2) represents the thermal potential (25 mV at 20°C)
I_{ph}: Photo current, or current generated by the illumination
I_s : Saturation current of the diode.
I_d : Current flowing in the diode.
R_s : Series resistance (Ω). ; R_{sh} : Shunt resistance (Ω).

Figure 3.2 – Equivalent diagram of a photovoltaic cell



Source: (ZAOUI, 2016)

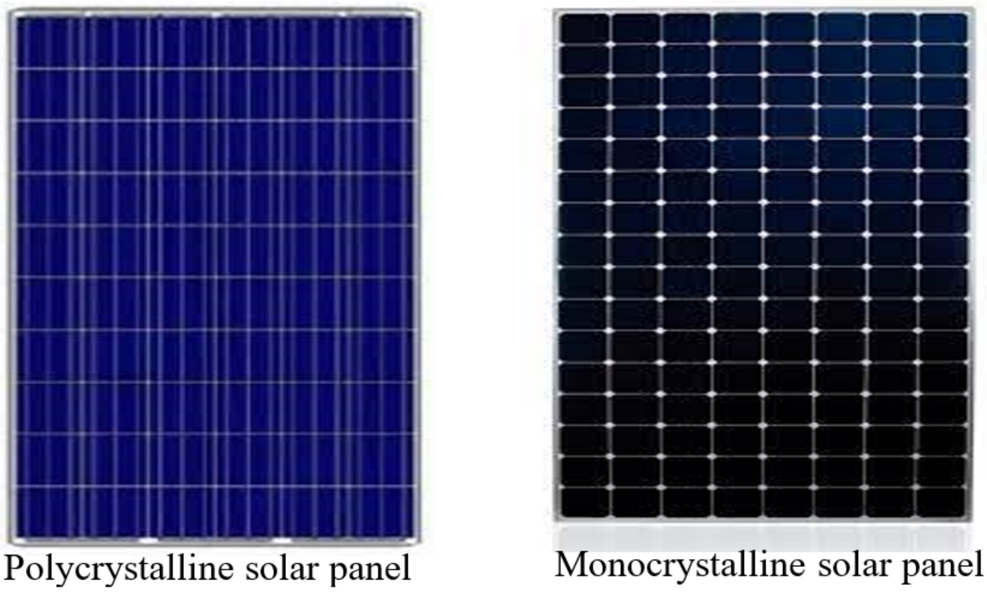
k : Boltzmann constant, $k = 8.62.10^{-5} JK^{-1}$
q : Charge of the electron $e = 1.602.10^{-19} C$
T : Temperature of the cell (K).

3.1.3 Photovoltaic modules study

There are different types of solar modules: Solar modules composed of photovoltaic cells that allow it to generate electric current when the sun's rays strike it; The photovoltaic cells, assembled in the form of modules, provide electrical energy proportional to the amount of sunlight. The mono-crystalline solar panel are composed of a single crystal of silicon and the poly-crystalline in several crystal of silicon; There are several types of solar panels:

- The mono-crystalline solar panel.
- The poly-crystalline solar panel is made of several silicon crystals.
- PERC (Passivated Emitter and Rear Cell).
- Thin-film panels.
  Therefore, among the different types of modules that allow to produce electricity thanks to solar energy, monocrystalline and polycrystalline solar panels are the most widespread.

Figure 3.3 – solar modules PV, Types



3.1.4 Effect of temperature on solar modules

The Photovoltaic cells are sensitive to temperature and various depending the inclination, the orientation, and temperature; For a good performance of photovoltaic modules, it is necessary to have a moderate temperature, because a high temperature decreases the efficiency of photovoltaic modules; While a low temperature increases the output of the module. The maximum power of a solar module is determined under standard test conditions (STC), i.e., at an illuminates of 1 000 W/m^2 and a cell temperature of 25°C and 1.5 AM spectrum (composition of the spectrum identical to the solar spectrum when passing through one and a half thickness of atmosphere, which corresponds to an angle of incidence of 41.8° with respect to the horizontal) (ZAOUI, 2016).

Table 3.1 – Module efficiency by type

Temperature (Ambient)	Monocrystalline	Polycrystalline	Amorphous
25°c	15%	14%	10.36%
30°c	13 %	12%	9.6%
35°c	12.8%	11%	9%
37°c	11%	10.2%	8.3%
40°c	9.9%	9.2%	7.9%
45°c	7.65%	7.5%	7.46%

Source: (EL-DIN; GABRA; ALI, 2014)

The table (3.1) shows the efficiency the solar modules PV is depending of ambient temperature. Another category of cells belonging to the third generation, based this time on a logic of very high logic of very high yields, are the multi-junction cells that can reach a yield of more than 40% in of more than 40% in the laboratory and a theoretical limit of 81% in the field (MAMBRINI, 2015).

3.1.5 Solar Radiance

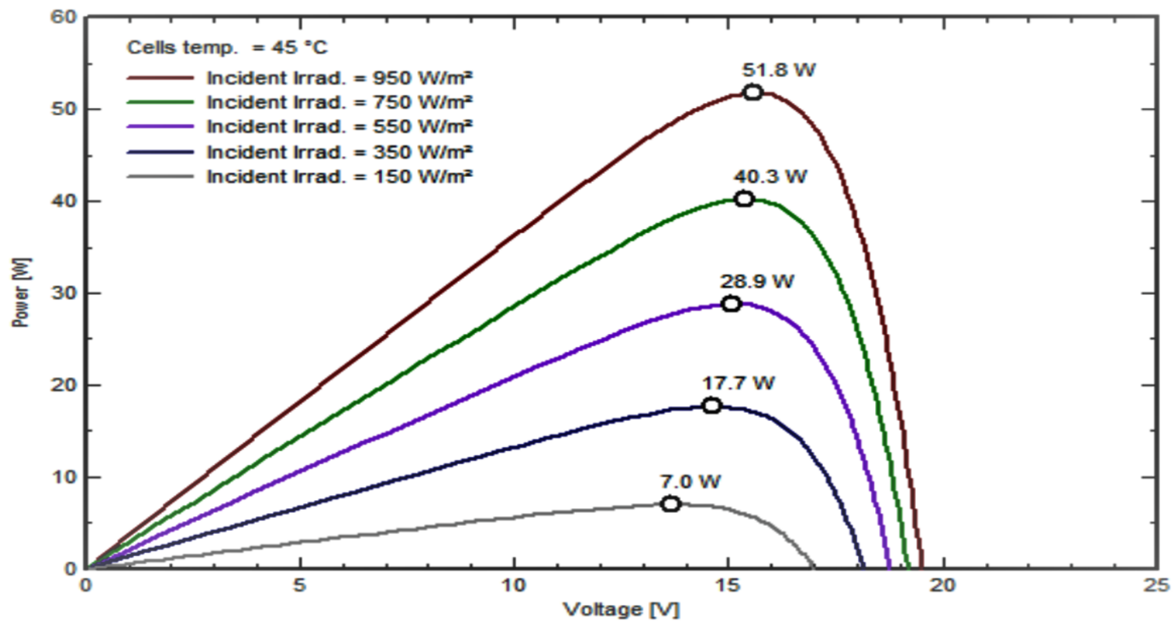
Solar radiance is a radiometric quantity that measures the amount of solar energy received per unit area of solar radiation incident on a surface. That is, the energy received during a time (J/m^2 or Wh/m^2. The solar radiation received on a surface therefore varies over time depending on the position of the Sun and the cloud cover. The maximum solar power at the Earth's surface is about for a surface perpendicular to the rays (ENERGIESPLUS, 2010). In reality, the total radiation received on a surface, called incident solar radiance (or global radiance), is defined by the sum of three components:

- Direct radiance, coming directly from the Sun. This component is cancelled if the Sun is hidden by clouds or by an obstacle.
- The diffuse irradiation, corresponding to the radiation received from the sky, excluding direct radiation. This energy diffused by the atmosphere and directed towards the surface of the Earth, can reach 50% of the total radiation received, when the Sun is low on the horizon, and 100% for a completely covered sky.
- The reflected irradiation, corresponding to the radiation reflected by the external environment, in particular the ground, whose reflection coefficient is called Albedo (ENERGIESPLUS, 2010).

3.1.6 Current-voltage power curves in photovoltaic modules

A photovoltaic module is composed of a set of photovoltaic cells. In the presence of sunlight, each of these cells produces a current I (A) and a Voltage (V). For each point of the previous curve, we can calculate the power P and draw the characteristic curve of power and voltage of the PV module. The points of maximum power are indicated by empty circles. The power delivered by the PV panel at these specific points is maximum due to Current at Maximum Power (IMP) and Voltage at Maximum Power (VMP) (KHAN et al., 2013). In the case of the above figure, the solar module delivers a maximum power according to the solar irradiation it receives, which varies from one power to another, under normal temperature conditions, ranging from 0^o C to 75^oC. (See figure 3.4)

Figure 3.4 – Power and voltage characteristics curve of a PV module



Source: (KHAN et al., 2013)

3.1.7 Peak power photovoltaic panel

The peak power of a photovoltaic panel is the electrical power delivered by the system under standard conditions of sunshine (1 000 W/m²), temperature (25°C) and standard light spectrum AM 1.5 . Example: a 200 Wp module (peak Watts) is a module that will produce an electrical power of 200 W if placed under a sunlight of 1 000 W/m² (ENERGIESPLUS, 2010).

3.1.8 Characteristic values of the solar panels

A typical solar module circuit allows the measurement of various characteristics such as: open circuit voltage (V_{OC}), short circuit current (Isc) and efficiency:

3.1.8.1 Open circuit Voltage

The open circuit voltage, referred to as Voc, is expressed in volts. It is the voltage supplied by the photovoltaic panel when it does not deliver electricity. When it is not connected and therefore no current is flowing.

3.1.8.2 Short-Circuit Current

The short-circuit current is referred to as I_{sc}. It is the current electricity supplied by the panel when it is short-circuited (zero voltage); that is, when the two terminals of the panel are connected to each other without resistance.

3.1.8.3 Efficiency of a solar panel

The yield is a value used as a reference to compare photovoltaic panels between them. We obtain the yield by the following formula (ENERGIESPLUS, 2010).

$$[N_{STC}] = \frac{PeakPower}{PowerSpectrumSTC} \tag{3.3}$$

With the Power of the Spectrum STC = 1 000 [W/m^2]. The efficiency of the conversion of solar radiation into electricity in the thermal system can be expressed as the product of the efficiency of all process steps:

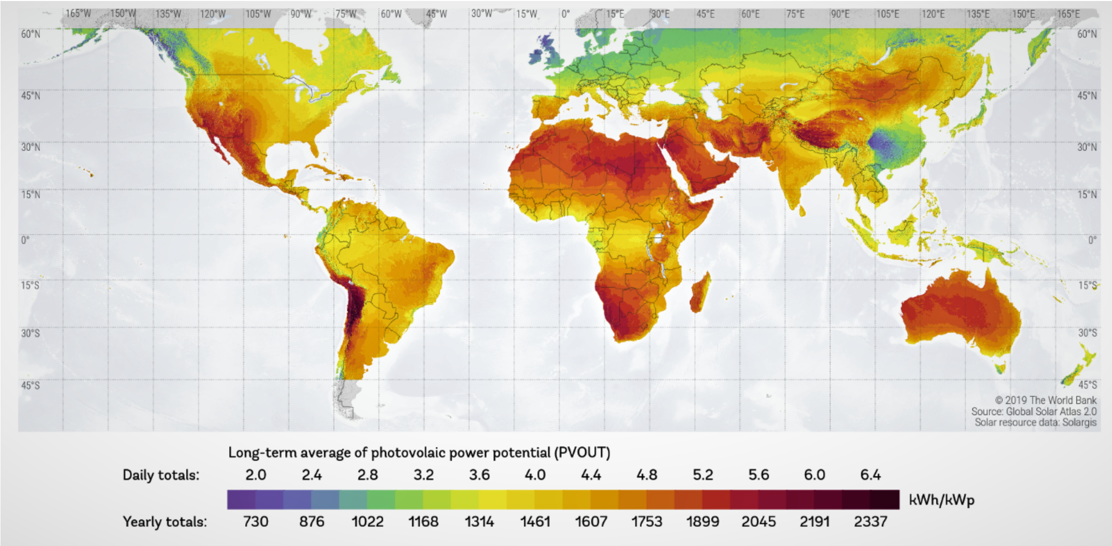
$$\eta = \eta_{opt}(C) * \eta_r ec(C, T_{rec})^* \eta_{pb}(T_{rec}) \tag{3.4}$$

η_{opt}: Optical efficiency (collector).
η_{rec}: the efficiency of the conversion of radiation into heat.
η_{pb} : the efficiency of the conversion from heat to electricity (power supply).
T_{rec}: temperature of the fluid leaving the receiver.

3.1.9 World, Solar Energy Potential

Global Solar Atlas (figure 3.5) is a mapping of solar radiation provided by the World Bank & SOLARGIS. This atlas allows the visualization of global data on solar potential around the world through maps for different countries of the world in 2019; The yellow color shows regions of high solar energy potential, such as South America and the Caribbean, with solar penetration ranging from 3.6 kWh to 4.4 kWh; The African region (in red) has the highest potential with solar penetration ranging from 4.8 kWh to 6.0 kWh. The solar deposit on a surface is eminently linked to the sun's path in the sky.
Indeed, the illumination at a given point on the surface of the earth varies during the day and the year in kWh/kWp. It is expressed for a surface inclined by an angle i. These equations are extracted from the document (KECILI; SAADA; NEBBALI, 2019).

Figure 3.5 – World solar Atlas, 2019

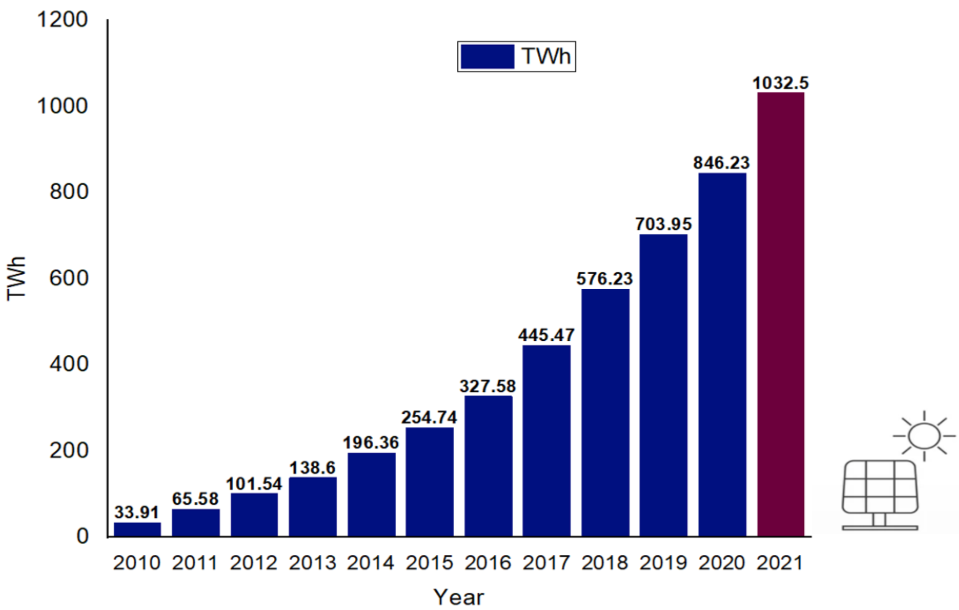


Source: Global solar Atlas (World Bank & SOLARGIS)

3.2 SOLAR PRODUCTION WORLDWIDE

Solar photovoltaic power generation has continued to increase sharply in recent years; Solar photovoltaic power was first developed to meet electricity needs in remote locations, such as mountain regions, islands, and rural areas in developing countries. The graph (3.6) show the global solar energy production between 2010 - 2021 in TWh.

Figure 3.6 – World solar installed capacity



Source: (IEA-WE, 2022)

In the global energy mix, solar energy contributed 2.7% of global electricity generation in 2019, up from 2.2% in 2018. During 2020, despite the impact of the COVID-19 pandemic, 717.5 gigawatts (GW) of Photovoltaic power total was installed (see figure 3.6). In 2021, it represents 3.72% in the global electrical matrix. The total global photovoltaic electric power for the same year was 773.2 GW; Taking into account this growth rate, according to IRENA, by 2025, the global solar power forecast will reach a power of 1.9 TW (IRENA, 2018). This figure varies increasingly since solar energy is the technology that attracts the most investment in the world; In terms of energy production, according to this source (PLANETOSCOPE, 2022), every year, 1 035.9 TWh of solar photovoltaic electricity is produced in the world, which is about 32.825 MWh per second (PLANETOSCOPE, 2022). In the objective of the energy transition, the big industrialized countries since some years begin to integrate the solar energy in their energy matrix; Solar photovoltaics, which can be rapidly deployed in many different situations, is one of the strategic situations, is one of the strategic renewable energy solutions needed to transform energy systems. It has the potential to produce more than 25% of all the electricity needed in 2050 and reduce emissions by 4.9 Gt per year by 2050, or 21% of the total mitigation emissions potential in the energy sector (IRENA; WTO; OMC, 2021). The table (3.2) represents the solar energy generation in the largest economic industrialized countries, in relation to the installation, production and demand in their energy matrices:

Table 3.2 – Top 15 countries in solar electricity evolution

No	Country	Inst. Solar(1996)	Solar Gen.(TWh)2015	Inst. Solar(2020)	Solar Gen.(TWh)2021.
1	China	<0.01	0.01	253.83	330.71
2	USA	0.01	0.54	73.81	163.70
3	Japan	0.06	0.54	67.00	89.59
4	Germany	0.03	0.01	53.78	49.41
5	India	0.00	<0.01	38.98	68.34
6	Italy	0.02	0.01	21.59	24.47
7	Australia	0.02	0.03	17.63	29.12
8	South Korea	<0.00	<0.01	14.58	23.71
9	U.K	<0.01	0.00	13.56	12.47
10	France	<0.01	0.00	11.72	14.66
11	Brazil	0.00	0.00	7.88	12.48

Source: (BPS, 2022)

In 2013, 52.4% of the electricity generated in LAC Country came from renewable compared to only 22% worldwide. This result is explained by the predominance of hydroelectricity, which alone provided 47% of the electricity generation (VINSON, 2016). According to the Inter-American Development Bank, the potential for renewable energy is so high that it could cover so high that it could cover 22 times LAC's electricity needs until 2050 (VINSON, 2016). The table (3.3) represents the solar energy generation in the member countries of OLADE (Latin American Energy Organization) [except Brazil and Mexico], in relation to the installation, production and demand in their energy matrices.

Table 3.3 – Evolution of photovoltaic energy in the last few years in the 27 member countries of OLADE (Latin American Energy Organization)

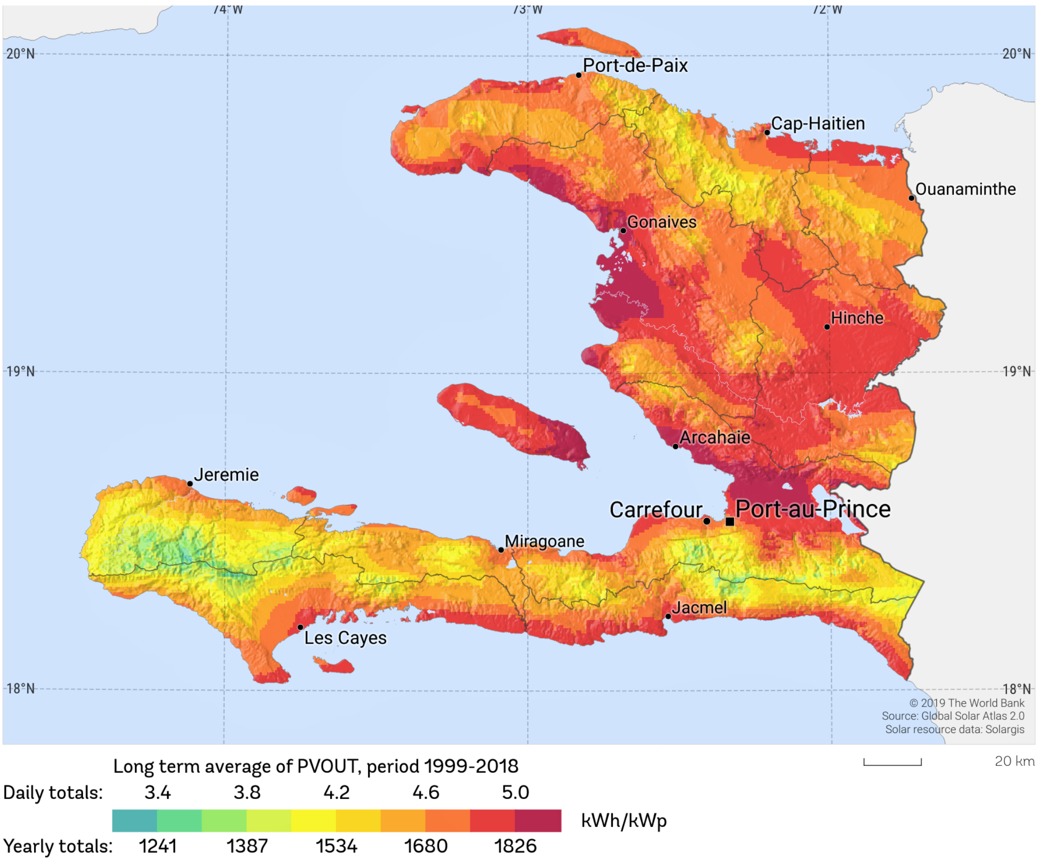
Country	Elec. demand (2000)TWh	Solar Gen.(TWh)2020	Elec. demand (2021)TWh	Solar Gen.(TWh) 2021
Argentina	86.5	0.01	149.1	1.35
Barbados	0.8	0.01	1.0 (2020)	0.04
Belize	<0.2	0.00	0.9	0.00
Bolivia	3.8	0.00	10.4	0.25
Chile	41.1	1.24	83.9	7.62
Columbia	42.2	0.01	70.8	0.19
Costa-Rica	6.4	0.00	11.6	0.06
Cuba	14.2	0.03	19.5 (2020)	0.25
Dominican Rep.	8.1	0.03	18.0 (2020)	0.26
Ecuador	10.4	0.04	31.1	0,04
Grenada	0.1	0.2	31.1	0.00
Guatemala	5.3	0.15	11.2(2020)	0.022
Guyana	0.9	0.00	1.2	0.02
Haiti	0.53	0.00	0.9	0.00
Honduras	3.9	0.42	10.8	1.12
Jamaica	6.2	0.00	4.2(2020)	0.05
Nicaragua	2.2	0.00	5.2 (2020)	0.02
Panama	4.9	0.02	17.6	0.00
Paraguay	5.6	0.00	12.1	0.02
Peru	19.5	0.00	55.3	0.85
El-Salvador	4.5	0.03	7.0	0.850
Suriname	1.4	0.01	3.2 (2020)	0.01
Trinidad & T.	5.1	0.00	8.6	0.00
Uruguay	7.9	0.05	12.0 (2020)	0.46
Venezuela	83.2	0.01	104.5	0.01

Source: (EMBER, 2022)

3.3 STUDY OF THE SOLAR ENERGY POTENTIAL IN HAITI

According to studies carried out by the World Bank, Haiti has a strong potential in renewable energy; Solar energy is an asset for the electrification of developing countries like Haiti and promotes the sustainable development of poor communities. With solar energy, rural areas can access development while protecting the environment. Solar energy will enable the operation and expansion of sustainable energy infrastructure in the country; The sunshine mapping in figure (3.7) it makes a presentation of the photovoltaic potential in kWh/kWp:

Figure 3.7 – Photovoltaic power potential of Haiti

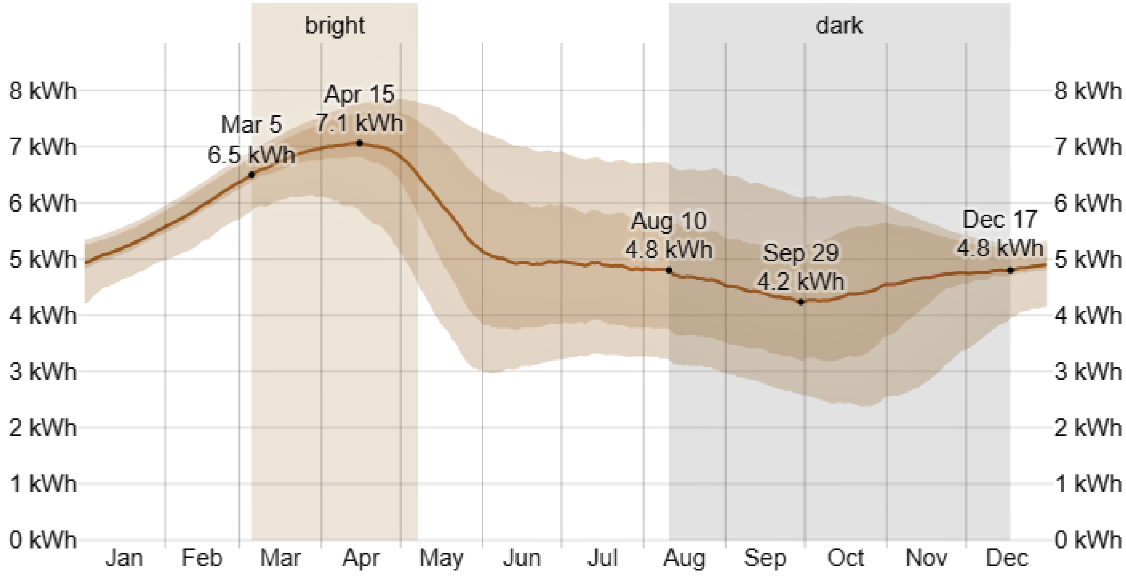


Source: (SOLARGIS, 2019)

3.3.1 Solar radiance in Haiti

Solar energy therefore offers relevant solutions to populations far from the electrical network and for whom the costs of connection are prohibitive. Haiti has been identified as ideal site for the production of solar energy (WORLDBANK.ORG, 2022). The evaluation of solar resources carried out by the (WEATHERSPARK, 2022) confirms an enormous solar potential with a global solar irradiation varying from 5 to 7.1 kWh/m²/day in most of the country (PNUD, 2019). The solar access map in figure (3.8) presents the photovoltaic potential in kWh, and thus provides information on the monthly solar penetration of the country.

Figure 3.8 – Haiti, solar radiance per year



Source: (WEATHERSPARK, 2022)

3.3.2 The optimal angle and the average temperature of the major cities of Haiti

Proposal of the optimal angle of inclination of the solar panels per month for some regions of Haiti per year; The table (3.4) above presented the optimal angle for some specific regions of Haiti, which represents the 4 cardinal corners: Port-au-Prince, Cap-Haitien, Jacmel, and Les-Cayes:

Table 3.4 – Optimal angle across some large regions of Haiti for PV operation

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Port-au-Prince	56°	64°	72°	80°	88°	96°	88°	80°	72°	64°	58°	48°
Cap-Haitien	56°	62°	70°	78°	86°	94°	86°	78°	70°	62°	54°	46°
Jacmel	56°	64°	72°	80°	88°	96°	88°	80°	72°	64°	58°	48°
Les-Cayes	56°	64°	72°	80°	88°	96°	88°	80°	72°	64°	58°	48°

3.3.3 Haiti, Solar irradiation by 10 regions (WEATHERSPARK, 2022)

Therefore, provide very detailed region mappings regarding the annual and monthly average energies of photovoltaic electricity supplied by the total installed capacity of a PV system in Haiti (WEATHERSPARK, 2022):

3.3.3.1 West

Latitude: 18,539° Longitude: -72,335° Altitude: 44 m
The brightest period of the year lasts 2.1 months, from March 3 to May 5, with incident shortwave solar radiation per square meter exceeding 6.4 kWh. The brightest month of the year in Port-au-Prince is April, with an average of 6.8 kWh. The darkest period of the year lasts 3.6 months, from September 14 to January 3, with incident shortwave solar radiation per square meter less than 5.0 kWh. The darkest month of the year in Port-au-Prince is October, with an average of 4.6 kWh.

3.3.3.2 Centre (Hinche)

Latitude :19,150° Longitude : -72,017° Altitude : 237 m
The brightest period of the year lasts 2.2 months, from February 28 to May 3, with incident shortwave solar radiation per square meter greater than 6.3 kWh. The brightest month of the year in Hinche is April, with an average of 6.6 kWh. The darkest time of year lasts 3.7 months, from September 16 to January 7, with incident shortwave solar radiation per square meter less than 5.0 kWh. The darkest month of the year in Hinche is October, with an average of 4.7 kWh.

3.3.3.3 Artibonite (Gonaives)

Latitude: 19,447° Longitude: -72,689° Altitude: 5 m
The brightest period of the year lasts 2.0 months, from March 6 to May 5, with incident shortwave solar radiation per square meter exceeding 6.4 kWh. The brightest month of the year in Gonaives is April, with an average of 6.8 kWh. The darkest time of year is 4.2 months, from September 3 to January 9, with incident shortwave solar radiation per square meter less than 5.0 kWh. The darkest month of the year in Gonaives is October, with an average of 4.6 kWh.

3.3.3.4 North-East (Fort-Liberté)

Latitude: 19,663° Longitude: -71,838° Altitude: 8 m
The brightest time of year lasts 1.9 months, from March 7 to May 4, with incident shortwave solar radiation per square meter greater than 6.4 kWh. The brightest month of the year at Fort-Liberté is April, with an average of 6.8 kWh. The darkest period of year lasts 4.2 months, from September 10 to January 16, with incident shortwave solar radiation per square meter less than 5.0 kWh. The darkest month of the year at Fort-Liberté is October, with an average of 4.6 kWh.

3.3.3.5 South (Cayes)

Latitude: 18,193° Longitude: -73,746° Altitude: 9 m
The brightest period of the year lasts 2.1 months, from March 5 to May 7, with incident shortwave solar radiation per square meter greater than 6.4 kWh. The brightest month of the year in Les Cayes is April, with an average of 6.9 kWh. The darkest time of year is 3.5 months, from August 20 to December 5, with incident shortwave solar radiation per square meter less than 4.8 kWh. The darkest month of the year in Les Cayes is October, with an average of 4.3 kWh.

3.3.3.6 North(Cap-Haitien)

Latitude: 19,759° Longitude: -72,198° Altitude: 7 m
The brightest period of the year lasts 1.9 months, from March 8 to May 5, with incident shortwave solar radiation per square meter greater than 6.4 kWh. The brightest month of the year in Cap-Haitien is April, with an average of 6.8 kWh. The darkest time of year lasts 4.4 months, from September 5 to January 16, with incident shortwave solar radiation per square meter less than 5.0 kWh. The darkest month of the year in Cap-Haitien is October, with an average of 4.6 kWh.

3.3.3.7 North-West (Port-de-Paix)

Latitude: 19,939° Longitude: -72,833° Altitude: 10 m
The brightest period of the year lasts 1.9 months, from March 10 to May 6, with incident shortwave solar radiation per square meter exceeding 6.5 kWh. The brightest month of the year in Port-de-Paix is April, with an average of 7.0 kWh. The darkest time of year is 4.6

months, from August 27 to January 15, with incident solar shortwave radiation per square meter less than 5.0 kWh. The darkest month of the year in Port-de-Paix is October, with an average of 4.5 kWh.

3.3.3.8 South-East(Jacmel)

Latitude: 19,939° Longitude: -72,833° Altitude: 10 m
The brightest period of the year lasts 2.0 months, from March 5 to May 6, with incident shortwave solar radiation per square meter greater than 6.5 kWh. The brightest month of the year in Jacmel is April, with an average of 6.9 kWh. The darkest time of year lasts 3.8 months, from September 7 to January 1, with incident shortwave solar radiation per square meter less than 5.0 kWh. The darkest month of the year in Jacmel is October, with an average of 4.6 kWh.

3.3.3.9 Grand'Anse (Jérémie)

Latitude: 18,650° Longitude: -74,117° Altitude: 12 m
The brightest period of the year lasts 2.0 months, from March 5 to May 7, with incident shortwave solar radiation per square meter exceeding 6.5 kWh. The brightest month of the year in Jeremiah is April, with an average of 7.0 kWh. The darkest time of year lasts 4.2 months, from August 11 to December 18, with incident shortwave solar radiation per square meter less than 4.8 kWh. The darkest month of the year in Jérémie is October, with an average of 4.4 kWh.

3.3.3.10 Nippes (Miragoâne)

Latitude: 18,442° Longitude: -73,088° Altitude: 46 m
The brightest period of the year lasts 2.0 months, from March 5 to May 6, with incident shortwave solar radiation per square meter greater than 6.5 kWh. The brightest month of the year in Miragoâne is April, with an average of 6.9 kWh. The darkest period of the year lasts 3.8 months, from September 2 to December 27, with incident shortwave solar radiation per square meter below 4.9 kWh. The darkest month of the year in Miragoâne is October, with an average of 4.5 kWh.

3.3.4 Average sunshine for some key regions of Haiti

The solar energy potential in Haiti is extremely high throughout the country and remains so throughout the year, even in winter (WORLDWATCH, 2014). The metropolitan area of Port-au-Prince, where a quarter of the country's population resides, has some of the most efficient solar and wind resources (WORLDWATCH, 2014). Yet solar photovoltaic systems continue to be used on a small scale in the country. It is estimated that six square kilometers of solar PV panels could produce as much electricity as Haiti currently produces (WORLDWATCH, 2014). Consider the level of annual sunlight in the city of Port-au-Prince, which holds the majority of the country's electricity (table 3.5) (CLIMAT-HAITI, 2019).

Table 3.5 – Annual Average irradiation in Haiti

Month	Day (kWh)	Total month	Min (°C)	white Max (°C)	Average (°C)
January	7	215	30	31	25.5
February	8	225	20	31	25.5
March	8	250	21	32	26.5
April	8	240	22	32	27
May	7	215	22	32	27
Jun	8	240	23	33	28
July	9	280	23	34	28.5
August	8	250	23	34	28.5
September	7	210	23	33	28
October	7	215	22	32	27
November	7	215	22	31	26.5
December	7	215	21	31	26

3.3.5 Solar Project in Haiti

In fact, currently, the exploitation of solar photovoltaic in Haiti is done on a small scale, while the solar photovoltaic microgrids is an effective way to achieve the electrification of isolated areas, while taking into account the requirements of economic and environmental sustainability. In this case, the Haitian government is committed through the Strategic Development Plan of Haiti (PSDH) to make the country an emerging economy by 2030. To do this, one of the priority sectors is energy. To this end, the Haitian government is working to draft major documents, including plans for the general electrification of the country to develop decentralized off-grid electrical systems by building micro electrical systems based on solar photovoltaic energy to provide the necessary electricity to households, public and private institutions including hospitals, schools and shopping centers, etc. Two major projects have already been put into action: The PHARES (Haitian Solar Energy Access Program for Rural Communities), launched in September 2020 and the program for rural electrification and women's autonomy; It should be noted that the political unrest is impacting the progress of the project, which is currently unfinished, and therefore completion is set for a later date. The objective is to bring energy to remote areas; However, these advances remain very insignificant compared to the national demand. Then the investment costs are enormous to achieve the electrification of the country in general, since private investment is very little in the energy sector. In terms of realization, the United Nations Development Program and the Haitian Government (ANARSE), with financing from Japan (total funds 6 412 612.82 USD) within the framework of a project in progress which is called: Rural Electrification and Empowerment of Women (RAEW), undertakes the construction of three (3) solar photovoltaic power plants of low power (see the table 3.6), in the North-East of Haiti, precisely in the communes of Mont-Organisé, Capotille and Vallières:

Table 3.6 – Some existing Microgrid operational in Haiti

Municipalities	Solar Power (kW)	Storage (kWh)	Diesel generator (kVA)	Number of connections
Mont-Organisé	289	800	400	1151
Capotille	202.5	430	250	308
Vallières	202.5	430	250	526

However, much remains to be done for the total electrification of the country, aiming to ensure an adequate energy supply for the needs of the population and capable of supporting the country's economic growth and increasing access to reliable electricity. To encourage investment in the solar energy sector in Haiti, the government is taking incentives to create a regulatory framework that encourages the development of sustainable energy supply and respect for the Haitian environment. In this regard, in Article 24, of the Budget Law 2017 - 2018, the government has decided to modify the customs and tariffs on imports of wind and solar materials and devices (solar panels, photovoltaic converters, solar generators; In order to invite citizens or companies to invest in microgrid (MEF, 2017 - 2018).

3.3.6 Some hybrid PV-Diesel microgrids already realized in some places in Haiti

3.3.6.1 Microgrid of Les Anglais (Area South of Haiti)[167]

In 2012, EarthSpark commissioned a private prepaid microgrid in Les Anglais, a small town in the southern region of Haiti that had never had grid electricity. The initial grid served only 14, then 54 customers. In 2015, EarthSpark expanded the network to 430 connections, directly serving more than 2 000 people with 24 hours. electricity powered primarily by solar energy and battery storage, reducing customers' energy costs by up to 80% compared to previous energy sources. Microgrid datasheet (PROJECTS, 2018).

Figure 3.9 – PV Champ of Les Anglais

Source: (EARTHSPARK-INTERNATIONAL, 2017)

- Microgrid Capacity: 100 kW
- Installed PV kW peak Generation Capacity: 93.3 kWp
- Effective solar capacity: 70 kW
- Installed Diesel Generator: 30 kVA
- Peak demand: surveyed at 40 kW
- Nominal solar daily power generation: 420 kWh (peak)
- Voltage of the medium-voltage distribution system: 7.2.2/12.47 kV
- Voltage of the low-voltage distribution system: 120/240 V (split phase)
- 400 kWh of battery capacity
- Kilometers of distribution line: 2.3 km medium voltage/3.7 km low voltage

3.3.6.2 Microgrid of Tiburon, (Area South of Haiti)

Like the previous one, this isolated micro-network is located in another region of southern Haiti. The network now has nearly 400 connections, directly serving about 2000 people. Datasheet of this microgrid (SMA-SUNBELT-ENERGY, 2018).

Figure 3.10 – Micro-grid PV-Diesel of Tiburon

Source: (EARTHSPARK-INTERNATIONAL, 2017)

- Microgrid Capacity: 138 kVA
- Installed PV kW peak Generation Capacity: 95.04 kWp
- Effective solar capacity: 80 kW
- Installed Diesel Generator: 55 kW
- Peak demand: surveyed at 50 kW
- Battery Capacity 11 200 Ah
- Nominal solar daily power generation: 485 kWh (peak)
- Voltage of the medium-voltage distribution system: 13.2/22.86 kV
- Voltage of the low-voltage distribution system: 120/240 V (split phase)
- Kilometers of distribution line: 2.3 km medium voltage, 3.7 km low voltage

3.3.6.3 Sigora Haiti's micro utility project

SIGORA Project realized in the North-West department with three hybrid micro-grids (Diesel + PV), for a total installed capacity of 1.25 megawatts (MW) of diesel, 0.2 MW (Môle Saint Nicolas microgrid: 208 kW; Jean Rabel microgrid 780 kW; Bombardopolis microgrid 245 kW).

Figure 3.11 – Micro-grid in Project of SIGORA, North-west of Haiti

Source: (SIGORA, 2017)

3.3.6.4 Project of the Hospital of Mirebalais, Area Centre/Haiti

Installed on an area of 205 000 m^2 the University Hospital of Mirebalais figure (3.12), is the largest solar hospital in the world in 2012 - 2013, as it is powered 100% by 1 800 photovoltaic panels installed on its roof (MEDIATERRE, 2020).
It was built by Partners in Health (American NGO) and Zanmi Lasante (Haitian NGO), will provide primary health care services to more than 185 000 people living in Mirebalais and surrounding communities. Equipped with 1 800 solar panels providing 0.4 MW of electricity, it produces enough energy to cover its needs, with any excess electricity being redistributed into the national grid (WORLDWATCH, 2014).

Figure 3.12 – University Hospital of Mirebalais, Area Centre of Haiti

3.3.6.5 Microgrid CEAC Cooperative (Area South/Haiti)

The first electricity cooperative in Haiti, Coopérative Electrique de l'Arrondissement des Coteaux (CEAC), contributes to promoting access to electricity for members, residents of the communes of the Coteaux district including Roche-à-Bateau, Coteaux and Port-à-Piment. This hybrid micro-grid (Diesel + PV) has a capacity of between 125 and 135 kilowatts of solar energy production and 200 kilowatts produced by diesel generators, to supply the 580 members of the cooperative (figure 3.13).

Figure 3.13 – Micro-grid of CEAC Cooperative, Area South of Haiti

3.3.6.6 Solar-diesel-wind hybrid station of Les Irois (EDH)

Les Irois micro power plant operate with 4 blocks of 36 wind turbines (phileol) of 166 watts each and a solar system of 380 panels, for a total combined production of 145 to

160 kilowatts. It will have a diesel backup generator with a capacity of 150 kilowatts and a bank of battery storage.

Figure 3.14 – Microgrid hybrid of Les Irois

3.3.7 Solar Pumping System

Solar energy also represents a great advantage to develop the solar pumping system, with the objective of increasing sustainable access to water in agricultural areas or in regions where access to water is difficult.

Figure 3.15 – Inauguration of some solar pumping by the Haitian president

During the last five years, the Ministry of Agriculture and Rural Resources has installed several pumping systems throughout some departments of Haiti such as Artibonite, North-East, Center and West, allowing to extract water from boreholes in the water tables for watering rice fields, vegetables, etc.

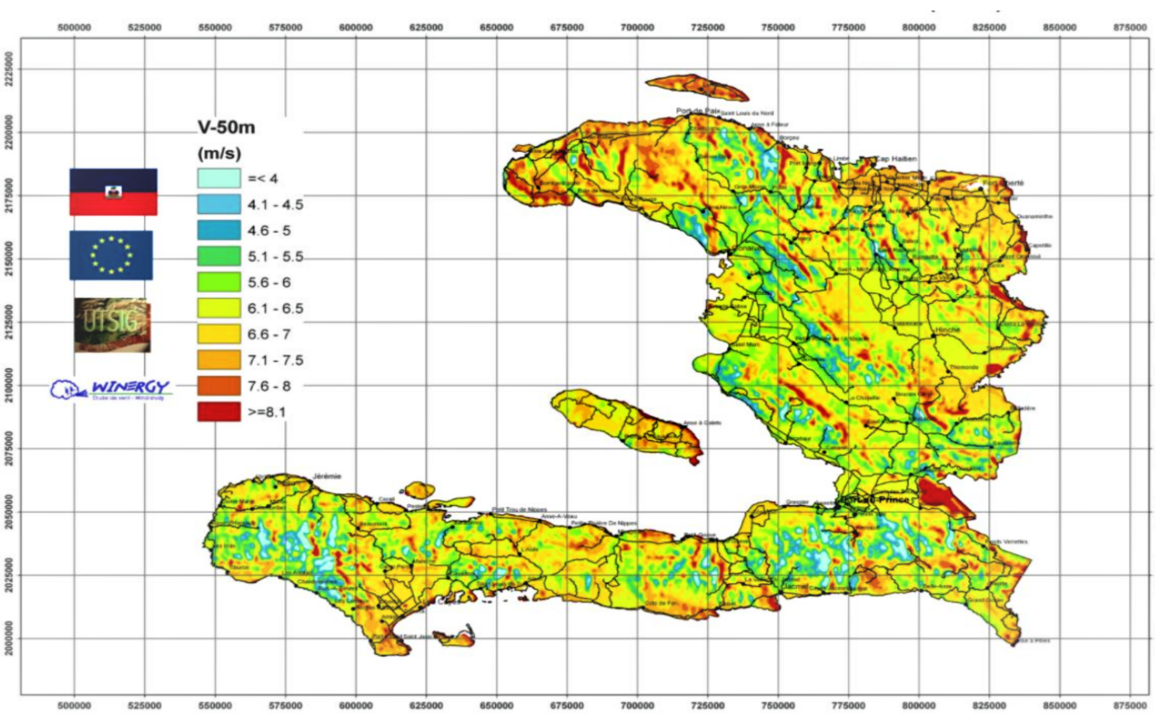
3.3.8 Standard voltage in microgrids

The standards of Electricité d'Haïti (EDH) for medium voltage lines are 12.47 kV for microgrids and 22.9 kV for rural areas (DANLEY, 2018). However, in rural areas, the 12.47 kV voltage level is often chosen for microgrids that have already been built in order to reduce installation and operating costs.

3.4 WIND ENERGY POTENTIAL IN HAITI

Like many of the Caribbean, Haiti benefits from the trade winds, regular winds throughout the year that enter the northeast region and strengthen in winter. Most of the country has sites where the average annual wind speed is at least 6 m/s at a pivot height of 80 meters (WORLDWATCH, 2014). Haiti enjoys good wind conditions and has a significant wind energy potential that deserves to be developed (BAVARDAY; GRELLIER; SURLA, 2014). All studies conducted show a strong wind potential in Haiti and this throughout the territory (BAVARDAY; GRELLIER; SURLA, 2014).
The regions well exposed to the East and Northeast have better wind potential (BME, 1989). The Haitian government has identified wind power as a national priority, determining that the resource should be developed wherever there is evidence that it may be economically viable. The figure (3.16) made by WINERGY 2016, shows the wind speed on the different parts of the territory of Haiti according to each color code; The green color indicates the regions where the wind speed is between 5.1 m/s to 5.5 m/s; The yellow color indicates the regions where the wind speed is between 6.1 m/s to 6.5 m/s; The red color indicates the regions where the wind speed is 7.1 m/s to 8.1 m/s. The Wind Atlas of Haiti identifies the area of Etang Saumâtre located near the border with the Dominican Republic as having a very favorable wind potential for the establishment of a wind power station. Etang Saumâtre has an exploitable wind resource: a power plant capable of supplying the Port-au-Prince network (5 to 10 MW) could be quickly planned. The exploitation of the Cap-Haitian resource is possible (WINERGY, 2014). Wind speeds are highest at Lac Azuéi from June to August, with average speeds during this period ranging from 9 m/s (August) to over 10 m/s (June and July). This corresponds to an average capacity factor of at least 75% during this period. April has the lowest average wind speed, although it is still near 7 m/s, which corresponds to an average capacity factor of just under 50% (WORLDWATCH, 2014). Several regions of Haiti that have good wind potential with winds of more than 6 m/s at 30 meters. These are mainly Môle St-Nicolas, Ile de la Tortue and Port-de-Paix in the North-West and the Cayes peninsula in the South. There are also some corridors in the Cul-de-Sac Plain and in the Central Plateau with winds of 5 to 6 m/s at 30 meters (WINERGY, 2014).

Figure 3.16 – Onshore Wind Atlas of Haiti, wind speed 50 m



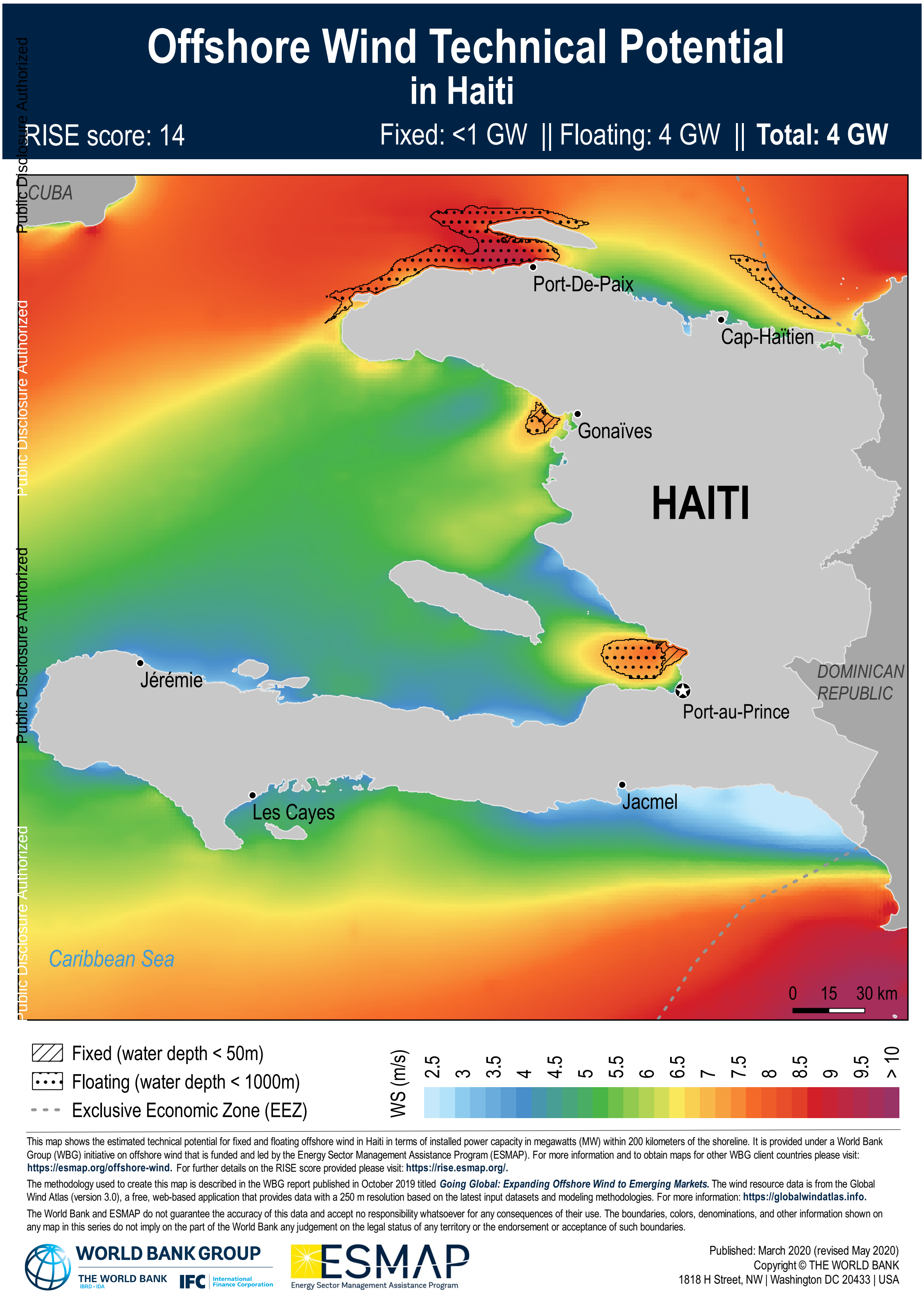
Source: (WINERGY, 2014)

The regions with the best potential are mainly those located at altitude or near the sea, especially those on the exposed northern coasts. Winergy has refined the wind atlas for two areas marked by an initial preference, namely, Cap-Haitien and Fort-Liberté and a new area Port-de-Paix. Average annual strong wind speeds of about 7 m/s are found near Miragoâne, Les Cayes, and the southern part of the Northeast Province (WORLDWATCH, 2014). According to a study conducted by the World Bank and ESMAP (Energy Sector Management Assistance Program) in 2020, it was revealed that Haiti has an offshore wind capacity of approximately 4 GW (WORLDBANK, 2020), which can meet 4 times the current energy needs of the country, since the total energy demand is approximately 800 MW to 1 000 MW. These meteorological data come from the WINERGY wind archive. For each large scale, a statistical chronicle containing the wind speed and direction every 6 hours from 1988 to 2001.

3.4.1 Potential Wind offshore mapping of Haiti

Haiti is an island country and the coasts stretches along a coastline of 1 500 km. All the points of the territory territory is less than 100 km from the sea and all the cities are located at the the sea (DUPLAN, 2005).

Figure 3.17 – Offshore Wind technical potential of Haiti, ESMAP



Source: (WORLDBANK, 2020)

In the figure (3.17), the blue color represents the region where the wind speed is less, which is a speed between 2.5 m/s to 4 m/s.
The green color represents where the wind speed is important enough for the operation of the wind turbine, which is an average speed in the range of 5 m/s to 6 m/s. The yellow color represents the regions where the wind speed can include in a range of 6.5 m/s to 7.5 m/s. The red color represents regions where the wind speed is very high, and is included in a range of 8 m/s to 9.5 m/s. Three regions of Haiti where studies have proven very abundant wind speed: Cap-Haitien (North), Port-de-Paix (North-West) Fort-Liberté (North-East), with an average speed of 5.5 m/s from November to May; minimum speed 4.4 m/s; maximum speed 6.3 m/s. The island is bathed in the north by the Atlantic Ocean, in the south by the Caribbean Sea. Windward canal is a maritime channel of class H - hydro-graphic in Haiti. This is because the country has great potential in wind energy. The Windward Passage is a strait in the Caribbean Sea, between the islands of Cuba and Hispaniola. The strait specifically lies between the easternmost region of Cuba and the northwest of Haiti. 80 km (50 mi) wide, the Windward Passage has a threshold depth of 1 700 m (5 600 ft). In electrical production, the wind energy production of Haiti is equivalent to zero. Given the geographical situation of Haiti and its wind potential, wind energy can be viable solutions in the energy production to the country. This can contribute to reduce the use of fuels in the energy production, whose fluctuating prices and scarcity causes a considerable reduction in the electrical production throughout the country. Wind energy is an energetic and technological advantage, allowing EDH to diversify its energy sources, while reducing production costs; Also limiting the release of dioxide into our atmosphere. Haiti being a country in debt, and at the same time facing a chronic sociopolitical-economic crisis, is in great difficulty to finance its major projects. In this regard, private investments or financing from international bodies such as the Inter-American Development Bank (IDB), the World Bank or the IMF were needed. Attempts to implement wind power in Haiti have ended in failure; The first wind power projects in Haiti date back to the 1980 with the installation of a power plant of 5 wind turbines of 30 kW in Port de Paix. Currently this plant no longer exists (BAVARDAY; GRELLIER; SURLA, 2014).

3.4.1.1 Wind classification

Wind energy is available locally and it is an intermittent energy; Therefore, for the operation of wind energy in a region, it is necessary to identify the characteristics of the wind; There are regions in which the winds are more frequent due to each season, both for the installations of wind turbines on land known as onshore, or for the wind installations on the sea known as offshore. The wind is therefore characterized according to its direction and speed in m/s or km/h. According to the IEC 614000-1 (MOLINARO; MULTON, 2020) standard, the wind characteristics make it possible to classify the wind in several classes I, II, III, IV, in order to better dimension the machines of a wind farm:

Table 3.7 – Wind Classification by speed

Criteria	Class I	Class II	Class III	Class IV
Average wind speed	Max 10 m/s	Max 8.5 m/s	Max 7.5 m/s	Max 6 m/s
Burst over 50 years	70 m/s	59.5 m/s or 153 km/h	52.5 m/s	42 m/s
50 year established wind	50m/s	42,5 m/s	37.5 m/s or 135 km/h	30 m/s

3.4.2 Haiti, wind activity by region per year

3.4.2.1 West

The windiest period of the year lasts 2.8 months, from May 28 to August 20, with average wind speeds above 9.2 km/h. The windiest month of the year in Port-au-Prince is June, with an average hourly wind speed of 10.3 km/h.

3.4.2.2 Centre (Hinche)

The windiest period of the year lasts 6.3 months, from November 1 to May 10, with average wind speeds above 10.0 km/h. The windiest month of the year in Hinche is December, with an average hourly wind speed of 11.8 km/h.

3.4.2.3 Artibonite (Gonaives)

The windiest period of the year lasts 6.3 months, from November 1 to May 11, with average wind speeds above 13.8 km/h. The windiest month of the year in Gonaïves is December, with an average hourly wind speed of 16.7 km/h.

3.4.2.4 North-East (Fort-Liberté)

The windiest period of the year is 2.3 months, from June 22 to September 1, with an average wind speed of over 16.2 km/h. The windiest month of the year in Fort-Liberté is July, with an average hourly wind speed of 18.5 km/h.

3.4.2.5 South (Cayes)

The windiest period of the year lasts 2.8 months, from May 19 to August 13, with average wind speeds above 16.4 km/h. The windiest month of the year in Les Cayes is June, with an average hourly wind speed of 19.2 km/h.

3.4.2.6 North(Cap-Haitien)

The windiest period of the year lasts 2.3 months, from June 21 to August 31, with average wind speeds above 17.2 km/h. The windiest month of the year in Cap-Haitien is July, with an average hourly wind speed of 19.8 km/h.

3.4.2.7 North-West (Port-de-Paix)

The windiest period of the year lasts 6.2 months, from November 2 to May 9, with average wind speeds above 19.9 km/hr. The windiest month of the year in Port-de-Paix is December, with an average hourly wind speed of 23.5 km/h.

3.4.2.8 South-East(Jacmel)

The windiest period of the year lasts 3.0 months, from May 24 to August 22, with average wind speeds above 12.9 km/h. The windiest month of the year in Jacmel is June, with an average hourly wind speed of 15.2 km/h.

3.4.2.9 Grand'Anse (Jérémie)

The windiest period of the year lasts 6.2 months, from October 30 to May 5, with average wind speeds above 14.2 km/h. The windiest month of the year in Jérémie is December, with an average hourly wind speed of 16.8 km/h.

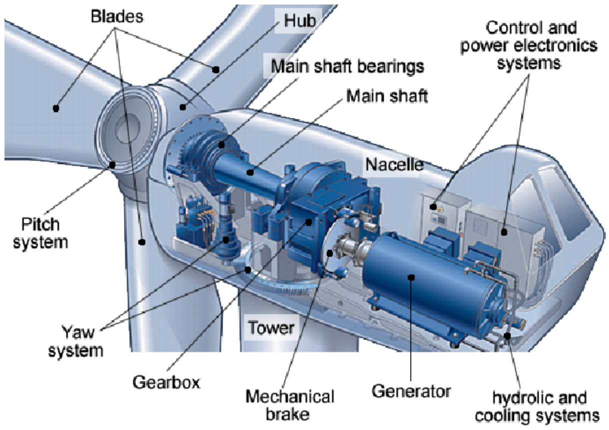
3.4.2.10 Nippes (Miragoâne)

The windiest period of the year lasts 4.4 months, from November 7 to March 19, with average wind speeds above 10.4 km/h. The windiest month of the year in Miragoâne is January, with an average hourly wind speed of 11.6 km/h.

3.4.3 Wind turbine components

Wind energy requires no fuel, and does not create greenhouse gases or produce toxic or radioactive waste. By fighting against climate change, wind energy contributes in the long term to the maintenance of biodiversity in natural environments. The figure (3.18) shows the typical utility-scale wind turbine main components; The wind drives the rotation of the blades of the wind turbine, which are mounted on a shaft (rotor), coupled to an alternator that will transform mechanical energy (the rotation of the blades).

Figure 3.18 – Wind turbine presentation



Source: (TCHAKOUA et al., 2016)

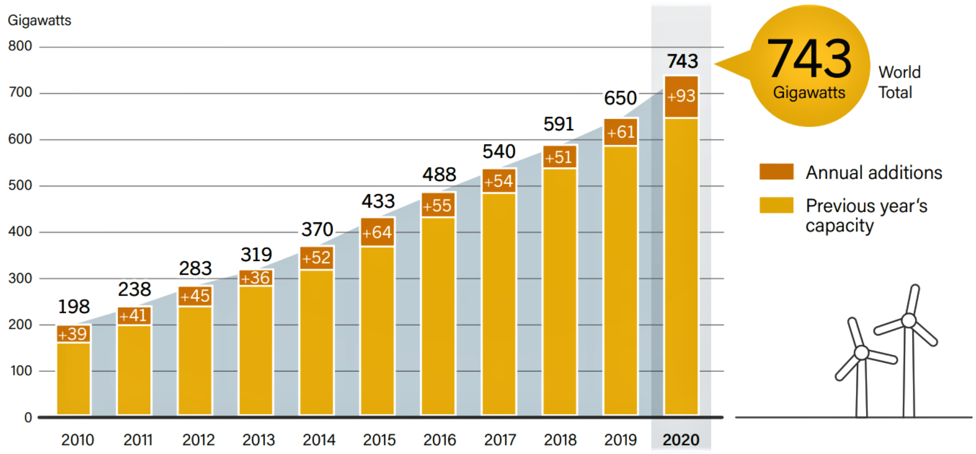
Rotors are often composed of two or three blades; the larger the diameter of the rotor, the more powerful the wind turbine. The advantage is that a wind turbine produces electricity with a natural and inexhaustible resource which is the wind; And all this, without emitting greenhouse gases.

3.5 WORLD WIND GENERATION

Wind energy plays a very important role in the energy matrix of its large countries, on the way to clean energy production. Wind energy is also used to provide energy to isolated sites, for example to produce electricity in the islands; indeed, wind turbines are in every way positive for society and the environment: less pollution, no greenhouse gases, no toxic or radioactive waste in particular. According to data published by the Global Wind Energy Council (GWEC), installed wind capacity worldwide has grown exponentially over the past decade, from about 198 GW installed in 2010 to 743 GW; 707.4 GW onshore and the rest offshore) of installed wind power in 2020 (See the figure (3.19)). China is the country with the largest installed capacity, followed by the United States with

288.3 GW and 122.3 GW respectively. In the figure published by GWEC (REN21) regarding the production of wind turbines in the energy mix of the countries operating wind.

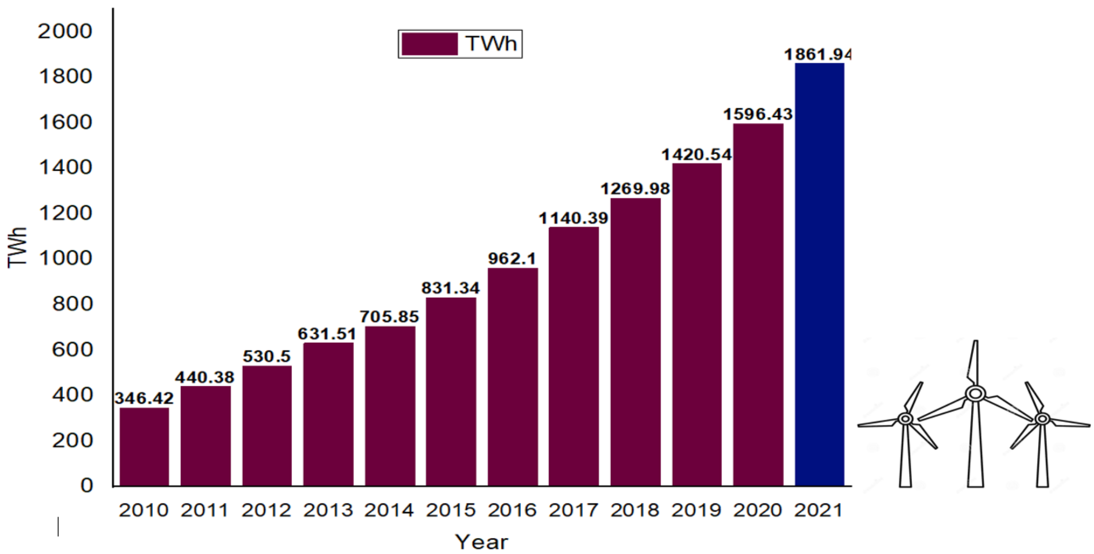
Figure 3.19 – Wind Power Global Capacity and Annual Additions, 2010 - 2020



Source: (REN21, 2021)

According to the World Wind Energy Association (WWEA), the world's onshore wind energy potential could provide nearly 200 000 TWh of electrical energy per year, assuming that wind turbines operate for 2100 hours in a year; 420 000 TWh is the annual global offshore wind potential (IFPEN, 2021). Wind energy is now expanding beyond the traditional markets of rich countries. Figure (3.20) shows the world wind generation of wind energy over the last decade (2010 - 2019) throughout the world (REN21, 2021);

Figure 3.20 – Global Wind energy production 2010 - 2019



Source: (BP-STATISTICAL, 2022)

In several countries around the world, the onshore wind park increased in recent years; In the table (3.9), GWEC publishes the wind power offshore generation during the year 2020 and 2021. During the year of 2020, USA increased its wind park by 8.67% and 13.24% in 2020; China increased its wind park by 10.59% in 2019 and 17.58% in 2020; Brazil increased its wind park 4.82% in 2019 and 12.94%; Canada its wind park by 4.45% in 2019 and 1.21%. The tables (3.8) shows the ranking all top countries in wind energy onshore production.

Table 3.8 – Onshore wind production by country 2020 and 2021

MW, Onshore	Add. Installations 2020	Total installations 2020	Add. Installations 2021	Total installations 2021
China	50 576	279 959	30 670	310 629
USA	16 913	122 275	12 747	134 354
Canada	165	13 578	677	14 255
Germany	1 431	55 122	1 925	56 814
India	1 119	38 625	1 459	40 084
France	1 318	17 946	1 192	19 131
Brazil	2 297	17 750	3 830	21 580
United Kingdom	122	13 739	328	14 064
Turkey	1 225	9 281	1 400	10 681
Australia	1 097	7 296	1 746	9 041
Mexico	574	6 789	473	7 262
Japan	551	4 373	211	4 523
Chile	684	3 444	615	3 444
Argentina	1 014	3 287	669	3 287
South Africa	515	2 495	668	3 163
Pakistan	48	1 287	229	1 516
South Korea	100	1 515	64	1 579
Vietnam	125	513	2 717	3 231
Philippines	0	427	0	427
Thailand	0	1 538	16	1 554
Sweden	1 007	9 811	2 104	10 002
Egypt	13	1 465	237	1 702
Kenya	0	338	102	440
Total onshore	88 437	708 901	72 499	780 275

Source: (GWEC, 2022)

The global offshore wind market grew nearly 30% per year between 2010 and 2018, benefiting from rapid technology improvements (IEA, 2019); Offshore wind's technical potential is 36 000 TWh per year for installations in water less than 60 metres deep and within 60 km from shore (or Global electricity demand is currently 23 000 TWh). Moving further from shore and into deeper waters, floating turbines could unlock enough potential to meet the world's total electricity demand 11 times over in 2040 (IEA, 2019). The table (3.9) show the wind energy offshore production in the world energy mix during the year 2020 - 2021 according GWEC:

Table 3.9 – Offshore wind production by country 2020 - 2021

MW, Offshore	Add. Installations 2020	Total installations 2020	Add. Installations 2021	Total installations 2021
United Kingdom	483	10 206	2 317	12 522
Germany	237	7 728	0	7 728
Belgium	706	2 262	0	2 262
Denmark	0	1 703	605	2 308
Netherlands	1 493	2 611	392	3 003
China	3 845	10 780	16 900	27 680
South Korea	60	133	0	133
USA	12	42	0	42
Total offshore	6 852	36 077	21 106	57 176

Source: (GWEC, 2022)

3.6 HYDROELECTRIC

3.6.1 Generalities

Hydroelectric energy is generated by converting the potential, kinetic and pressure energy contained in the different water flows into electrical energy. This being said, hydroelectric power is any energy obtained by the force of water, whatever its form; It is about capturing the driving force of water to produce electricity. This energy can be produced by waterfalls, rivers, sea currents, tides, waves, etc. This is a renewable energy source, almost inexhaustible; It is clean to produce, and does not create toxic or radioactive waste.

3.6.2 Hydraulic Power potential of Haiti

Hydro-power is a relevant alternative because of its ability to generate electricity in a decentralized and sustainable manner, without producing greenhouse gases, while allowing the decentralized and sustainable exploitation of local, renewable natural resources (See table 3.10).

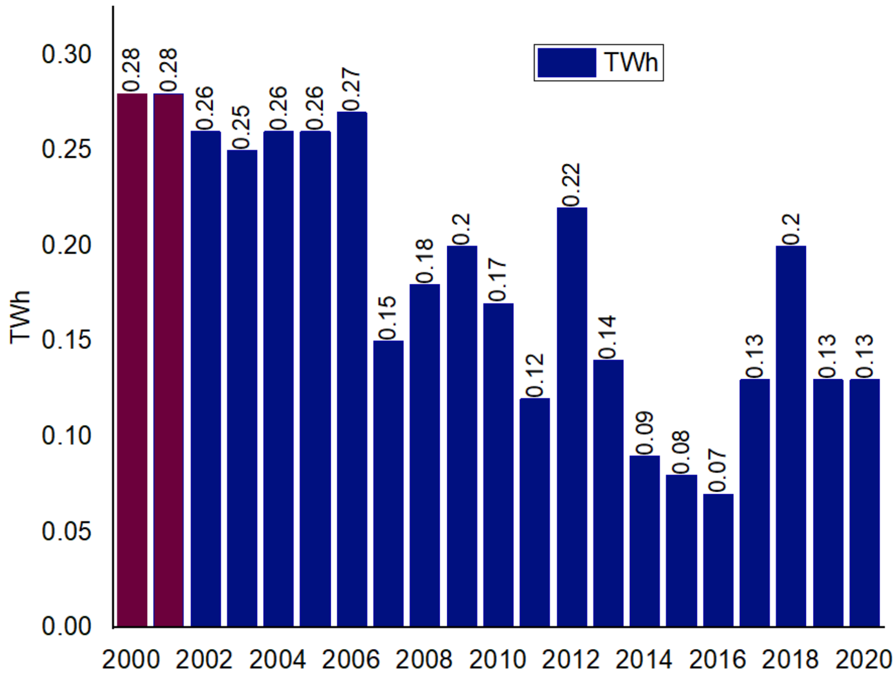
Table 3.10 – Hydroelectric Potential of Haiti by region

Region	Number Sites Eval	Qty sites (>1 MW)	Qty Sites(0.1 MW–1 MW)	Qty Sites(<0.1 MW)	Gen.	Annual E.
					MW	GWh
West	27	11	9	7	36.6	320.7
South-East	18	3	14	1	17.9	157.2
Grand-Anse	9	6	3	0	14.4	126
Nippes	5	2	3	0	10.3	89.9
Centre	24	0	18	6	7.3	64.3
South	8	4	3	1	6.2	54.0
Artibonite	23	0	8	15	3.6	31.9
North-West	13	1	2	10	2.9	25.5
North	9	0	8	1	2.0	17.7
North-East	4	0	4	0	1.1	9.3
Total	**140**	**27**	**72**	**41**	**102.3**	**896.5**

Source: (WORLDWATCH, 2014)

According to ongoing assessments Worldwatch Institute University in 2014, on the Haiti's hydro-power resource potential, she mentioned that the country has at least 102 MW of additional hydro-power capacity, which could produce up to 896 GWh (table 3.10) of power annually (WORLDWATCH, 2014). Currently, the use of hydro-power in the field of electricity generation has long been the majority source of renewable energy in production in Haiti. The Péligre hydroelectric dam is the largest hydraulic dam in Haiti; Its construction was launched as part of the agricultural project in the Artibonite Valley in the 1930 and was completed in 1956 - 1957. In 2020, hydroelectricity represents 16.56% of Haiti's energy matrix. The Peligre hydroelectric power station is 72 m high and has a nominal power of 54 MW, based on three (3) Francis type turbines with a capacity of 18 MW (SURLA, 2016). However, the average power of Péligre during the year is about 30 MW in the rainy season and 10 MW in the dry season (MTPTC et al., 2011). The figure (3.21) represents the generation curve of hydraulic electricity in Haiti 2001 - 2020.

Figure 3.21 – Hydro-energy Production Haiti (2000 - 2020)



Source: (WORLD.ENERGY, 2022)

Péligre operates with a production shortfall because deposits of garbage and silt have often reduced the activity of the power plant, reducing its capacity to produce electricity. Table (3.11) presents the hydro power capacity that exists throughout each department of Haiti, according to Worldwatch Institute University data in 2014. Some hydraulic installations already in operation in Haiti:

Table 3.11 – Hydro-power install in Haiti

Hydroelectric power station	Region	Date of Construction	Capacity
Péligre	Centre	1971	54 MW
Pico-hydro	North-East	2016	11 kW
Saut-Mathurine	Camp-Perrin (Cayes)	1983	1.6 MW
Marion	Grand-Bassin(Nord-Est)	2020	53 MW
Centrale hydro d'onde verte	Ouest	1946	750 kW
Centrale hydro de Drouet	Artibonite	1980	2150 kW
Centrale Hydro De Caracol	Grande rivière du Nord	2017	800 kW
Centrale Hydro De Gaillard	Jacmel	1895	500 kW
Délugé	Montrouis		1100 kW

Source: (EDH, 2022)

Very often, one or two of the three engines may be at a standstill simultaneously due to mechanical and maintenance problems. The river is sometimes subject to boycotts between Haiti and the Dominican Republic, which reduces the water flow. The hydroelectricity production in Haiti is in total regression during the last years, especially in Peligre where the turbines work in an intermittent way because of the reduction of the water flow by the dryness or the breakdown of the motors; During the year 2000 and 2001, the energetic production was of 0.28 GWh; In 2019 and 2020, the production dropped to 0.12 GWh. The figure (3.22) represents the hydraulic power plant and micro-hydro already exist in Haiti:

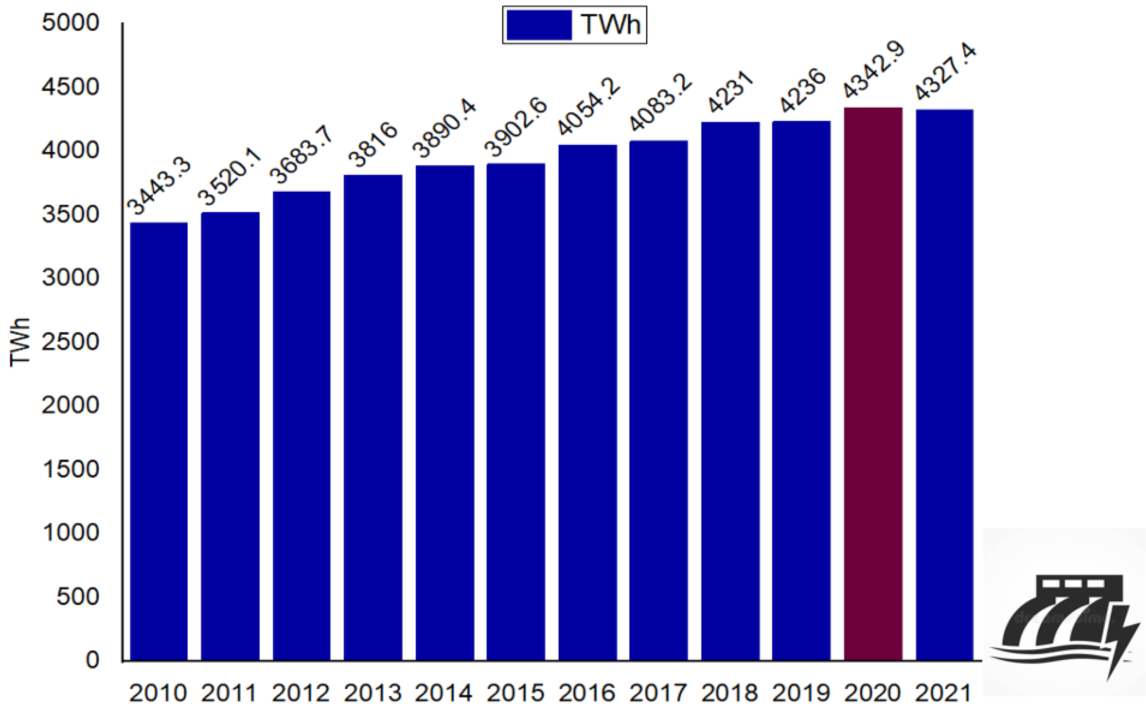
Figure 3.22 – Hydro-Electric Power in Haiti

Peligre hydroPower station, 54 MW　　Saut Mathurine, micro-hydroPower station, 1.6 MW　　Onde verte, micro-hydroPower station, 6.5 kW

3.6.3 Hydropower generation in some countries of the world

In 2021 global hydropower generation decreased by 15 TWh (down 0.4%) to 4 327 TWh. The drop in generation was caused by persistent droughts in hydropower-rich countries such as Brazil, the United States, Turkey, China, India and Canada, leading to lower than usual hydro capacity utilisation (BOJEK, 2022). However, hydropower represents a green source of electricity production worldwide. According to the data of (WORLD-ENERGY, 2022), the year 2020 had the highest level of hydropower production in the world. The hydropower sector represents around 16 % of global electricity production, more than all other renewable combined. As a technology, hydropower is an ideal complement to modern clean energy systems. No country has come close to achieving decarbonization without hydropower (IHA, 2021). Hydropower is the world's largest producer of renewable electricity (IHA, 2021). The figure (3.23) shows the global hydropower generation since of 2010 - 2021:

Figure 3.23 – World, hydropower consumption



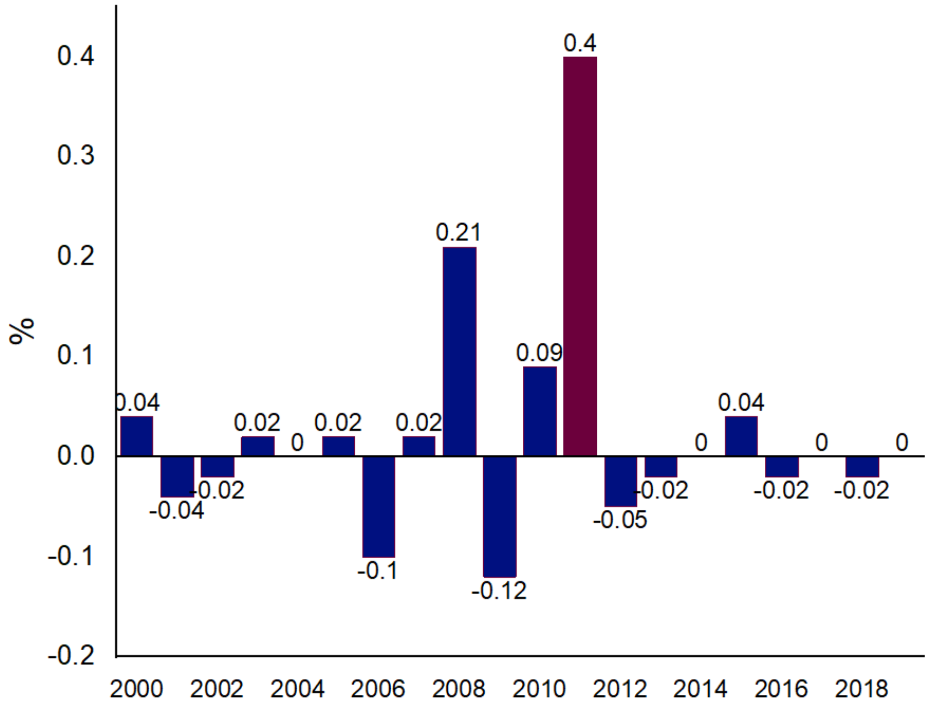
Source: (BOJEK, 2022)

3.7 INVESTMENT AND IMPACT ON THE ENERGY PRODUCTION

The level of energy production in Haiti from 2000 to 2020 is still stunted in spite of the huge expenses made by the Haitian government in order to improve the energy production of Peligre, which is the largest hydroelectric plant in Haiti.

It is a recurring problem and is dependent on the bad choice of the Haitian government. During the year in 2010, 61.2 million and in 2020, 100 million dollars were invested, as part of a financing of the IDB and the German Development Bank (KFW), for the repair and rehabilitation of two turbines of 18 megawatts, among the three turbines of Peligre, have again broken down respectively 3 months and 1 year and a half after their total rehabilitation (NOUVELLISTE, 2019). Such investment could contribute in the implementation of hybrid micro-grids throughout the country in the production of energy, as they are less demanding in terms of maintenance costs. The lack of investment has major impacts on the country's energy production. According the figure (3.24), it can be seen that in the year 2000 - 2001, there is another increase of 4%; The production is decreased by 4% during the year 2001 - 2022, and 2% during the year 2002 - 2003 and 0% during the year 2019 - 2020:

Figure 3.24 – Haiti, energy production variation by year (2000 - 2020)



Source: (BPS, 2022)

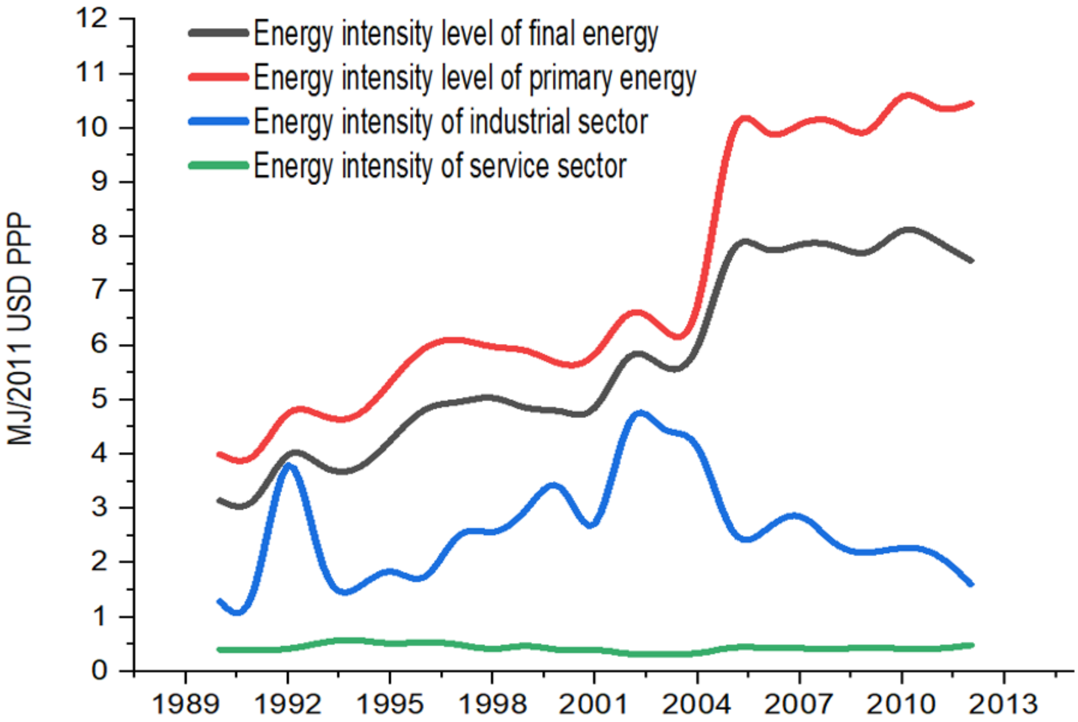
3.8 ENERGY INTENSITY OF HAITI

The final energy intensity of a country is the amount of final energy used in the economy in a given year to produce one unit of GDP. It is calculated as the ratio of final energy consumption to GDP and is usually expressed in tons of oil equivalent (toe) per monetary unit in PPP (Purchasing Power Parity) (TABARLY, 2007). A decrease in energy intensity means that the country can produce more with the same amount of energy: it is therefore more productive in terms of energy (TABARLY, 2007). This being said, lower energy intensity corresponds to higher energy efficiency, because the higher the energy efficiency, the lower the energy intensity. Taking into account the objectives set by Haiti to reduce energy intensity to 30% by 2030 (NREL, 2015); Many challenges must still be met in its transition to clean energy and better efficiency. In fact, energy intensity in Haiti has been increasing steadily from 1990 to 2012, both in the service and industrial sectors. According to the figure 3.25, taking 1990 as a reference year, primary energy intensity was 3.99 MJ/USD, final energy intensity was 3.14 MJ/USD, industrial energy intensity was 1.29 MJ/USD and energy intensity for services was 0.40 MJ/USD (SE4ALL, 2017).

Referring to the year 2012, the primary energy intensity increased to 10.45 MJ/USD, while the final energy intensity increased to 7.56 MJ/USD; On the other hand, the industrial energy intensity increased to 1.60 MJ/USD and the energy intensity for services was 0.48

MJ/USD. This being said, efforts must be multiplied in order to improve the energy efficiency in the country (SE4ALL, 2017).

Figure 3.25 – Haiti, energy intensity by sector



Source: (SE4ALL, 2017)

Energy efficiency improvements on both the demand and supply sides would enable the system to reach more customers and to improve energy services and reliability with less additional capacity (LUCKY; AUTH; OCHS, 2014). Utilizing energy efficient cook-stoves (cooking accounts for a majority of Haiti's residential energy consumption) enables Haitians to use less energy and save money(LUCKY; AUTH; OCHS, 2014).

4 RURAL ELECTRIFICATION AND PROCESS

4.1 GENERAL CONSIDERATION

In this chapter, we have proposed models of sustainable solutions, based on hybrid micro-grid technology, capable of sustainably increasing access to energy in isolated rural areas, far from electrical networks; In small underdeveloped urban communities; And in urban centers (departmental capitals). As a pilot project, the commune of Abricots (Grand'Anse), a small, poor and underdeveloped rural community, totally lacking in basic infrastructure and difficult to access, was chosen for the implementation of this solution.

4.1.1 Rural Electrification

Decentralized rural electrification is a global goal as we approach 2030; But especially a challenge in Haiti. Microgrids have become one of the most attractive and reliable solutions in recent years when planning electrification of small rural communities. Under optimal conditions, thanks to improved technology and significantly reduced production costs, they are an alternative to be seriously considered. They are complementary to conventional strategies and they have more presence in the energy policies of different countries due to their great potential to rapidly improve the quality of life of the inhabitants. Since rural electrification is a great means to reduce poverty, precisely in Haiti, the unavailability of energy is also an obstacle to the socioeconomic and social development of this rural community, which is largely marginalized, and to the nightlife and economy of the community of Abricots. Promoting access to energy is already a prerequisite for the take-off of this rural community. In this chapter, we have proposed models for inclusive solutions that can sustainably increase access to energy in remote rural areas, far from the electricity grid, in small, underdeveloped urban communities, and in urban centers (departmental capitals). As a pilot project, the commune of Abricots (Grand'Anse) was chosen, being a small, very poor and underdeveloped rural community, totally devoid of any basic infrastructure and with difficult access for the implementation of this solution. There is a need to find better solutions for the electrification of isolated localities:

- In the rural areas of Abricots, an inclusive energy solution will be proposed, taking into account a sustainable environmental efficiency promoting access to electrical energy to this highly vulnerable and disadvantaged segment of Haitian society, namely the peasants, many of whom have never had the opportunity to see an electric light bulb lit in their home.

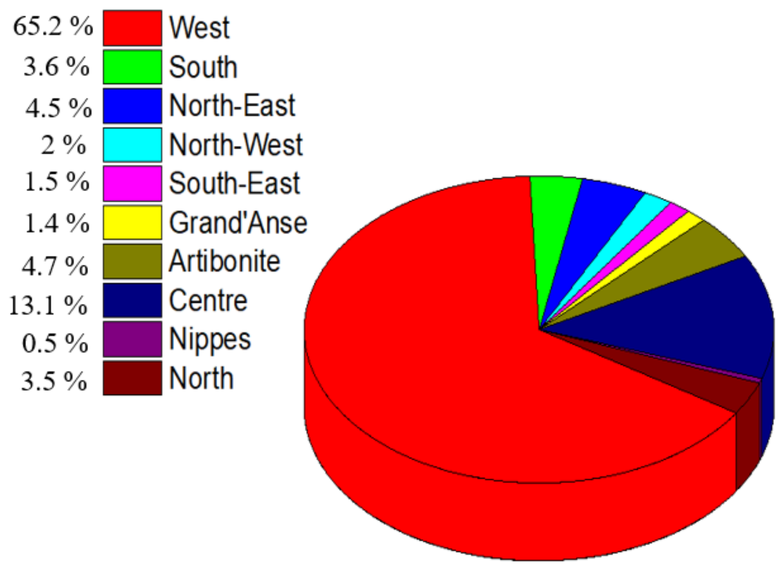
- In the urban areas, a hybrid PV-Diesel-storage microgrid will be designed, which will contribute to improve the living conditions of the inhabitants of the region in terms of economic growth.

Electrification allows to increase the standard of living of the inhabitants, and constitutes a tool of first choice towards development. Particularly in rural areas, it allows to reconcile economic development, sustainability, respect of the environment, but also resilience to climate change. Nevertheless, it is important to take into account the indirect effects of the lack of electrification on the living conditions of the poorest households in rural areas, such as job creation, mass exodus of the population, chronic and accelerated poverty, etc. In terms of benefits, the integration of electric power in rural areas has the following impacts:

- Precondition for social development;
- Emergence of small businesses and development of economic activity;
- Creation of jobs and productive activities;
- Reduction of the rural exodus;
- Knowledge acquired by local populations through technology transfer;
- Improvement of the quality of life of the vulnerable population (especially school children);
- The use of local resources and the creation of activities;
- Promote social emancipation, especially for women.

Reliable access to electrical energy is increasingly rare in rural areas throughout the developing world, particularly in Africa and Haiti; Rural electrification aims to facilitate rural people living in remote areas to have access to electrical energy. Access to energy in remote rural areas allows rural people to be included in the recovery of their socioeconomic situation. It is evident that rural electrification has a positive impact on poverty indicators; Indeed, access to electricity has a primary role in reducing poverty in developing countries. Microgrids are a technology that can increase access to electricity in rural areas, while harnessing locally available energy sources; in particular to reduce the cost of energy production. In Haiti, the rural electrification rate is 5%; However, this 5% fringe has electricity by chance and in an unstable and unreliable manner, despite the availability of renewable resources throughout the territory. With the Department of the West holding the largest share of electrification, 63.07% (figure 4.1), because it centralizes virtually all political, economic and commercial activities, and holds virtually all the country's infrastructure:

Figure 4.1 – Haiti, total electrification rate of the country in percentage (2019)



4.1.2 Presentation of the Region of Abricots

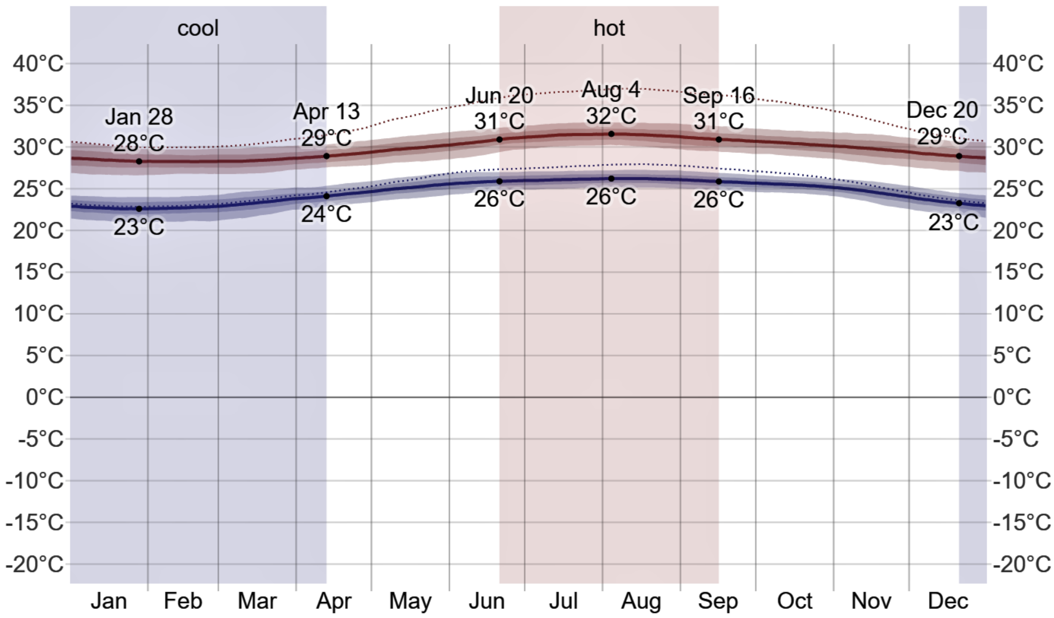
Abricots is a commune with an area of 102.89 km² (figure 4.5); It is located in the department of Grand'Anse, district of Jérémie. It was elevated to the rank of commune in 1789 and is currently subdivided into four (4) communal sections, fifty-eight (58) localities and forty-five (45) neighborhoods. In 2015, according to data from the IHSI, its total population was estimated at 37 675 inhabitants; However, more than 96% of the population lives in rural areas; That is, 1 353 inhabitants (286 households) live in urban areas (0.15 km², density 9 020) and 36 322 inhabitants (6 921 households) live in rural areas (102.74 km², density 354), with a density of inhabitants/km² ((IHSI), 2015), with a Longitude of -74.3092° and Latitude 18.6486°. The hydrology of the region presents the following rivers: Anse-du-Clerc River, Balisiers River, Danglise River, Cap River and La Seringue.

Figure 4.2 – Satellite view of Abricots

The dominant relief of the commune of Abricots is the mountains; It is a coastal town which, due to its geographical position, generally enjoys a normal climate; However, it is a climatically vulnerable town because quite often it has been swept away by natural disasters which destroy all the town's infrastructure and each time its inhabitants had to go back to work to rebuild it.

4.1.3 Average Temperature in Abricots

Figure 4.3 – Temperature of Abricots by season



Source: (WEATHERSPARK, 2022)

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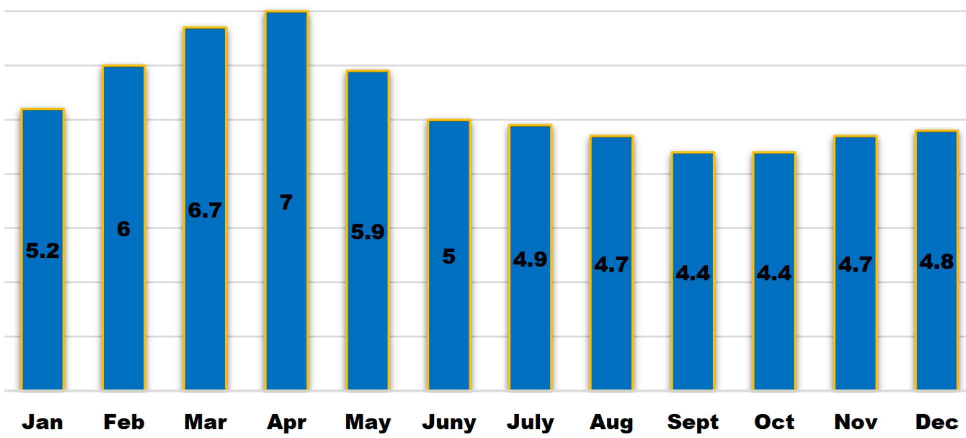
The town of Abricots is almost isolated from the rest of the country, because due to its remote geographical position, it often suffers from supply problems of all kinds, especially fuel, which hardly penetrates the region, since it is difficult to reach by road. In terms of environmental vulnerability, the region has often been hit by major climatic events over the past 68 years (see Table 2.9).

The hot season lasts for 2.9 months, from June 20 to September 16, with an average daily high temperature above 31°C. The hottest month of the year in Abricots is July, with an average high of 31°C and low of 26°C. The cool season lasts for 3.8 months, from December 20 to April 13, with an average daily high temperature below 29°C. The coldest month of the year in Abricots is January, with an average low of 23°C and high of 28°C (figure 4.3).

4.1.4 Solar irradiation in Abricots by season

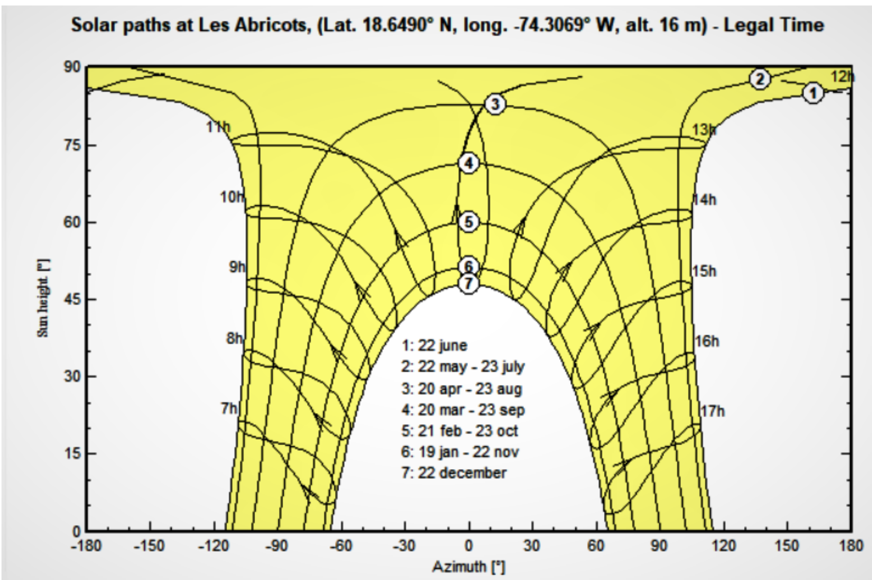
At Abricots, the average daily incident shortwave solar energy experiences seasonal variations throughout the year. The brightest period of the year lasts for 2 months, from March 5 to May 7, with an average daily incident energy per square meter of over 6.5 kWh (figure 4.4).

Figure 4.4 – Solar Irradiation of Abricots by season



The brightest period of the year in Abricots is April, with an average of 7 kWh. The darkest period of the year lasts 4.2 months, from August 10 to December 17, with an average daily incident shortwave energy per square meter of less than 4.8 kWh. The darkest month of the year in Abricots is October, with an average of 4.4 kWh (WEATHERSPARK, 2022). The PV-Syst software allows to see in the figure (4.5) the sun path, the azimuth and the elevation of the sun above the horizon for a given position and time in Abricots:

Figure 4.5 – Solar path of Abricots



4.1.5 Socioeconomic condition of Abricots

In Abricots, being one of the most precarious regions of Haiti, while it is extremely rich in seafood, the region was for a long time nicknamed the fisherman village because fishing is the most profitable economic activity for the population. However, due to the lack of electricity, fishing is practiced only for quick consumption and personal feeding of the fisherman, as there are no freezing facilities. As a result, more than ¾ of the population live in total economic precariousness, having no determined and continuous income; Nevertheless, the exploitation of fishing requires a prerequisite which is the energy for the conservation of the products. To ensure a minimum of survival, the production of charcoal has become one of the main commercial activities, allowing the population to obtain a minimum purchasing capacity and to support his families. The settlements are not electrified either, as they are very scattered and isolated from each other. The majority of villagers are in a situation of energy and economic insecurity because they do not have the possibility of obtaining a solar energy system to listen to the radio, charge their telephones, light their houses, allowing schoolchildren to study at night; To light themselves at night, they use kerosene lamps or fig candles.

Figure 4.6 – Lighting of houses with kerosene lamps in Abricots

Source: analyseht.com

As a result, children cannot study at night because the lamp does not last too long (figure 4.6); moreover, the burning of kerosene is harmful to the environment because of the release of carbon into the environment, and in fact, it affects the health of children's eyes in the long term. Few households use solar energy or generators; The privileged household that has the possibility to buy a solar panel at home, makes a micro-business out of it, as villagers pay between 15 and 25 Gourdes to charge their phone at the neighbor's.

4.1.6 Charcoal-based energy

Haiti is suffering from a serious degradation of its natural environment, and in particular from a strong pressure on the national natural resources (WORLDBANK, 2019); For the production of charcoal, fruit trees such as mango trees, avocado trees, breadfruit trees, etc. are cut down by peasants; In fact, the cutting of trees for charcoal production is strongly among the main causes of Haiti's environmental degradation. However, the majority of the Haitian population depends on charcoal as a fuel resource to meet their daily cooking needs and nationally, approximately 70% of energy needs are covered by firewood and charcoal (WORLDBANK, 2019); The wood energy sector represents 9% of Haiti's gross domestic product and is a source of income for 150 000 people, including 67 000 charcoal makers (RAKOTOMALALA, 2012). In the figure (4.14), shows the charcoal production chain for household consumption in Abricots.

Figure 4.7 – Charcoal energy production in Abricots

4.1.7 Facilitate electric access to rural area as alternative and sustainable energy solution at Abricots

Haiti is a tangible proof that demonstrates the interrelation that exists between energy and poverty. This being said, in order to solve the energy problem of Haiti in a sustainable way, the term Energy Eclecticism should be used, applying the best existing solutions through other countries, which had the same energy characteristics as Haiti, now being on the way to development after a sustainable energy solution. According to experts, access to energy precedes development, because energy is a prerequisite for development. It is imperative that the Haitian state takes decisions on energy reform in order to promote energy inclusion and increase access to energy in rural areas of Haiti, which today represents under 5% of energy coverage, aiming to reach the most vulnerable layers in order to attack poverty in its depth. To achieve this, it is imperative for the Haitian state to implement significant actions to promote access to energy to more than 7 million Haitians by 2030, in accordance with the UN's SDG7.

4.1.8 Range of solutions and recommendations

Enabling the penetration of electrical infrastructure in rural Haiti is not easy; it would be necessary to find efficient ways to reach peasants who are scattered in rural areas. In this part of the document, we have presented a range of solutions as proposal. The solutions are different and take into account the reality of each region. As recommendations, they are adaptable in:

- The rural areas totally deprived of any electrical infrastructure;
- Small towns (small cities);
- Large cities (departmental capitals).

4.1.9 General Characteristic of an urban and rural household in Haiti

Characteristic of an urban and rural household in Haiti (IHSI, 2000) According to studies conducted by IHSI, the average household in Haiti is composed of 4.7 persons; in rural areas, the average household is composed of 4.8 persons, while in urban areas, the average household is composed of 4.6 persons (IHSI, 2000). In rural areas, 38% of households are headed by a woman; in urban areas, 50% of households are headed by a woman (IHSI, 2000).

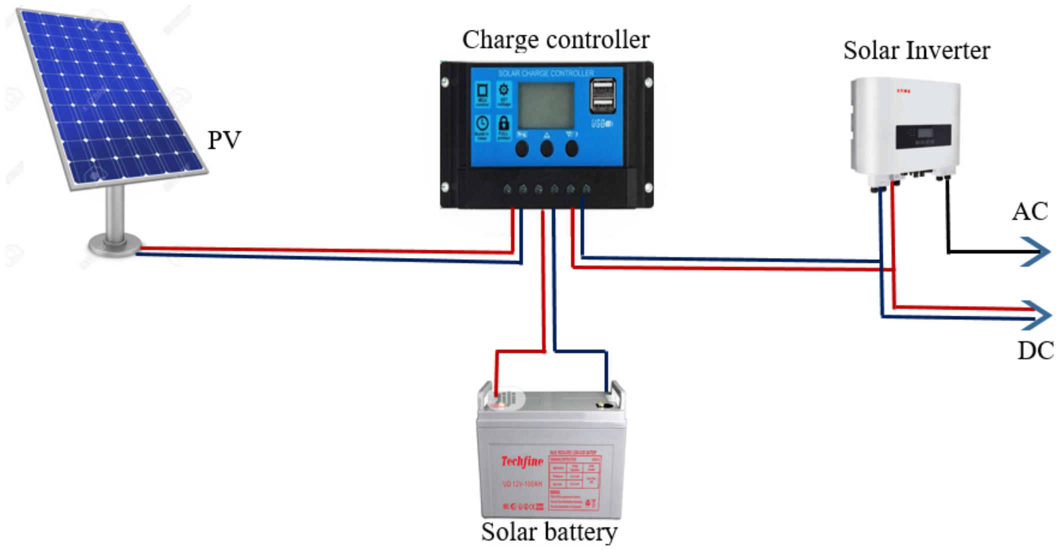
4.2 SOLUTION APPROACH

First and foremost, the rural area of the commune of Abricots, Grand'Anse region of Haiti was chosen as the focus of the pilot project, with 6 921 rural households. This type of isolated individual systems program should have a rebound effect throughout all of Haiti's rural communities, i.e., the 571 communal sections of Haiti, over a 72 months period (2024 - 2030). This experience should be repeated throughout all rural areas, i.e. the 571 communal sections of Haiti, in order to achieve the total energy integration of Haiti, which will have a real and lasting impact on the living conditions of the energy excluded.

4.2.1 Proposal 1

The first solution is exclusively for rural areas; it is a mini photovoltaic solar power plant commonly called Individual Isolated Systems, consisting of a package with a 100 W solar panel, a solar MPPT controller, a 12 V battery (30 Ah), a 150 W inverter (see figure 4.14). This individual micro-system has the capacity to create an autonomy in energy during 6h/day in a habitat containing two bulbs of 10 W each; an AM/FM radio of 15 - 25 W; and a telephone charger of 5 to 10 W. This micro generation system will be installed directly in each household's home individually, all using solar energy resources.

Figure 4.8 – Schematic of Individual Isolated Systems



4.2.2 Recommendations and mode of appropriation of the energy kits to households

In order for the package to be appropriate for people with low purchasing power in rural areas; The beneficiary must meet the prerequisites to have access to the sustainable energy inclusion project. This project should be subsidized at 15% by the Haitian State, and/or in collaboration with international donors, making access to electrical energy a national concern in the problematic of the development of Haiti and in a perspective towards 2030 that takes into account the following process:

- Implement a comprehensive energy reform policy, accompanied by legislation making energy a priority and a prerequisite for development;
- Implement Rural Energy Integration Programs from individual isolated systems, targeting each rural household (with at least two people);
- Create a decentralized Directorate across the 10 departments of Haiti, which is under the supervision of the Ministry of Public Works, Transport and Communications (MTPTC), or the Ministry of Economy and Finance (MEF) and the mayor's office in each region;

- Initiate a process of identifying each household in the region in question, assigning each house a tracking code;
- Sign a sales contract with the head of each household, in which the person commits to partially reimburse his or her purchase amount over a period of time defined in the agreement between the two parties [i.e., the regional office and the head of the household];
- Educate new customers to be active consumers, who use electrical energy responsibly and how to use their mini home network efficiently;
- A public or private banking institution will be in charge of receiving the monthly payment of the customers until the end of their contracts;
- Train qualified professionals in the field and in each region to carry out the installations in households.

4.2.3 Approach to Project Costs

This solution is less expensive than extending the electrical grid to rural areas, or creating a wind farm in the region (table 4.1).

Table 4.1 – Project Cost/Unity

Equipment	Cost ($US)	Cost (Gourdes)
Solar module (100 W) Poly-crystalline	79	7900
Charge controller (MPPT)	45	4500
Inverter (150 Watts)	150	15000
Battery Gel 12V-100 AH	135	13500
Cable & others accessories	65	7274.50
TOTAL	474	48174.5

This proposal effectively contributes to facilitating access to affordable energy for people with low incomes who find themselves far away through the electrical networks. However, in the event of making access to energy a priority in the country, as a way of creating wealth and moving towards development, this will serve in the decision making for a better and prosperous Haiti.

4.2.4 Proposal 2

Study of the implementation of a strategy to facilitate access to energy in the urban community of the municipality of Abricots. The intervention area and target population for this phase of the project are the 286 households in the urban area of the village of Abricots. The objective is to design a hybrid PV-Diesel micro-grid to meet the primary energy needs of the energy excluded in the small urban community of Abricots. The microgrid is sized not only to meet the current consumption needs but also to be flexible enough for the growth of demand for the next decades.

4.2.5 Solution approach

To dimension an autonomous hybrid microgrid, capable of supplying energy continuously to the community. The technical study of the network allows it to meet a consumption need of 478.307 kWh per day (figure 4.13) three-phase system and constant frequency 60 Hz. It is composed of the following sources:

- A photovoltaic field composed of 320 PV modules;
- Solar inverter;
- A back-up generator;
- An energy storage system with batteries.

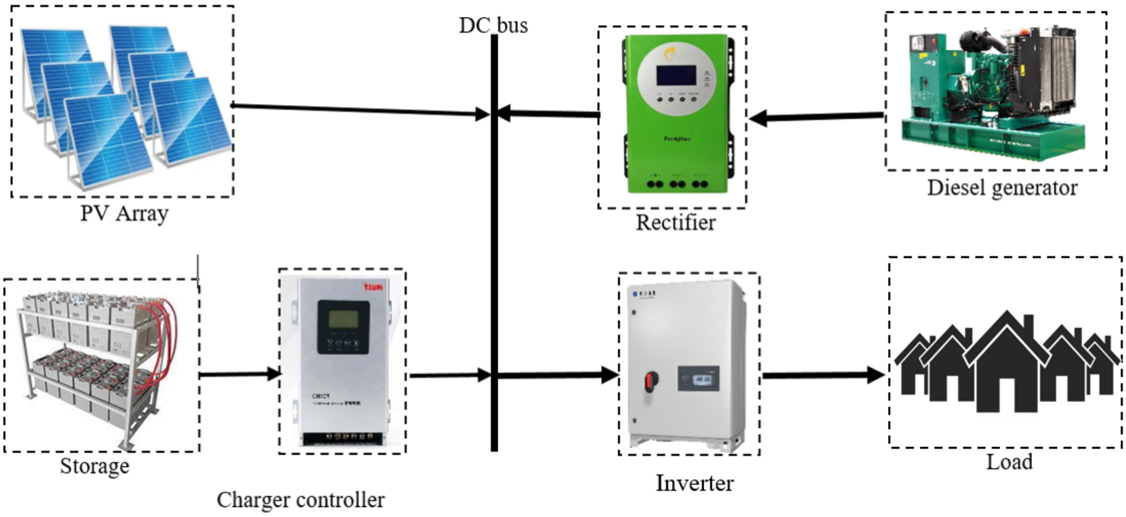
4.2.6 Hybrid Energy System

The Hybrid Energy System is a multi-source electrical energy generation system, which combines renewable sources or with conventional sources (diesel generator, gas turbines, etc.), different storage elements and different loads.

4.2.6.1 Series connection

The PV grid, the storage system are connected to the DC buses; the diesel generator is also connected to the DC bus via a rectifier. The inverter converts the DC/AC signals to power the loads. A typical hybrid system with a series connection is shown in the following diagram (STOYANOV, 2011):

Figure 4.9 – Hybrid system with DC bus connection



4.2.6.2 Advantages

- Easy to size;
- The start of the diesel generator is not linked with an interruption of the power supply;
- Good efficiency of the inverter;
- The generator can be used to recharge the batteries with a rectifier;

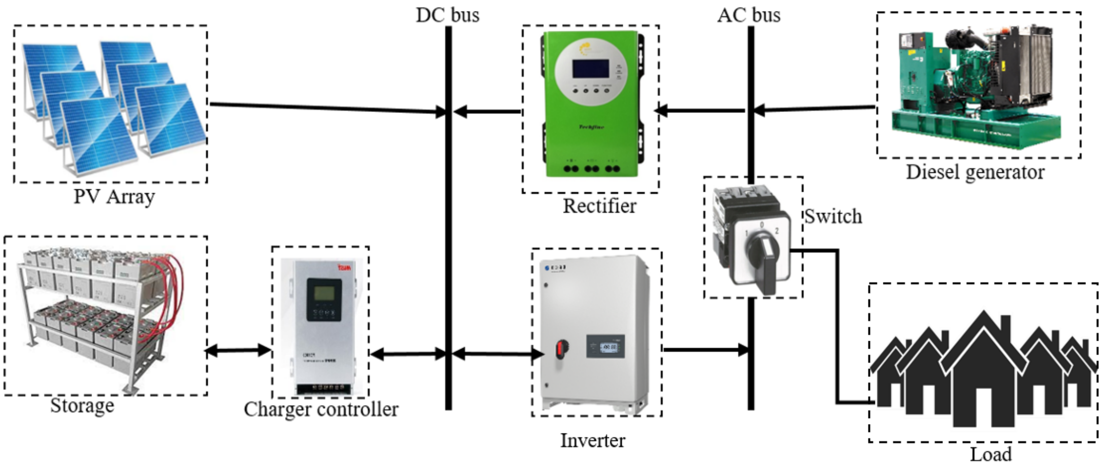
4.2.6.3 Disadvantages

- The inverter cannot work in parallel with the diesel generator;
- Low efficiency of the generator;
- The battery must have a large capacity.

4.2.7 Switching connection

In this type of connection (STOYANOV, 2011), the consumer can be supplied either by the generator or by the PV system and the battery via the inverter. However, it is technically impossible to supply both at the same time. In this type of connection, a variable speed/frequency drive needs to be integrated. The use of an electronic power converter between the generator and the battery allows him to recharge the battery.

Figure 4.10 – Schematic switching connection system



4.2.7.1 Advantages

- High efficiency;
- Inverter failure does not automatically create a blackout;

4.2.7.2 Disadvantages

- Small outage during switching of sources;
- Complex construction and management.

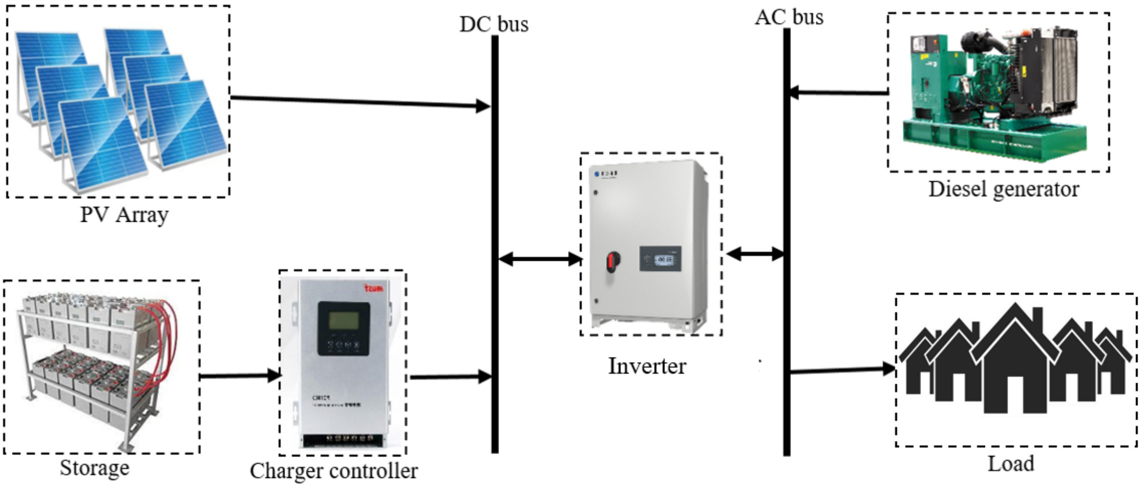
4.2.8 Parallel connection

In this connection (STOYANOV, 2011), the diesel generator is interconnected on the AC bus, on the other side, the photovoltaic field and the battery are connected in the DC bus. The AC and DC bus are connected by means of a bidirectional electronic converter, which acts as a rectifier to charge the battery when the generator alone is feeding the load; And acts as an inverter when the panels or the battery is feeding the load.

4.2.8.1 Advantages

- Loads can be fed from both sources at the same time;

Figure 4.11 – Hybrid system with parallel connection



- Better efficiency;

4.2.8.2 Disadvantages

- Automatic control is mandatory for the correct functioning of the system;
- Rapid aging of the batteries because there is no charger in the system.

The system with Switching connection (figure 4.10) is allows the use of the energy from the diesel generator without going through the conversion process by the electronic components, minimizing losses. Also, if necessary, the inverters and the diesel generator can be of different power, without limiting each other. Others advantages of such a system for the community of Abricots, as it will allow the generator to feed the loads during the night, since in rural areas, when all users are asleep, the loads of the network can drop to a very low level. The generator will be configured to automatically take the load, in order to prevent the inverter from burning out in case of under-load.

4.3 IMPLEMENTATION AND FEASIBILITY STUDY OF THE SYSTEM

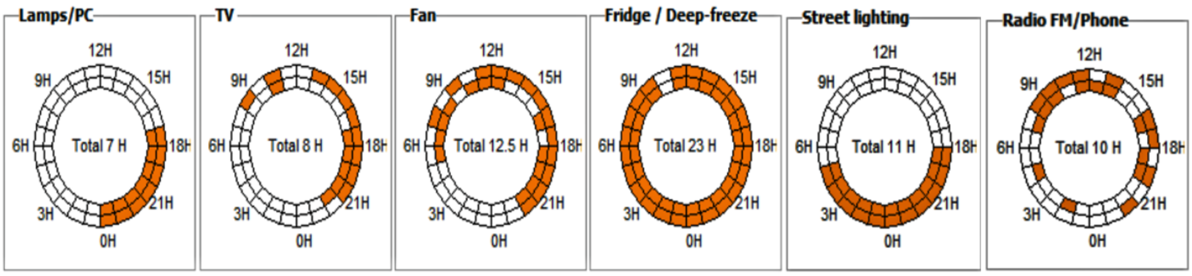
4.3.1 Study of daily consumption profile

The energy consumption profile is done for an increasing demand of 286 households in the urban areas of Abricots. In order to better size the network, it is important to identify the types of loads, i.e., the different equipment commonly used in the homes such as: telephones, radio, fans, television, lighting, refrigerators, etc.

4.3.1.1 Hourly Distribution

The consumption needs will be in variable hours throughout the day. The figure opposite shows the daily hourly distribution in the Abricots micro-grid:

Figure 4.12 – Hourly Distribution



4.3.1.2 Consumption characteristics

In this project, consumers were divided according to their purchasing power, allowing them to obtain goods and services. In Abricots, not all households will use the same equipment; therefore, four types of consumption are distinguished:

- Households with low purchasing power (LPP);
- Households with average purchasing power (APP);
- Micro-businesses that will develop;
- And the public road that will be illuminated by lamps.

Table 4.2 – Load characteristics in the migrogrid

Equipment	Households LPP	Households APP	Micro-business	Public road
Lamp	✓	✓	✓	
Radio FM	✓	✓	✓	
TV		✓		
Phone charger	✓	✓	✓	
Fan		✓	✓	
Refrigerator		✓	✓	
Iron		✓		
Computer		✓	✓	
Freezer		✓	✓	
Street Lightning				✓

The estimated daily energy consumption is 478.307 kWh; however, it is recommended to increase this value by a safety percentage due to losses and other uncertainties such as weather variations, module efficiency, cable losses, etc. This percentage should be between 10% and 25%. Therefore, an increase of 18% is applied as a margin or safety factor to compensate for losses. The energy to be produced (Wc) is then:

$$W_t = Wc + Losses \tag{4.1}$$

$$W_t = 478.307 + (478.307 \times 0.18) \tag{4.2}$$

$$W_t = 564.402kWh \tag{4.3}$$

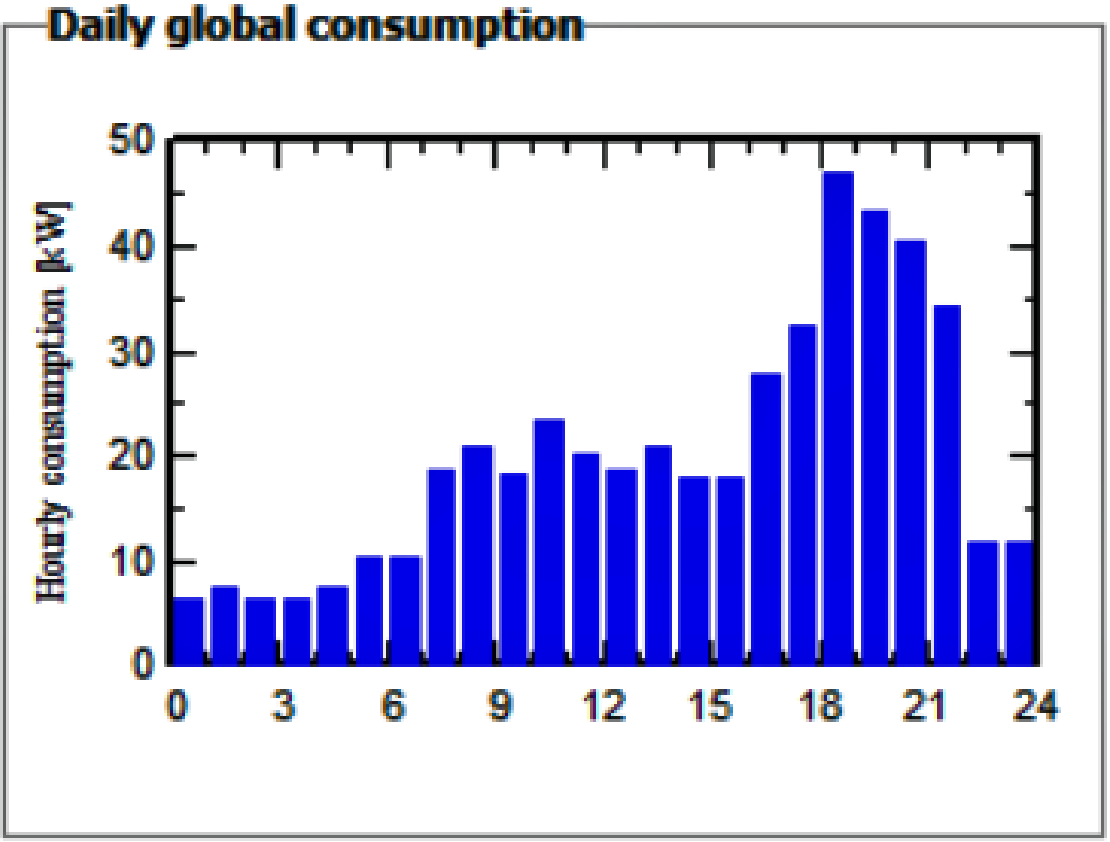
4.3.1.3 Consumption Curve

When dimensioning the system, it is important to take into account :

- The maximum daily consumption (kWh);
- The value of the maximum peak in high season (kW);
- Time and the amount of energy required
- The value of the maximum peak in high season (kW)
- The maximal power (kW).

The consumption troughs during the periods of low demand, usually at night (kWh, beginning and end of period). According to the figure (4.13), the peak consumption is about 48.5 kW and occurs between 18:00 and 22:00 when all inhabitants are at home.

Figure 4.13 – Consumption Curve



The consumption is mainly below 7.5 kW between 1:00 and 6:00 am when the inhabitants are asleep. The overall electricity consumption will follow the cycle of daily, weekly and seasonal, and this depends on climatic factors, economic activity, seasonal festivals, or others. Table (4.3) refers to the energy consumption per day, month and year in the commune of Abricots:

Table 4.3 – Projected Energy consumption by period

Period	Energy consumption (kWh)
Day	564.402
month	16 932.06
Year	203 184.72

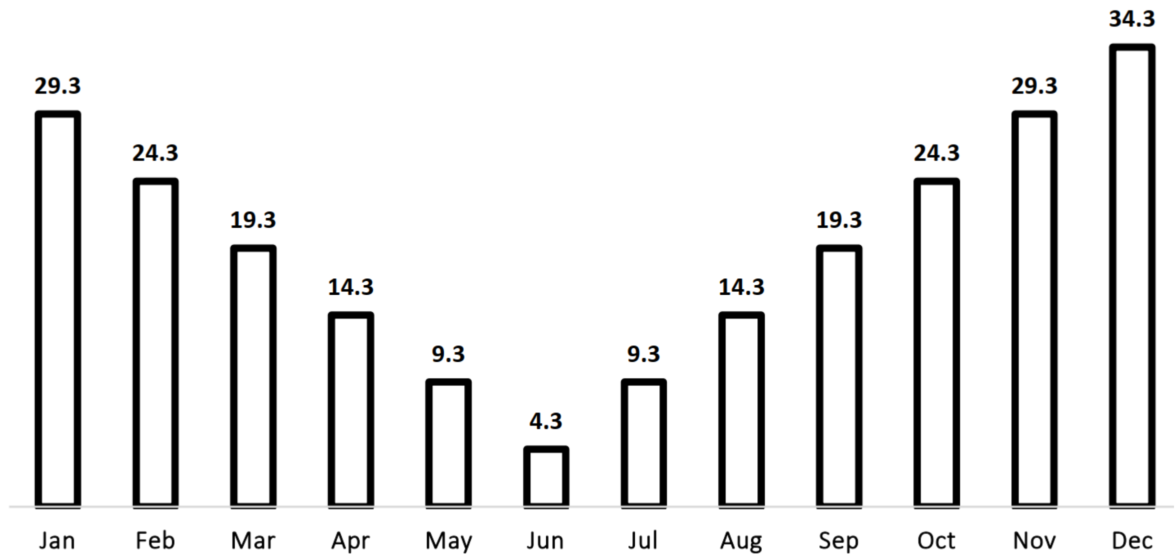
4.3.1.4 Irradiation of Abricots

The potential solar energy in Abricots is very rich. In order to better size the grid, it is always necessary to know at least the incident radiation that penetrates the region. The brightest period of the year lasts for 2 months, from March 5 to May 7, with incident shortwave solar radiation per square meter exceeding 6.5 kWh. The brightest month of the year at Abricots is April, with an average of 7 kWh (WEATHERSPARK, 2022). The darkest period of the year lasts 4.2 months, from August 10 to December 17, with incident shortwave solar radiation per square meter less than 4.8 kWh. The darkest month of the year in Abricots is October, with an average of 4.4 kWh (See figure 4.4) (WEATHERSPARK, 2022).

4.3.1.5 Optimal tilt for the solar module

In Haiti, the sun always faces south, so the modules must face south. The tilt that is the angle between the horizontal plane and the modules should maximize the energy production. The inclination of the panel in this paper is considered to be fixed. They are the solar panel angle by season in Abricots:

Figure 4.14 – Tilt optimal of Abricots



In the Northern Hemisphere, place the solar module outside facing south, in a location that gets sunlight all day, and is well ventilated if possible. Haiti is located 7 894.85 km south of the Northern Hemisphere. Since the photovoltaic system is intended for an off-grid microgrid, the inclination of the panels must maximize the minimum monthly production.

Based on the optimum angle for December, the energy production for a fictitious 1 kWp system it was generated using the site (ATLASOCIO.COM, 2020). However, as show in the table (4.4), when the optimal angle for December is chosen, the production of June is strongly affected. Thus, an inclination is chosen that maximizes the energy production of the minimum month. The table (4.4) shows that the optimum tilt is 22°, with ensures that the all month of the year has an energy production greater than 129.1 kWh.

Table 4.4 – Projected daily energy consumption

Tilt	Month with minimum energy production	Minimum Energy production
34°	June	112.6 kWh/month
32°	June	115.8 kWh/month
30°	June	118.9 kWh/month
28°	June	121.8 kWh/month
26°	June	124.6 kWh/month
24°	June	127.3 kWh/month
22°	November	129.1 kWh/month
20°	November	128.0 kWh/month

4.3.2 Sizing of the PV array

The production of electricity from solar energy is obviously produced during the hours of sunshine. The production level of solar generators is directly correlated with the energy consumption and depending on the irradiation. The remaining 28.9% of daylight hours are likely cloudy or with shade, haze or low sun intensity (SLEIMAN; SALAMEH, 2014) The nominal power (P) of the photovoltaic system that the must be determinate. The amount of solar energy that will be transformed into electrical energy depends of the average Irradiation (Ir) for the chosen tilt (22°), which for the region of Abricots is 4.5 kWh/m^2/day for the lowest energy production month (November). The nominal power is determinate by equation:

$$P_{peak} = \frac{W_t \times 1000}{I_r} \tag{4.4}$$

$$P_{peak} = \frac{564.402 \times 1000}{4.5} \tag{4.5}$$

$$P_{peak} = 125.422 kWp \tag{4.6}$$

$$\tag{4.7}$$

The solar modules must provide a total peak power of 126 kWp. In order to know the number of modules needed for the installation, a correlation is made between the maximum total power (P) of all the modules and the maximum power of a single panel (PU).The Mono-crystalline panel type with a power of 400 Wp is chosen for this micro-grid. These modules were chosen for this project because of their efficiency and comes with a 25 years linear performance guarantee. Table (4.5) show the solar module Datasheets:

Table 4.5 – Datasheets of solar module

Characteristics	Datasheets
Maximum power	400 Wp
Panel type	Mono-crystalline
Max-Power Voltage Vpm (V)	40,78
Max-Power Current Ipm (A)	9,82
Open-Circuit Voltage Voc (V)	49,55
Short-Circuit Current Isc (A)	10,59
PV Module Efficiency (%)	20.61%
Size panel	1956×992×35/40mm
Cell temperature	25^o

The number of solar modules (N) is determinate by the equation:

$$N = \frac{P_{peak}}{PU} \Rightarrow N = \frac{126 \times 1000}{400} \Rightarrow N = 315 \tag{4.8}$$

To have a better dimensional of the system, 320 solar modules are needed for the PV system. This equation allows the report between the number of modules in series (N_{series}) (strings), and the System Voltage (U_{syst}) and the Open-Circuit Voltage (V_{oc}):

$$N_{series} = \frac{U_{syst}}{(V_oc)} \Rightarrow ; N_{series} = \frac{480}{49.55} \Rightarrow ; N_{series} = 10. \tag{4.9}$$

With 10 modules are needed in series, this formula allows knowing the number of modules in parallel (N_P) by strings; Is the report between the quantity of modules (N) and quantity of module in Series (N_{series})

$$N_P = \frac{N}{N_{series}} \Rightarrow N_P = \frac{320}{10} \Rightarrow N_P = 32 \tag{4.10}$$

4.3.3 Dimensioning of the solar Inverter

The inverter is a power electronics device that generates alternating voltage and current from an electrical energy source of different voltage or frequency. In a photovoltaic system, it is used to convert the direct current (DC) produced by the solar modules into alternating current (AC). The table (4.6) represents the inverters datasheets.

The inverter's control unit ensures that the photovoltaic array is operating at the optimal operating point (Maximum Power Point or MPP) to guarantee maximum electrical energy production (DIDIER, 2007).

Table 4.6 – Datasheets of solar inverter

Characteristics	Datasheets
Continuous Power Output	65 KW
Efficiency (%)	93%
AC Voltages	220V
AC Frequencies	60 Hz
Phase	3 Phase
Maximum DC Input Voltage	600 VDC

Like all energy converters, the inverter has an efficiency expressed as a percentage, i.e. the ratio between the energy absorbed and the energy returned with a given power factor. The inverter is dimensional to meet the peak load of 48.5 kWh, adding a safety margin of 30% to compensate for losses. One solar inverter of 63.05 kW, is necessary power for the installation, while respecting the required clearance distance.

4.3.4 Sizing of the storage system

Due to the intermittency of the generation, it is necessary to store energy using batteries; this stored energy will be redistributed when the solar energy supply is no longer available. The microgrid's storage system will be sized to allow an autonomous operation for 2 days. As for durability and longevity of the storage system, Lithium-ion batteries are preferred, with the advantages of 30 years lifetime, Lightweight, No maintenance, Low self-discharge, Good tolerance to low or high temperature, Very high cycle load (between 2 500 and 5 000 cycles). The calculation of the capacity (C) in ampère/hour (Ah) of the battery bank depends on the number of days of autonomy, the total energy consumed in watt/hours day, the admissible depth of discharge of the battery and the voltage. Table 4.7 shows recommended voltages for a PV installation for different peak powers (VAITCHEME, 2019).

Table 4.7 – Range voltage Table

System Power (Wp)	Recommended voltage range (U_{bat})
0 - 500	12 V
500 - 2000	24 V
2000 -10000	48 V
>10000	> 48 V

In this micro-grid, the system nominal voltage is 480 V in order to reduce the current and to avoid large diameter cables. This formula is used to determine the storage capacity of the batteries pack:

$$Ct(Ah) = \frac{W_p \times A}{U_{bat} \times DoD \times \eta} \Rightarrow; Ct(Ah) = \frac{564.402 \times 2}{480 \times 0.8 \times 0.85} \Rightarrow Ct(Ah) = 5879.18Ah \tag{4.11}$$

W_p: Energy produced / day; A: Autonomy during 2 days
U_{bat} : Voltage System Battery (480 V); DoD: Depth of discharge (80%)
C_b: Capacity of a battery; Ct: Total capacity of the battery pack
η: Efficiency of the battery pack (85%); V_{bat}: Voltage one battery (24 V);

The total number of batteries in the micro-grid storage system is the product of the number of batteries in series by the number of batteries in parallel. The calculation having been made with batteries of 24 V and 500 Ah, and to determine the quantity of battery necessary by every string to allow a 2 days autonomy. In Table 4.10, is inserted the number of cycles that can support each battery technology with a maximum discharge at 40% (P.MANIMEKALAI; R.HARIKUMAR; S.RAGHAVAN, 2013).

Table 4.8 – Battery types and and longevity

Battery Types	Cycles	Energy Density (Wh/Kg)
Lead Acid	700	30
Ni-Cd	1000 - 1500	45
Lithium-ion	500 - 1000	90

This calculation allows us to determine the number of battery in parallel (Q_{BP}); this equation is obtained by the report between Total capacity of the battery pack (Ct) and the capacity of one battery (Cb):

$$Q_{BP} = \frac{Ct(Ah)}{Cb(Ah)}; \Rightarrow Q_{BP} = \frac{5879.18}{(500)}; \Rightarrow Q_{BP} = 11.75 \simeq 12 \tag{4.12}$$

This equation allows us to calculate the quantity of battery in series by string (B_S); is the report between the voltage system (U_{syst})and the voltage of one battery (V_{bat}):

$$B_S = \frac{(U_{syst})}{(V_{bat})}; \Rightarrow B_S = \frac{480}{24}; \Rightarrow B_S = 20 \tag{4.13}$$

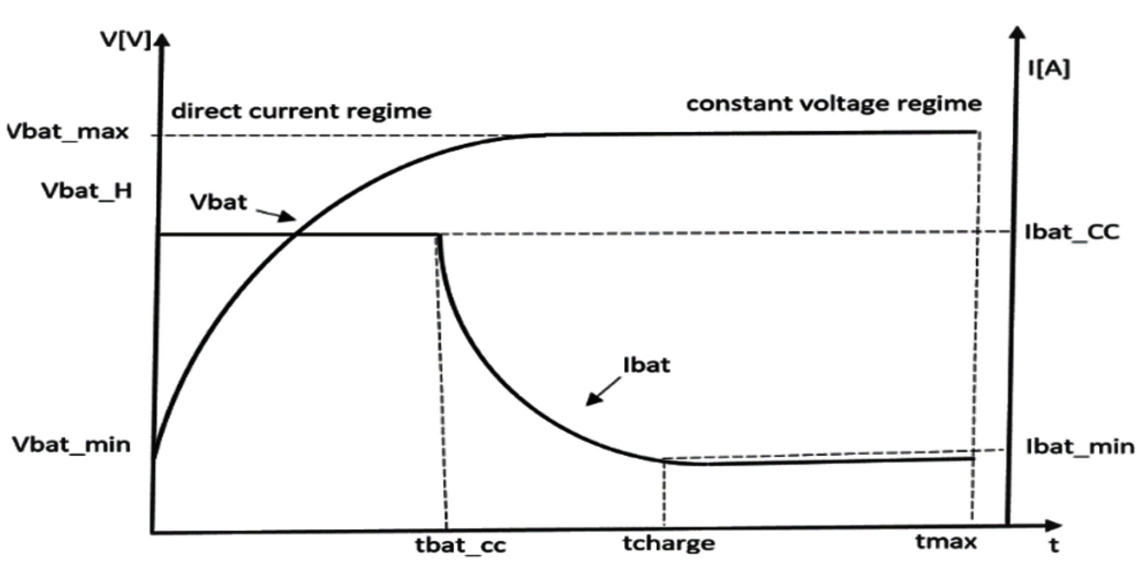
Table 4.9 – Storage system data sheet

Characteristics	data-sheet
Battery type	Lithium ion
Battery capacity	24V/500 Ah
Quantity of Battery	240
Battery pack voltage	480 V
Global capacity	5879.18 Ah
Autonomy	2 days

4.3.5 Sizing of the solar controller

The charge controller is the central element of an autonomous photovoltaic system. It controls the flow of energy. Solar modules do not send a continuous flow of electricity at all times of the day. The charge controller therefore regulates the flow in order to supply the batteries evenly and to protect them. On the other hand, when it is very cloudy, and the modules are not delivering power, the user may need power. This would cause a significant discharge of the batteries. The controller will then have to intervene to avoid a too deep discharge that would damage the batteries. The charge controller must provide both monitoring and protection functions. At the input: it is necessary to ensure that the controller has a current intensity greater than or equal to that produced by the panels.

Figure 4.15 – Typical charge and discharge curve of a battery



Source: (REYNAUD, 2011)

The specific parameters for battery recharging are the constant current charge current noted Ibat-cc defining in (figure 4.15), show the characteristics of the current I_{bat} and voltage (V_{bat}) of the battery during the application of a constant current and constant voltage charging regime. This being said, when the battery is discharged, the voltage at the battery terminal is minimum; To recharge the battery, it needs a constant current. The MPPT regulator is chosen within the framework of this micro-grid because of its capacity to respect the battery charge criteria in its three phases: bulk: sends a high charge current, 25% of its capacity; absorption: maintain the high voltage to complete the charge in a reasonable time; float: reduce the voltage (compensate for self-discharge). The maximum charging current I_{max} accepted by the controller must be compatible with the power of the panel (**??**). In order to store the maximum amount of energy produced, it is necessary to use lithium-ion phosphate batteries, with an efficiency higher than 95%, priority is given to longevity 1 000 - 10 000 charge/discharge cycles. In its operation, the

Table 4.10 – Data sheet of solar controller

Characteristics	data-sheet
Nominal voltage of the battery pack	480 V
PV Max. Input voltage (open circuit)	880 V
Nominal PV Current	350 A
Max PV Power	96 kW

controller must meet the following conditions :

$$V_{out} = V_{bat} \tag{4.14}$$

$$I_{sc} <= I_{max} \tag{4.15}$$

$$V_{oc} <= V_{max} \tag{4.16}$$

The equation that determines the maximum voltage V_{max} allowed by the solar regulator is obtained by the correlation between the maximum voltage (V_{oc}) of a module by the strings of modules in series (N_{series})

$$V_{max} = Voc \times Nseries \Rightarrow V_{max} = 49.55 \times 10 \Rightarrow V_{max} = 490.5 < 880 Volts \tag{4.17}$$

This value represents the maximum power that the solar modules can produce under temperature conditions (25 °C) and an irradiation of 1 000 W/m^2. In this optics where the open circuit voltage can exceed the V_{oc} of the panel; In this case, the voltage is increased by a coefficient of 1.1. We determine the maximum intensity I_{max} that the solar regulator can support by the report between the Current short-circuit I_{sc} by the quantity of module in parallel (Np):

$$V_{max} = 490.5 \times 1.1 \Rightarrow V_{max} = 539.55 Volts (< 880 Volts) \tag{4.18}$$

4.3.6 Diesel generator sizing

A generator is a stand-alone device capable of producing electricity to ensure continuity of production. It is equipped with a thermal engine that runs on gasoline or fuel oil (diesel) that drives an alternator. The PV-Diesel hybrid system allows the combination of a flow energy source (renewable) which is primary and a stock energy source (Generator) which is secondary and is available on demand. In such a system, the generator plays the role of backup especially during rainy seasons, cyclonic, where the sunshine is totally reduced, it takes over to recharge the batteries and supply the demand; and allowing that the flow energy (solar) is used to the maximum of its capacity and that the generator energy (fuel) is used to the minimum possible, while having a balance, the loads that are supplied with energy to cover the consumption The major disadvantage of the generator is its high operating cost due to its dependence on fossil fuels whose cost is also high; In addition, there is environmental pollution such as greenhouse gas emissions, nitrogen oxide emissions.

4.3.7 Principles of operation of a generator set

The diesel generator set is considered available if it can respond to automatic starting and load taking and has a minimum fuel reserve, allowing continuous operation for a few or several days. It is necessary to take into account the evolution of the demand for the next years and the important maintenance operations that the equipment requires for its good functioning. It is also necessary to take into account the parameters of production and the control of the good performances of the electronic equipment of the PV system. In case of power decrease to feed the load, the starting time of a generator being on average a few seconds, the inverter alone ensures the continuity of the power supply. The generators must start automatically, accelerate and supply the loads when the batteries are almost empty and the excess energy recharges the batteries at the same time; To stop when the batteries are sufficiently charged, while allowing the system to respect the balance constraint. The ignition of the generator can be done either manually or automatically (in order to reduce the time of functioning of the generator and to make some reserve in fuel). The automatic control can be realized with auxiliary relay of the DC/AC converter by setting it for which battery level the generator must start, facilitating its operation at a constant power regime. For its correct operation, it is necessary to take into account: the starting time, the current demand and the frequency stability.

4.3.8 Characteristics power of a generator

- The active power $P = U \times I \times Cos(\varphi)$ is expressed in kW.
- The reactive power $Q = U \times I \times Sin(\varphi)$ is expressed in kVAR.
- The apparent power $S = U \times I$ is expressed in kVA.

Appearance power (S) of the generator (with $Cos\varphi = 0.8$)

$$S = \frac{Pg}{Cos\varphi} \Rightarrow S = \frac{65.6}{0.8} \Rightarrow S = 82kVA \tag{4.19}$$

Table 4.11 – Diesel generator datasheets

Characteristics	datasheets
Maximum power	82 KVA / 65.6 kW
Continuous power	70 KVA / 56 kW
Engine power	87 HP
Voltage	400 V
Frequency	60 Hz
Phase	3
$Cos\varphi$	0.8
Current	1220,87
VDC (V)	24 V
Efficiency 4/4 (%)	93.40
Speed	1500 rpm
Consumption/hour (at 75%)	(12 L/h
Autonomy at 75%	15 h

4.3.9 Hybrid System Setup Rules and Configuration

In the figure (4.10), which illustrates this configuration, the PV array, the diesel generator and the storage battery can act independently as the master source to satisfy the load and provide voltage and frequency control for the system. The cohesion of the sources will be ensured by an automatic control system that ensures that the load is fully supplied. During the day, the PV array provides power to the load and the surplus power recharges the batteries; During the evening, the storage system supplies the load. When the load reaches a discharge level (i.e. 40%), the generator will automatically start to supply the load and the surplus power recharges the batteries; once the batteries are fully charged, the generator is automatically turned off. The system is dimensional to reduce the generator operation (i.e. 7 hours per day) and to optimize the fuel consumption.

4.4 ENERGY RECOVERY AND FACTURATION PROBLEM OF EDH

The quality of production and distribution of electrical energy in Haiti needs to be coordinated with bill collection, since this is one of the major problems that creates a huge annual deficit in the coffers of EDH. The company has about 300 000 active customers, which is very little compared to the size of the population. In terms of collection, only a small portion of regular consumers pay it; While the company does not have the capacity to compel its customers to pay their bills. In response, the company has undertaken disconnection campaigns for debt. In an article published in November by EDH in 2018, it was mentioned the following: 80% of EDH customers refuse to pay their electricity bill (HAITILIBRE, 2018). In this article, the following data was published, indicating that only 1 330 (or 51.5%) of the 2 578 consumers classified as large customers paid their bill. For ordinary customers in outlying areas such as Pétion-Ville, Delmas, Tabarre and Carrefour, the situation is worse: the commercial service prepared and issued 36 313 invoices to customers in the commune of Pétion-Ville: only 6 445 paid (or 17.7%). In Port-au-Prince, out of 21 700 consumers, 5 044 have paid (23%). In Delmas, out of all the customers counted, only 6 963 (or 23%) out of 29 787 paid their bill (HAITILIBRE, 2018).

4.4.1 The dilemma

In the first time: the customer refuses to pay for a service that he has not received, because the electricity is not available ; Secondly: EDH is unable to meet the needs because it is totally in deficit. The majority of homes do not have electricity; EDH collects less than USD 5 million monthly from its customers while the Haitian state pays between USD 10 and USD 12 million each month to purchase electricity from three private suppliers. The subsidies received by the company are only to meet the fixed and variable costs of the company, but not for investments. Meanwhile, the company's insolvency keeps it away from banking institutions to obtain additional funds for investment, as well as to rehabilitate the infrastructure to improve the quality and reliability of service. To avoid the systematic drain of the company, apart from the subsidies received by the company in public funds, the company has decided two solutions:

- Tariff adjustment (Table 4.13);

- Prepayment electric meter;

4.4.2 Tariff practical system of EDH

In terms of charging for energy consumption, the company adopts a tariff that varies according to the type of customer; The table (4.12) shows the EDH tariff schedule, adopted since 2009 in Gourdes (G), the local currency:

Table 4.12 – EDH, tariffs for energy consumption (2009)

Customer service fee	Consumption	Semi autonomous producer	P-au-P & provinces
Sector: Residence			
First 30 kWh	1 - 30 kWh	6.90 G/ kWh	4.80 G/ kWh
Residual kWh	31-200 kWh	7.25 G/ kWh	5.10 G/ kWh
from 201 and more kwh	201 kWh and more	12.74 G/ kWh	12.74 G/ kWh
Sector : business			
First 30 kWh	1 - 30 kWh	11.51 G/ kWh	11.51 G/kWh
Residual kwh	31-200 kWh	13.43 G/ kWh	13.43 G/kWh
from 201 and more kWh	201 kWh and more	14.38 G/kWh	14.38 G/kWh
Sector : industries BT			
kWh	1 kWh and more	13.97 G/kWh	13.97 G/kWh
Sector : industries MT			
Off-peak hours	1 - 30 kWh	12.74 G/ kWh	12.74 G/ kWh
Peak hours	31-200 kWh	13.97 G/ kWh	12.74 G/ kWh13.97 G/ kWh
Sector: Public organism			
First 30 kWh	1 - 30 kWh	14.12 G/ kWh	14.12 G/ kWh
Residual kwh	31-200 kWh	14.12 G/ kWh	14.12 G/ kWh
from 201 and more kwh	201 kWh and more	14.12 G/ kWh	14.12 G/ kWh
Sector : Street lighting			
First 30 kWh	1 - 30 kWh	14.12 G/ kWh	14.12 G/kWh
Residual kWh	31-200 kWh	14.12 G/ kWh	14.12 G/kWh
from 201 and more kWh	201 kWh and more	14.12 G/kWh	14.12 G/kWh
Sector :Autonomous organism			
First 30 kWh	1 - 30 kWh	14.12 G/ kWh	14.12 G/kWh
Residual kWh	31-200 kWh	14.12 G/ kWh	14.12 G/kWh
from 201 and more kWh	201 kWh and more	14.12 G/kWh	14.12 G/kWh

Haiti is one of the countries where the kWh is sold at a very high price in the region; while it is a country where the standard of living of the population is lower. However, unlike Haiti, in neighboring countries where citizens have a better purchasing power, electricity is sold at an affordable and sustainable cost. According to this table of EDH rates, is compared with the price of kWh worldwide in USD (in current USD rate in 2011): Residential USD 0.28; Commercial USD 0.37; Industrial USD 0.39; Public Authorities USD 0.37; Public Lighting USD 0.37; (NREL, 2015). Equivalence of the cost per kWh with the average rate in the world (in 2022) which is 0.138 USD for households and 0.131 USD for Business (GLOBALPETROLPRICE.COM, 2021). Notice: According to the BRH reference rate: In 2011, USD varies from 39.97 Gourdes in January to 41.02 Gourdes in December; In 2022, USD varies from 99.04 Gourdes in January to 117.41 Gourdes in December (BRH, 2011).

4.4.3 EDH's new recovery policy

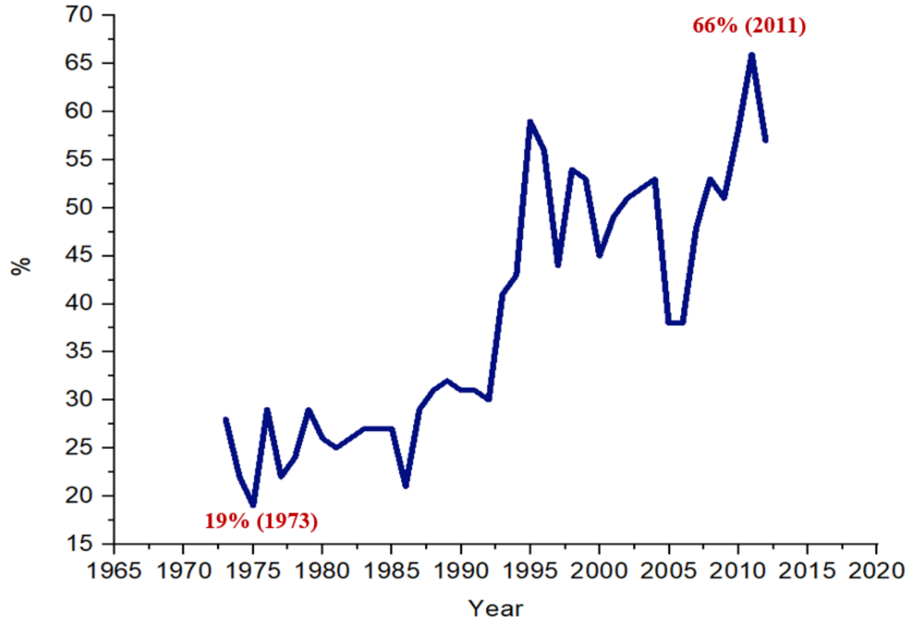
The prepaid billing system is a technological solution already initiated by EDH to improve the recovery of energy production. Prepayment aims to make the customer pay for a service before it is used. It is a way to give access to sustainable energy to all. Since March 2021, it has decided to install 70 000 units of mixed smart meters (post-paid and prepaid) throughout several neighborhoods in the Port-au-Prince metropolitan area. The introduction of prepaid meters is an obligation for EDH, which wants to stop selling on credit in order to maximize customer satisfaction (ALPHONSE, 2022):

4.4.4 Advantages & Disadvantages of prepaid system

- Advantages
  - Solution to the problems of unpaid invoices and non-collection;
  - The customer is in control of his consumption;
  - Improvement of the producer's cash flow;
- Disadvantages
  - Automatic load shedding at 0 flow rate at the customer;

The technical and non-technical losses in the Haitian electrical system are enormous and vary from year to year; According to the data collected by the World Bank regarding losses in the electrical networks, it was mentioned that the lowest level of losses recorded during the years 1960 to 2012 is about 19% in 1973 and the highest level of losses recorded was about 66% in 2011 (See graphic 4.16).

Figure 4.16 – Electricity losses during transmission and distribution in Haiti (% of Production)- 1960 - 2012 in Haiti



Source: (BANQUE.MONDIALE, 2014)

4.4.5 Considerations

The high cost per kWh is provoked particularly by the rise in fuel prices on the international market; The high production costs; Also the rather high purchase price per kWh, practiced by the independent producers who sell to EDH; The low billing and recovery rate and the technical and non-technical losses are among the main causes of this problem. However, customers are often dissatisfied because the tariff per kWh is high for unreliable and poor quality electricity service, which is not affordable for most consumers in a country with the lowest per-capita income in the region. In this regard, the Haitian state must implement a tariff policy that favors a minimum tariff for the most needy, especially in the slums and precarious neighborhoods; The fact that the customer knows exactly how much energy his or her household consumes allows him or her to better manage consumption and save money. The prepaid system effectively contributes to improving the reliability of billing and increasing the company's cash flow. Meters keep track of household energy use based on kilowatt hours consumed. However, in the case of Haiti, the problem remains as long as there is no availability of energy, the customer will always remain in the blackout despite the meters. Therefore, the prerequisite for effective pricing is the improvement of electricity production in the country.

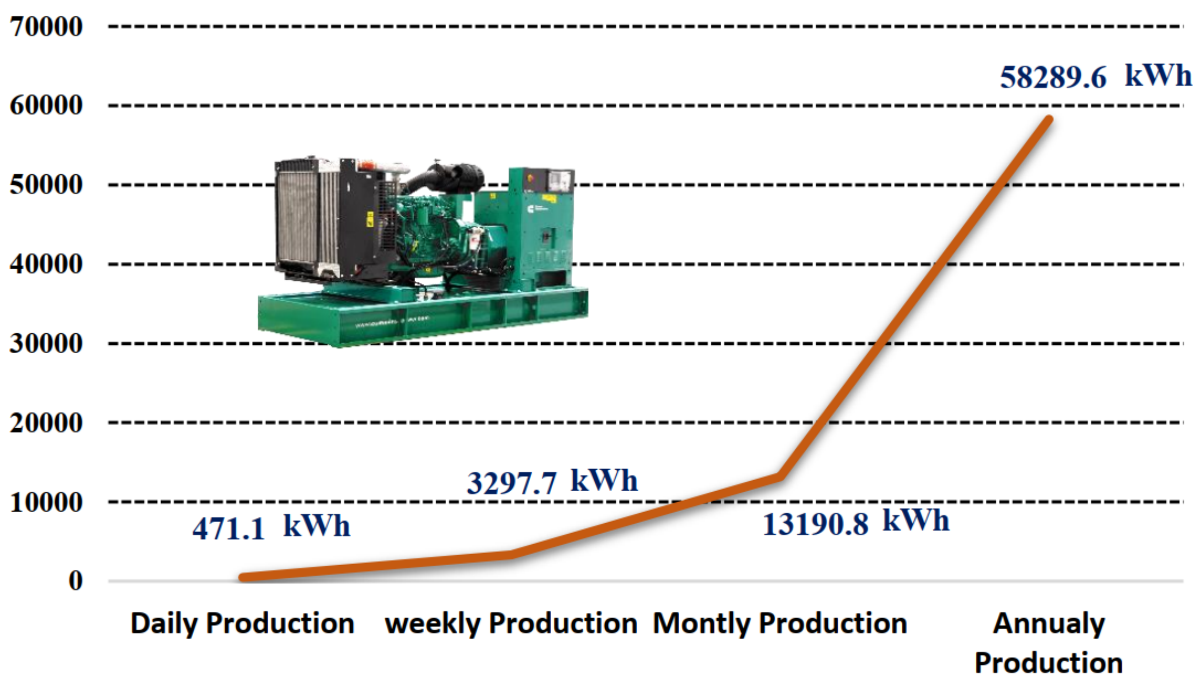
In the case of the proposed microgrid, the cost of operating the diesel generator can be estimated to be 12 liter/hour when the generator operating at 70% of capacity; However, the generator is designed to operate at 75% of its rated power, i.e. 65.6 kW. With an efficiency of 93.4%, the generator will provide an effective power of 61.27 kW that can feed the total load (see table 4.11).

Table 4.13 – Fuel consumption of generator

Period	Hours	Liter/Consump	Cost / liter (USD)	Total production cost (USD)
Daily Consumption	7	84	0.801	67.3
Weekly consumption	49	588	0.801	471
Consumption per month	196	2352	0.801	1883.96
Annual consumption	2352	28224	0.801	22607.43

As can be seen in table (4.13), for 84 liters of fuel consumed in a day, an amount of 67.3 USD is allocated; For 588 liters, the production cost amounts to 471 USD for a production of one week. The production of the generator (figure 4.17) as a function of operating time allows us to assume the energy production per period by the generator. With a power delivered at 75% of its capacity, which is 67.3 kW, the energy produced during a day at a rate of 7 hours/day amounts to 471.1 kWh; 3 297.7 kWh for a week, 13 190.8 kWh for a month and 158 289.6 kWh for a year. .

Figure 4.17 – Diesel Generator generation by period



5 CONCLUSION AND RECOMMENDATION

Given the importance of electricity in the socioeconomic development of populations and its preponderant role in the fight against poverty, it can be concluded that electricity precedes development. Indeed, it is crucial for the proper functioning of strategic economic sectors such as agriculture, trade, industry, tourism, health, education, infrastructure; moreover, it contributes to improving the well-being of the population and reducing the level of insecurity. Within the context of our work, we have been able to prove that there are problems in the Haitian electrical system; however, solutions also exist; as a way to alleviate these chronic problems, we have proposed sustainable energy solutions, following the example of the energy projects that are currently being implemented around the world. It is important for the Haitian public authorities to anticipate and plan for the future population, while also providing for the energy needs of the current population. Our proposals are the following:

- Increasing access to electricity is a huge challenge for Haiti as it approaches 2030; as a recommendation for the implementation of an inclusive energy system that is accessible to all. It is mandatory to establish an official national energy policy that expresses a long-term vision for sustainable development, containing coherent objectives and clear guidelines for development, in order for Haiti to achieve its goals by 2030, in accordance with the UN's SDG7.

- To advocate and exploit all sources of renewable energy on the national territory of Haiti, as alternative energy sources, which can contribute to increase the production of electricity, gradually reducing the use of fuels in the energy mix of the country helps to reduce the dependence of the network on fuels, optimize the production of electricity, but especially to limit the production of dioxide in our atmosphere.

- Undertake further the process of digitization of the electrical system, with particular emphasis on the distribution and billing of customers using smart meters, in order to better leverage the investment.

- Undertake the privatization of the public company EDH, in order to ensure that energy is available and accessible 24 hours a day for the needs of consumers and the sustainability of the company. The privatization of the company will allow to improve the productivity and the quality of the services, which will have an impact on the increase of the financial profitability.

- To design and make isolated mini power plants and hybrid photovoltaic microgrids an efficient and effective tool to facilitate access to electricity for the energetically excluded, i.e. the peasants, located throughout the isolated areas of Haiti.

- It is now of capital importance for Haiti to diversify the generation matrix. and develop renewable energy resources which is a wealth available throughout the territory, such as solar photovoltaic energy, hydraulic, wind energy and biomass.
- Reduce energy production costs and stabilize prices so that they are more accessible to the majority of the country's low-income population, by moving towards other sources of green and sustainable energy.
- In conclusion, this document should serve as a guide to the Haitian authorities, and as a source of research for students and researchers in the field of energy; This document should be used as a catalyst and advocacy for the electrification of Haiti's rural areas, while promoting equitable access to electricity everywhere and for everyone. Providing a reliable, efficient, accessible, and sustainable energy service financially, economically, environmentally and socially, with the ultimate goal of combating energy exclusion, and putting Haiti on the path to desired change and development.

To promote sustainable, reliable and cost-effective electric power in rural and remote areas of Haiti, hybrid photovoltaic (PV+Diesel) systems represent the ultimate alternative to increase energy access to all, across regions far from city centers, where EDH will not have easy access to expand the grid. Alternative does exist with renewable energy sources; the solutions proposed in this document are an effective way to address this problem in a sustainable way and will allow Haiti to reach the UN target by 2030.

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