Master's Thesis / Research Report

Photovoltaic Technology Usage in Smart Mini-Grids: A Solution for Energy Security in Rural Areas in Mexico.

by

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Abbreviations

AC Alternating current. It refers to the continuous flow of electrical charge through a conductor between two points of different potential and electric charge, whose magnitude and direction vary cyclically. It is the type of electrical energy and is the one normally used in residential installations.

CCHP Combined Cooling Heat Power. Are CHP technologies that are able to generate cooling services.

CFE Comisión Federal de Electricidad (In Spanish). The Federal Electricity Commission is a productive company responsible for controlling, generating, transmitting and commercializing electricity throughout Mexico.

CHP Combined Heat Power. Are technologies through which it is possible to simultaneously generate electrical energy and thermal energy in the form of steam or water.

CONAE Comisión Nacional para el Ahorro de Energía (In Spanish). It is the Mexican National Commission for Energy Saving that is on charge of advising governments of states, municipalities and individuals regarding the efficient use of energy as well as the use of renewable energy.

CRE Comisión Reguladora de Energía (In Spanish). It is the main Mexican agency in charge of regulating the energy sector in terms of electricity and fuel gas.

DC Direct current. It refers to the continuous flow of electrical charge through a conductor between two points of different potential and electrical charge, which does not change direction with time. It is the type of electrical energy coming from car batteries and solar cells.

DER Decentralized Energy Resource. Are devices that generates electrical energy by means of many small distributed sources and are placed as close as possible to the final load.

EMF Electromagnetic Field. It is an effect produced by those elements electrically charged over a certain space capable of affecting the behavior of other particles with electric charge.

EROEI Energy Returned on Energy Invested Ratio.

GEF Global Environment Found. Is a global alternative asset manager established in 1990 to invest in high-growth clean energy, energy and resource efficiency.

IEA International Energy Agency. I an international organization that seeks to coordinate the energy policies of its member states, in order to ensure reliable, acquirable and clean energy for their respective inhabitants.

IRENA International Renewable Energy Agency. An intergovernmental organization that promotes the Sustainable Energy usage

LSPEE Ley del Servicio Público de Energía Eléctrica (In Spanish). The Public Electricity Service Law promulged in 1975.

MOLP Multi Objective Lineal Optimization. A methodology that aim to optimize a complex decision-making problematic searching for a balance between it interest factors.

PSE Programa Sectorial de Energía (In Spanish). Is Sectorial Energy Program established in 2000 and promoted the installed capacity of electricity generation from renewable sources.

RES Renewable Energy Resources.

SEN Sistema Eléctrico Nacional (in Spanish). Is the Mexican National Electric System.

SENER Secretaría De Energía (In Spanish) Mexican Secretariat in charge of designing, planning, executing and coordinating Mexican Energy public policies.

UNDP United Nations Development Program. Is the United Nations' global development network.

WBG World Bank Group. It is a multinational organization specialized in finance and assistance that is defined as a source of financial and technical assistance for the so-called developing countries.

MXN Mexican Peso. It is the official currency used in Mexico.

Units of Measurement

W	**Watt.** Equivalent to 1 July per second (1 J/s) and 1 kg m^2/s^3. is the coherent derived unit of the International System of Units for Power. Expressed in electric units, can be expressed as W = V · A
V	**Voltage**. Is the unit derived from the International System for the electric potential, the electromotive force and the electrical voltage. Is defined as the potential difference along a conductor when a current of one ampere consumes one watt of power.
A	**Ampere.** Is the unit of electric current intensity in the international unit system. It is defined as the constant current that, maintained in two parallel straight conductors of infinite length, of negligible circular section, and placed at a distance of one meter in the vacuum, would produce between these conductors a force equal to 2 x 10-7 newton per meter of length
kWh	**Kilowatt Hour.** Unit of energy expressed in the form of units of Power × Time. It expresses the magnitude of energy (in Watts) that can be produced and sustained during that hour.
Wh	**Watt Hour.** Unit of energy expressed in the form of units of Power × Time. It expresses the magnitude of energy that can be produced and sustained during that hour.

Glossary of Terms

Energy Poverty Term used to describe a situation where the economic income or available resources are not enough to satisfy the amount of energy sufficient to meet daily needs.

Energy Security Considered as one of the necessary pillars for sustainable development. It is the result of the relationship that exists between national security and the availability of resources for consumption. It focuses on the problem that many countries are not capable of satisfying their own energy demand and causing their dependence on the import of these. Turning it into a political deterrence tool.

Climate Change It is the variation of the characteristics of the climatic environment (such as temperature, variation of rains, water levels in the seas). Which can respond to a natural process or can be accelerated by human activities.

Capital Cost It is the amount of total expenses made to produce a service or good. It includes the assets acquisitions like purchase of land, buildings, technology and equipment used for this purpose.

Load It is the amount of electrical energy that must be provided to a system for its operation

Solar Radiation It is the set of electromagnetic radiations generated by the sun in different wavelengths.

Irradiance It is the magnitude used to describe the power of electromagnetic radiation exerted on a body or area determined from a source such as the sun. It is expressed in W / m2 or kW / m2

Peak solar hour It is the irradiance value received at a site during the course of the day. It is expressed as the number of hours with an ideal irradiance of 1000W / m2 or J / m2

Load profile The average power demand in Watt-hour per day that can be obtained by itemizing all appliances and their hours of use each day

Certification Page

I, Barron Leon Roberto Enrique on ID 51217621 hereby declare that the contents of this Master's Thesis / Research Report are original and true, and have not been submitted at any other university or educational institution for the award of degree or diploma. All the information derived from other published or unpublished sources has been cited and acknowledged appropriately.

BARRON LEON, Roberto Enrique
2019/06/14

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I dedicate this work to my mother who has always given me support and has taught me through her example the value of effort and never giving up.

To my father who has always motivated me to pursue my dreams and taught me to always keep moving forward.

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Abstract

The use of photovoltaic technologies in smart mini-grids systems can be considered as feasible strategy to provide energy security in isolated rural communities and promote more sustainable lifestyles.

Currently in Mexico, exist an approximate of 3,5 million people living in isolated villages that still lack of electric service (SENERb, 2018). In accordance to the he “2018-2032 Energy Development Plan” elaborated by the secretary of energy in Mexico (SENER), populations located in a distance further than 5 kilometers from the main grid distribution line will not receive electrification through it, and will require to gain access to the electric service by the implementation of any type of Off-Grid power generation system, preferably composed of photovoltaic technologies (SENERa, 2018).However, there are still some concerning regarding what could be an accurate practical solution to provide energy security to these communities through the time.

The current investigation focuses on identifying, defining and proposing Photovoltaic Smart-Mini grid systems that could be technically implemented to provide long term energy security to these isolated rural areas in Mexico, as well as describing the current challenges and opportunities identified in the current technological, social, economic and political framework within this country.

[**Key Words:** Photovoltaic Systems, Mini-Grids, Rural Development, Decentralized Energy Resource Systems, Energy Policy Frameworks]

1. Introduction

1.1.Background and Motivation

During the last decades it has been a crescent worldwide initiative to satisfy the energy demand around the world, to the point of being reflected as the goal number seven of the 2030 United Nations agenda for sustainable development (UN, 2015). As a result, the number of people that lacked access to the electric service has been reduced from 1.7 billion in 2000 to less than one billion in 2017, most of them by the extension of the local main power grid system that relays on fossil fuel resources like coal, natural gas and oil. However, it is estimated that approximately the 14% of the total worldwide population still do not have access to a clean and reliable source of electric power, and 84% of them are residing in a rural area (International Energy Agency, 2017). The reasons that are considered origin of this problematic can be summarized in the following points (Nishant et al, 2016; Bandyopadhyay and Palit, 2016; Elusakin et al, 2014; Harries et al, 2009; Chea, 2011; Allen, 2008; Gothwal et al, 2018):

- The target areas are remote located and low densely populated, making the extension of the power grid not cost effective, in terms of energy transmission factor and maintenance,
- Transporting energy sources to those areas results complicated due geographical conditions that difficult the access,
- The main power-grid has not been developed yet due local governments economical restrains, even when the main power grid extension is possible,
- The current legal framework defined in the target region does not allow that private investors participate in the energy local market,
- The decisions of governmental sector and policy frameworks has indirectly made less competitive the other technical solutions that could satisfy the

electric power necessity in those regions, through the use of policy tools like subsidies and taxing.

However, during the last few years, these barriers have begun to change and have gradually diminished, to the point that nowadays researchers around the world have demonstrated that providing electric service to isolated communities in a sustainable way is technically and economically possible without relaying in the main grid distribution system through the implementation of off-grid systems (OGS). An OGS is a tailored electric power system that is particularly designed to satisfy the power consumption of a target population without been connected to the main grid system (MG) Distribution network, and is located geographically closely or even within its target area (Alkhalidi et al, 2018; Ranjan et al 2017; Gothwal et al, 2018) allowing to reduce the losses associated to the MGS distribution line.

In the same way as the MG, a OGS can be designed to run through the use of fossil fuels, however this tend to create a strong dependence on the supply of fossil fuels for a proper functioning, therefore was till the inclusion of renewable energy technologies that was possible to add more reliability to the OGS and finally to start considering them as a solution for isolated rural communities (Erdinc and Uzunoglu, 2012) as is shown in already implemented cases in Uganda (Comodi et al, 2017), India (Kamalapur and Udaykumar, 2014), Nigeria (Elusakin et al, 2014), Peru (Tozzigreen,2018) and other parts of the world. Nevertheless, there are still some challenges that the current off-grid renewable systems (OGRS) need to overcome in the technical, economic and the politic framework in order to be considered as reliable and robust systems in terms of power generation, like the big capital cost of investment, legal restrictions and long term scalability (Baulcha et al, 2018; Elusakin et al, 2014) but undoubtedly, one of the greatest challenges in terms of design and performance of OGRS is the possibility of maintaining a stable electric production capacity that could satisfy the population needs without become dependent on the fossil fuel backup generator systems (Hafez and Kankar, 2012; Elusakin et al, 2014; GIZ, 2013). This problematic is clearly illustrated due the factor that population consumption has a constant tendency to increase during the time after been energized (Ndeye et all, 2007) and which to be ignored reverberates in a set of problems ranging from low performance and shortcuts, to irremediable damage in the OGRS (Ruralelec, 2014) Therefore, it becomes evident the need of including devices that could monitor the OGRS performance, in order to prolong its useful life, to efficiently use the backup generators, to identify when an upgrade of the installed capacity is required and to protect and ensure the correct use of the grid components.

Any type of electrical grid that includes sensors, computers, automation and communication systems that allow monitoring and delivering real-time information and immediate react to balance loads in the system and achieve energy stability in terms of supply and demand is known as smart grid (US DOE, 2010; Murphy,2010; Ataul et al, 2014). In the recent year's new technologies that allow to implement this kind of functionalities has started to be implemented in OGRS achieving to control, monitor and operate the energy system through the use of internet or even trough cellphones in real time (Arbab-Zavar et al, 2019; Shaukat et al, 2018; Kabalci, 2016) opening a wide range of possibilities that allow to administer the OGRS in a more convenient way.

Currently in Mexico, there exist 3,5 million people who do not have access to any kind of electric power service, most of them distributed in around 6,000 isolated communities within the country. From those, 4000 completely lack of any type of electric power generator system, depending mainly on the use of biomass and fuels to meet their daily lighting and cooking activities, and the rest has partially granted access to the electric power service through the use of diesel generators and photovoltaic cells, been able to satisfy basic consumption needs, such as lighting and other basic appliances. (SENERb, 2018). According to the “2018-2032 Energy Development Plan” elaborated by the secretary of energy of the Mexican government (SENER), the 75% of the mentioned isolated populations in Mexico will be grant electric power service through the extension of the main grid distribution lines, however the rest of communities that are located in a distance further than 5 kilometers from the main grid distribution system or own a very reduced population will receive electric power due the implementation of OGS composed as much as possible of photovoltaic generation stage in order to reduce to the maximum dependence of a fuel bank in the community (SENERa, 2018). However, there are still several concerning regarding what could be an accurate resilient and practical solution to provide electric power service to these communities.

The current investigation focuses on identifying, defining and proposing a photovoltaic smart-mini grid system that could provide long term energy security to these isolated rural areas in Mexico, as well as describing the current challenges and opportunities identified in the current technological, social, economic and political framework within this country.

1.2.Research question and Objectives

The research questions aimed to solve in the current investigation are:

- What are the technical and economic limitations and potentials of implementing Photovoltaic technologies in Smart Mini-grids in rural areas of Mexico?

- What legal, societal, financial and managerial barriers of prevailing practice in Mexico affect the implementation of PV-based Smart mini-grids in rural areas of Mexico?
- What are the (dis-) advantages of PV-based mini-grids compared to currently implemented hybrid mini-rid systems and solar home systems in economic and technical perspective

Therefore, the main objectives of the current investigations can be listed as:

- Define the characteristics of a PV-based smart mini-grid system,
- Design and structure up a PV-based mini-grid system covering varies settlement sizes in rural areas,
- Identify and analyze the current barriers of prevailing practice faced by PV-based mini-grids in Mexico,
- Predict and calculate the levelized cost of energy (LCoE) of the different PV-based mini grids and compare it against the current price of electricity and/or opportunity cost faced by rural areas,
- Draft policy recommendations for the roll-out of PV-based mini grids in rural areas of Mexico.

1.3.Scope and Limitations

The information presented in this document was elaborated trying to refer in the more trustworthy way to the Mexican energetic framework and may be different from the ones implemented in other countries. However, this investigation aims to work as a reference for researches the context of renewable off-grid system design.

As a result of time constraints, the proposed investigation is just focused on the analysis of photovoltaic technologies and do not consider other decentralized power generation systems like wind generators, waste to energy, cogeneration or hydro power that could also work as a possible answer to the exposed problematics.

The statistical data used within the current investigation like energy consumption per household, demographic characteristics and social income are mainly obtained from open information provided by the Mexican national governmental offices and the public census data base generated by the Mexican institutions INEGI and SEDESOL within the years of 2010-2018.

Technical data, device characteristics and cost was retrieved from standard technologies in the market, as well as data bases included in the official software for photovoltaic system designs PVSol (version 2019) and PVSyst (version 6.79).

Irradiance and weather conditions are modeled by using the National Aeronautics & Space Administration's (NASA's) global weather database generated from the monthly surface meteorology and solar energy data observation trough the period from 1983 to 2005, in addition to the NREL's Electric Systems Center and the National Solar

Radiation Data Base (NSRDB) composed by the typical meteorological information during the period from 1961 to 2016.

1.4.Methodology

Literature review shows that the habitually approach to compare and select between different energy generation systems is by performing economic analysis (Hawkes and Leach, 2007; Ajah et al, 2007, Shimizu et al, 2010, Mancarella and Chicco, 2009; Kalantar and Mousavi,2010), and particularly by using the Levelized Cost of Energy (LCoE). This is because LCoE has a versatility that allows to compare different types of power plants structures in terms of cost (Allan et al 2011; Gross et al 2007; Konstantin 2013; Lai and McCulloch 2016).

The LCoE is a net present value (NPV) calculation that results from the comparison of all costs involved in the lifetime of a given Power Plant, that is, the costs necessary for the construction and operation of a given power generation structure plus the sum of the amount of energy generated during its cycle of life (KOST et al, 2018; Konstantin, 2013) Currently, this is a method internationally accepted, and considered as a standard point of reference to perform economical assessment when evaluating the economic feasibility of diverse power generation technologies (Allan et al., 2011; Lai and McCulloch 2016; Liu et al 2015; Orioli and Di Gangi 2015). Because of that, it was decided to adopt this approach to evaluate and compare the proposed photovoltaic smart-mini grid systems against each other, as well as against the possibility of the extension of the Main Grid System.

Figure 1 explain the structural methodology performed during the current investigation.

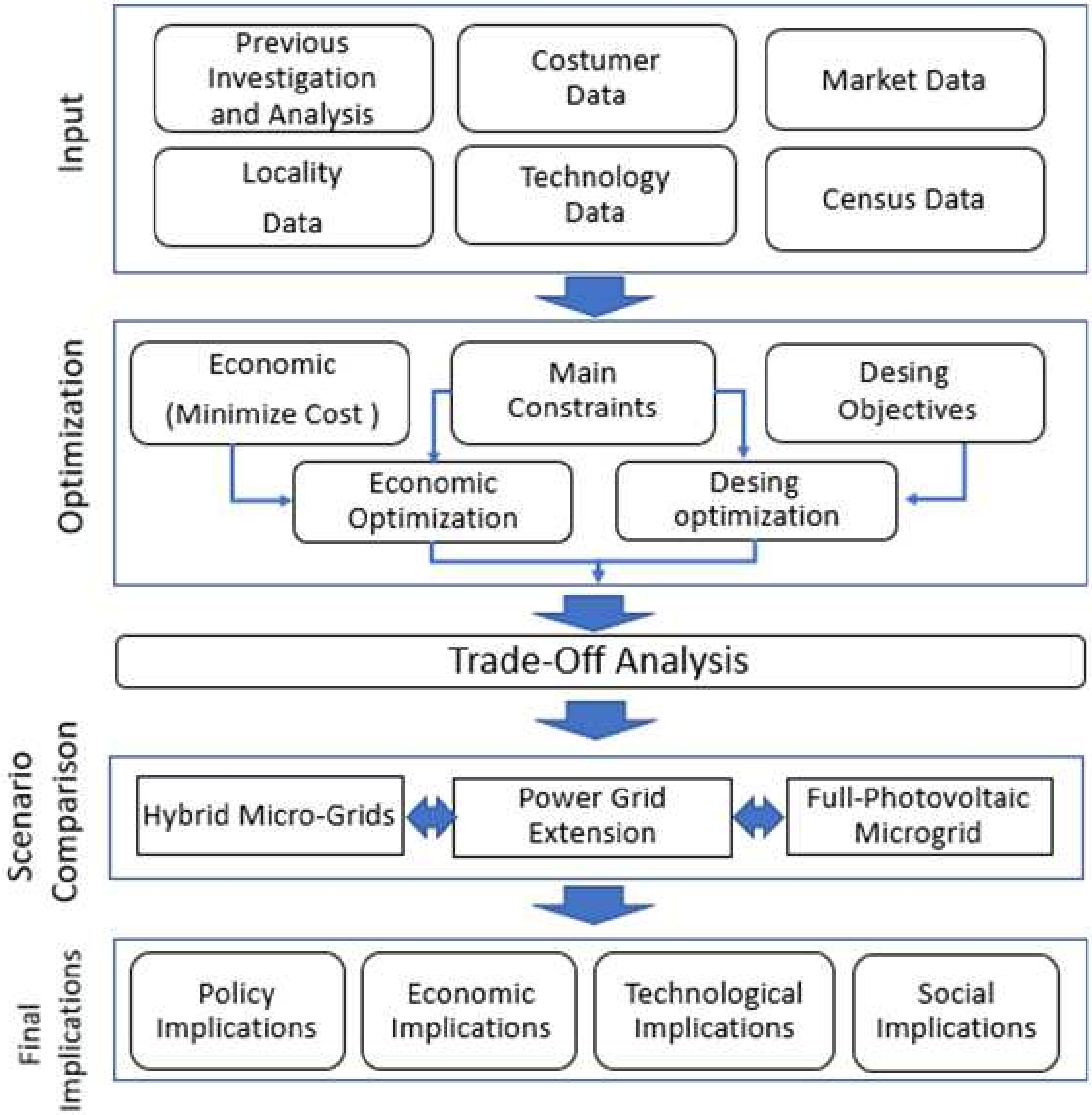

Figure 1. Methodology Structure

First the method integrates the necessary input of market technologies, local community data and similar sociodemographic profiles, local weather data such as humidity, temperature and solar irradiation data and other relevant data to delimitate the scale of the off-grid system. Then, a trade-off analysis was performed between the possible power generation plants configurations and the proposed optimizations constrains and the defined design criteria. So finally, a scenario comparison of the most could be performed by using its respective LCoE, assuming the NPV close to zero as the economic preferred Scenario.

Furthermore, a brief policy and barrier analysis is performed to predict and evaluate any other potential drawback to the technical and economical solutions. As well as its social and environmental implications.

1.5.Document Structure

In order to describe in a more structured way the information presented in this investigation, the chapters have been organized as follows:

Chapter one describes the general scope of the investigation introducing the background and motivation of this research, followed by the explanation of the objectives, the limitations of the research scope and the presentation of the followed methodology.

Chapter two focuses on covering the performed literature review and the theoretical background, it includes a general explanation of the electric power concepts, the general classification of power grids, the photovoltaic technologies principles, the Mexican energetic regulatory framework and the main policies related to mini grids, as well as the current state of the solar energy sector in Mexico.

Chapter three describes the data and the criteria used for the design of the smart mini grid.

Chapter four is focused on the mathematical formulation and sizing of each of the components of the mini grid system as well as the selection of the Smart Grid components.

Chapter five shows simulation results and the main findings of the implementation of the grid in terms of its LCoE.

Finally, Chapter six explain the general conclusions and recommendation in terms of technological, social, economic and legal framework.

2. Literature Review and Theoretical Background

2.1. Electric Power Systems Concepts.

2.1.1. Conventional Power Distribution and the Centralize Production Paradigm

The Electric Power System can be defined as a network system where products, goods or services are used, transformed or exchanged in order to cover the needs of Electric power necessity in the populations, allowing the generation of wealth within a community, city, region or country (Küfeoğlu et al, 2018). In a high-level scale, the Electric Power System is mainly composed by the following stages:

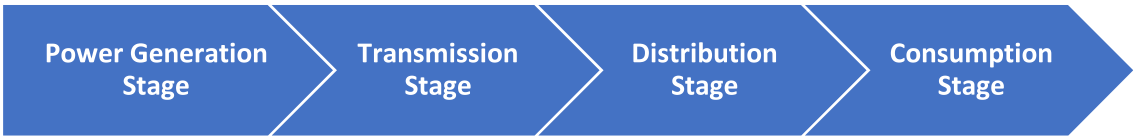

Figure 2. High level scheme of the Electric Power System
(Source: Elaborated by the author with the information provided in Küfeoğlu et al, 2018)

Firstly, in the power generation stage, a kind of energy resource (chemical, kinetic, thermal, light, nuclear, solar, among others) is transformed into electrical energy in facilities named Power Plants. In a very high level the power plants are differentiated based on the type of resource it uses (renewable or not renewable) to generate electric energy, been the non-renewable power plants the ones that produce more than 80% of the total energy in the world (REN21,2018**)**.

The power generation stage is performed in a centralized way for a given community within facilities that are usually located far from populated areas as a result security concerns, pollution emissions or in the search for proximity to the necessary resources during the generation process, such as water or other type of raw material, and later the produced energy is transferred to the community through the electric power transmission stage (Martin, 2009).

The power transmission stage, or electric power transmission network is made up the necessary elements to bring the electric power after its generation in the power plants over great distances till reaching the final distribution points for consumption. To do so, the electric transmission networks transport the electricity in high-voltage (in ranges over 400kV, 275kV and 132 kV depending on the country) (Küfeoğlu et al, 2018; Mc Donald, 2008) through the use of several conductor elements, usually made of steel, copper or aluminum cables, and are held by high-rise structures, normally built in steel lattice, whose main function is simply support the structures. All this infrastructure is defined by a high investment oriented to raw material purchase and extraction, which values increases year by year and made up over the 30% of the total cost of the electric power system (IEA, 2002).

Finally, the distribution stage is composed by third stage of the electric power system, and is the closest one to the final user, and it represents approximately 50% of the total cost (IEA, 2002) of the electric power system and is mostly composed by equipment like distribution lines, transformers, substations, metering devices and transmission lines, that allows to safely and reliably provide electric power in the different voltage that the final user might need (Mc Donald, 2008).

Particularly from the nineties, the increase in the efficiency and reliability of the conventional centralized electrical power system, allowed to stablish a greater degree of integration and decrease the marginal cost of electricity production (US DOE, 2007). In few decades the conventional electric service was multiplied to almost all the inhabited areas of the world allowing of the population (IEA, 2017 ; World Bank, 2014) developing a phenomenon known by certain authors as the "centralized electricity paradigm" where government and investment systems favored centralized generation technologies, displacing the competitive advantages of others systems and reducing the development of alternative technologies that allow for smaller distributed generation capacities (US DOE, 2007; Martin, 2009; El-Khattam et Salama, 2004; Pepermans, 2005).

Despite its advantages, the conventional electric power system has several setbacks which have begun to accentuate during the current decade. Together with a highly expensive transmission and distribution system in terms of raw materials and the emissions generated during the fossil fuels generation stages (IEA, 2002), drawbacks such as energy losses during its distribution and transformation become more relevant as prices on fossil fuel increased (IEA,2009; REN21, 2018). Because this loses that are result of physical factors characteristics in its structures like electrical resistance and parasitic capacities in cables, or by the magnetic hysteresis in the nucleus of the transformers (Dalessandro et al, 2007; McLaren, 1984; Say, 1983) not just represented an adding a cash cost to the LCoE, but also was identified as been an implicit cost in terms of greenhouse gas emissions. In other words, fuel is consumed to produce electricity that is not reaching the final consumer and is lost during transmission/distribution stage (Martin, 2009). Since transmission lines can cover short distances or hundreds of kilometers in length, it’s possible to identify that the longer the line, the greater the losses in term of economic and environmental impacts.

However, the greatest limitation identified to the centralized power distribution system is its infeasibility, in terms of costs, to satisfy the energetic demand of low dense populations in rural areas or located in remotely places like as islands or mountains, requiring large capital expenditures to perform the overhead line connections across large distances, to justify small amounts of consumption compared to the lost ones (Carley, 2009; Lethonen et Nye, 2009). Rural electrification probed in this way to be costly, and consistently has proved to be more economical feasible to rely on different generation strategies, like the distributed generation systems.

2.1.2. Decentralized Energy Resources and Distributed generation.

The distributed generation is a relative new field of research and therefore its conventions have not completely homogenized. Been the more recurrent references in the literature “microgeneration systems”, “decentralized generation systems”, “distributed energy resources (DER)” and “dispersed generation” (Pepermans et al, 2005). It is possible to identify that the main discrepancies between the authors reside between two points: whether or not a DER is connected to the conventional distribution network and the installed production capacity of the system in question (Martin 2009).

Being the location near the end user the feature that represents the most value for the present investigation. In the current investigation the concept of DER or distributed generation system will be used as: “A small-scale power generation system located in geographical terms as close as possible to the final load and might be connected to a distribution network or directly to the final customer”.

The characteristics of a DER allow various benefits that reduce the negative effects identified in the centralized production of energy, like loss reduction during the distribution and transmission stages given the proximity to the load (IEA,2002), emissions reduction and increase energy efficiency by allowing the use of lower power generators (Mancarella and Chicco, 2009; Hongbo et al, 2019; IEA, 2009), inclusion of less polluting technologies such as alternative fuels or renewable technologies (Alanne and Saari, 2006; ECPEESD, 2001), greater flexibility of operation by allowing distributed generators in congested areas that are just used during the peaks ((Mancarella and Chicco, 2009; Hongbo et al, 2010),reducing the size of the network allowing them to be constructed in a fast, efficient and tailored way even in areas far from the main network (Ajah et al, 2008; Houwing et al, 2008), as well as the development of legal strategies that allow the introduction of new players to the energy sector (IEA,2009; Küfeoğlu et al, 2019).

However, there are still some challenges that should be overcome to achieve a correct integration of the DER systems into the current centralized distribution system in terms of cost competitiveness and technical performance. Firstly, because the support that the centralized technologies received during the last years allowed a technological development that caused a backlash and diminished the competitive advantages of other technologies that today are used in the DER (Pehnt 2006). Secondly, because most of the current operating level voltage and implemented technologies around the world were designed to support the operational levels of the conventional electric power system, and do not match the optimal performance characteristics required by the DER systems (Pehnt and Schneider, 2006) forcing them even to include particular protection systems in order to avoid the creation of faults within the network (Jenkins et al., 2000) Therefore which currently, many of the DER technologies are still considered more conducive to isolated implementation than in union to the main network

It is truth that this might require time as well as economic investment. But it is a process that is already on transition. In fact, the distributed generation systems have been supporting the centralized power system for decades in terms of production, but its relevance has recover strength given current legal initiatives around the world like the liberalization of the electricity market and the concern over the green house permissions during the current las decades(IEA,2009, Martin, 2009; Küfeoğlu et al, 2018) bringing new actors to the energy production market and encouraging the development of new opportunities.

Figure 3 illustrates the main technologies used in the of power generation stage of the DER system are:

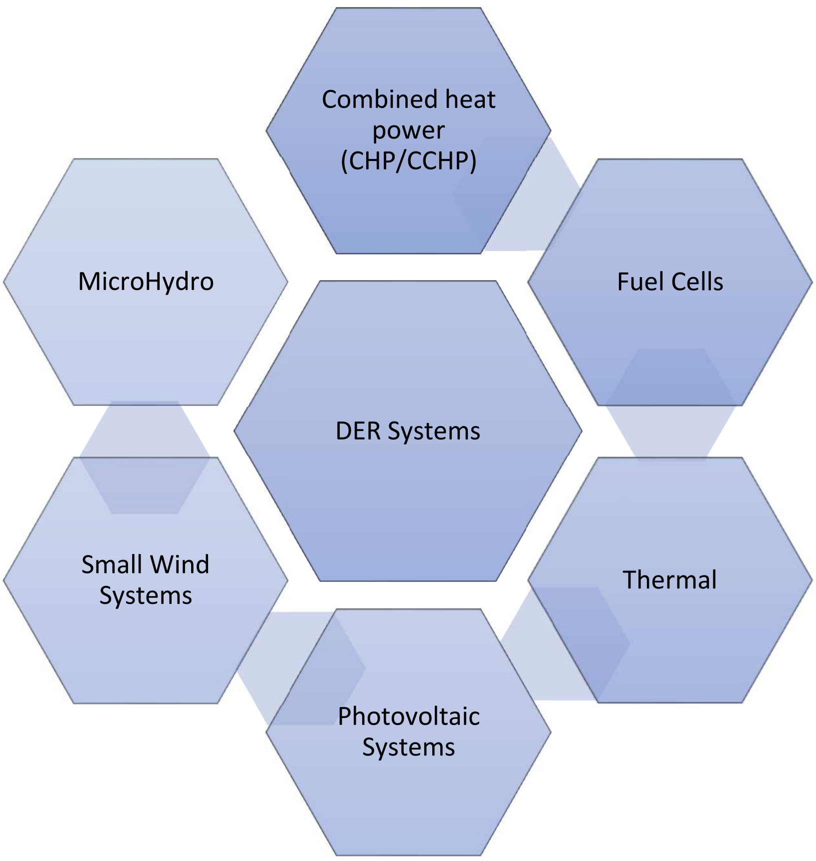

Figure 3. Technologies used for distributed generation
(Source: Elaborated by the author with the information provided in Kumar et al, 2017; Martin, 2009; REN21,2018)

2.2.Power Grids Systems Concepts

2.2.1. Main Grid System (Wide Area Synchronous Grid)

As explained in last section, most of the electricity generated in the industrialized countries is provided by large centralized facilities (International Energy Agency, 2017; REN21, 2018; Küfeoğlu et al, 2018) and previously transported the satisfy the necessities of diverse costumers in the industrial, public, residential and commercial sector. This interconnected system of centralized power plants, transmission and distribution lines are known as the Main Grid (MG) (IRENA, 2018, GIZ, 2017)

The main characteristic of this type of grid is that operates under specific standards of synchronized frequency and all its coupled members are uninterruptedly electrically tied in terms of electric consumption and resource sharing during its normal operations, as might be the North American Main Grid that is synchronized at a nominal frequency of 60Hz or the synchronous grid of Continental Europe that operates under a 50 Hz standard (World Bank, 2014; International Energy Agency, 2017). Figure 4 illustrates the operational frequencies used in countries around the world:

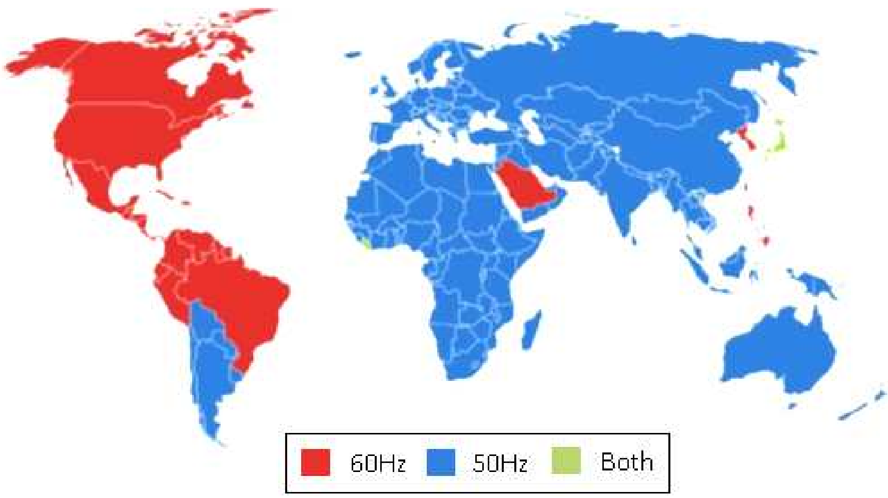

Figure 4. Operational frequencies used in countries around the world (Source: International Energy Agency, 2017)

As can be observed, the number of participants that join this network are spread across its entire geographical extension of the world. A given geographical area that is satisfied by a synchronous grid is known as a Synchronous zone (ENSO-E, 2015, ENSO-E, 2017), and it main advantages come from the possibility of interchanging the power generated from the facilities within the grid to balance the electric load demand, which is translated in the reduction of operation, schedule maintenance and power generation cost, as well as other benefits like protection of energetic reserves, the possibility of equalizing the load in the network, as well as the possibility of creation market structures for the power generators participants by the creation of long term contracts or short term power exchange schemes that are useful in events that case of disturbance of normal operation in the network (Sivanagaraju and Sreenivasan, 2009).

The generation capacity of this kind of grids are located in tens to hundreds of Giga Watts, some of the more developed Synchronous Main Grids in the world are shown in the following table:

Name	Covers	Installed capacity	Source
Synchronous grid of Continental Europe (UCTE)	The largest synchronous electrical grid in the world. It provides 24 European countries.	859 GW	ENTSO-E, 2017
Indian national grid	Provide electric service to the country of India.	329 GW	CEA,2019
Western Interconnection	Provide to the western area of USA and Canada and the north western area of Mexico.	265 GW	WECC,2016
National Grid (Great Britain)	Provide service to UK	85 GW	DUKES,2018
National Electricity Market	Covering Australian States.	50 GW	EAR, 2019

Table 1 List of more developed synchronous main grids in the world

Even when undoubtedly the wide area synchronous grid extension will still play an important role in providing energy as stated in the United Nations 2030 universal energy access plan, some geospatial studies has shown that decentralized power systems, especially the ones relaying in solar and hydro renewable resources, will be a most cost-effective solution for over than two-thirds of the rural areas who are expected to gain electricity access in the next years, forecasting a paradigm change in the policies scenarios that point to a total additional annual investment cost of around $24 billion per year to 2030, equivalent to 1.7% of total global energy investment (International Energy Agency, 2017) already reflected in an approximate amount of 500,000 isolated systems set in rural areas of developing countries by the support of Work Bank (WB) during the last decade (Martinot, 2000).

2.2.2. MiniGrid, MicroGrid and PicoGrid System (Small Area)

The predominant concepts used to refer to the small area power grids are: mini grids, mili grid, micro grids, nano grids and pico grids (GIZ, 2017; IEA, 2017; IRENA, 2015; U.S. DOE, 2019) However, literature review shows that there is not a clear convention of this terms among the researchers, and usually those concepts are used interchangeably without respecting the differentiation criteria (Bhattacharyya, 2018). When it comes to the international agencies, it is found that the main criterion of differentiation is the installed capacity of the structures, but once again, a very weak convention can be identified between the institutions. This is evident when compared the concept of mini grids, sometimes defined as systems owning an installed capacity of “few” megawatts (Cloke et al, 2017), but in this context GIZ suggest it in values below 10MW (GIZ,2017), UNFCCC describe covering it including with a maximum capacity of 15 MW (UNFCCC, 2014) and IRENA suggest values till 100 MW (IRENA,2015). On the other hand, Micro-grids ranges are specified 1 kW to 10 kW (Bhattacharyya, 2018), but some researches point to systems till 100 kW (Schnitzer et al, 2014; IRENA,2015).

For the convenience of this research, it was chosen to take as reference the following criteria, which has been generated from an extensive review:

Local Grid Systems	**Commonly Used Size**	**IRENA Proposed Categorization**	**Size used for this investigation**
Mini grids	10 to few MW	0–100 MW	100 kW to 100 MW
Micro grids	1–10 kW	5–100 kW	5–100 kW
Nano grid	0.5–1 kW	0–5 kW	1–5 kW
Pico grid	0–0.5 kW	0–1 kW	Less than 1 kW

Table 2. Small area power grids classification according to its installed Capacity (Source: Generated by the author with information from Bhattacharyya, 2018)

From the functional point of view, a small area power grid can be understood as an electric power system like the MG, but with a smaller installed capacity and distribution area. In other words, it is also made of components such as power generators, storage devices, distribution lines and interconnected and controllable loads (Chaurey and Kandpal, 2010). They are mainly differentiated for having a limited power production range, a clearly defined geographical boundary of service and a delimited infrastructure that don’t allow to provide electric service beyond that area, however, are completely designed to be independent and self-sufficient, and to satisfy the energy demands of its final consumers without relaying in the MG. (GIZ, 2017; IEA, 2017).

The design characteristic of operating without been connected to the MG is named "Island-Mode” (US DOE, 2019) and during the last years several communities around the world has gained access by this approach particularly in Africa (IEA, 2017) where they have proved to be a better “cost-effective solution” than extending the MG due efficiency reasons (Bansal et al, 2013). Anyway, most of the small area power grids were also designed with the possibility of been interconnected to the MG and exchange generated power to the costumer if needed (GIZ, 2017), in fact it is estimated that most of the small area power grid that has been installed in United State of America operates connected and synchronized with the Main Grid (U.S. DOE, 2019).

Given that the networks are designed specifically depending on the available resources and the requirements of the load, the configuration of a small electric power network tends to vary (GIZ, 2017). However, there are basic components that are possible to find in most market configurations, which are described in the following figure.

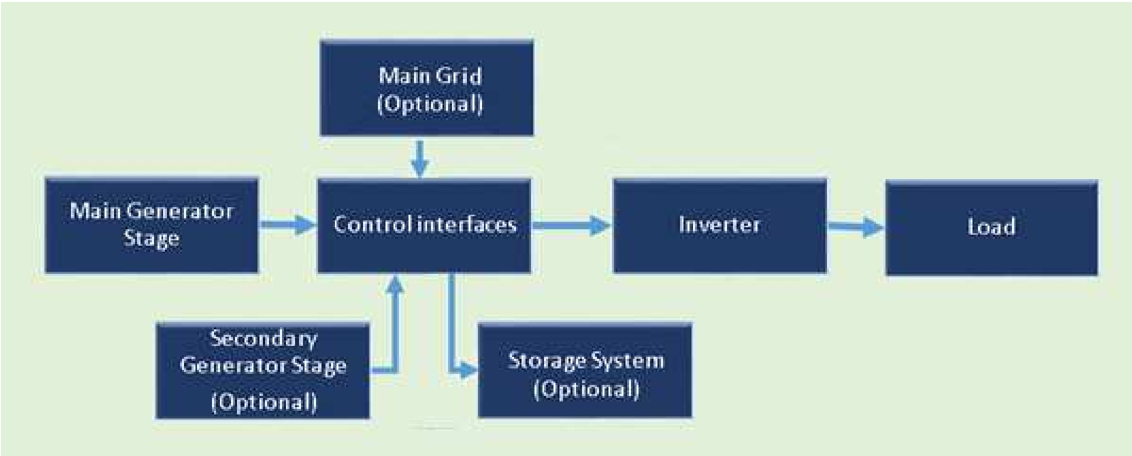

Figure 5 Conventional small area power distribution grid

Where the main functionality of each component is described in the following table:

Main Category	Components
Main power generation stage	It is the component that contributes in a greater way to the energetic generation of the network. Their type and installed capacity tend to be selected focusing mainly on the energy

	resources available in the area, so as to reduce the cost of generating energy as much as possible. The energy resources used for it can be renewables or non-renewable. Conventional mostly systems are composed solar panels, CHP generators, wind generators, micro turbines or fuel cells. This stage is might be connected to the rest of the grid by using an interface based on power electronics, that allow to reach the needed voltage in the grid.
Secondary Generator Stage	It covers the same function as the main stage of power generation; However, it is considered in the design as a stage of support for reasons of cost or convenience and is intended to run only in case the stage the main stage of generation is not able to provide enough energy. They are usually composed of generators whose ignition is convenient and rely on easy to store energy resources.
Storage Stage	Composed by batteries, thermal storage devices or electrical to thermal conversion devices and its main function is to store the surplus of generated energy, for its future consumption.
Control interfaces	Are interfaces in charge of operating and monitoring the correct functioning of the network, and are mainly composed by: •Building Energy Management System (BEMS) that is the central Control System of the micro grid. • Local controllers (To control the generators and loads) • Communications devices required for distribution operation •A Distribution of control logic that usually is segmented into Primary control and secondary regulation and auxiliary services)
AC/DC Inverters	Allows the power conversion from Alternate current to Direct current or vice versa, in case is required.
Loads	The final consumers of the generated power.

Table 3 Main components of conventional small area distribution Grids
(Source: Made by author with information obtained from Arbab-Zavar et al,2019; US DOE, 2019, Falvo et al, 2013

Depending on the types of coupling used in the grid the small area distribution grids are also classified in to DC coupling, AC coupling or mixed coupling (Tunlasakun et al, 2004; Williams and Maher, 2008; Bansal et al, 2013). The differences between these systems relay in in transforming the direct or alternate current by the use of AC/DC converters, and then provided to the central power bus by the use of charge controllers that might be provided to the final load or using converters in case of needed (Arbab-

Zavar et al, 2019). The main reason for implementing this kind of system depends on the type of appliances that the final costumer owns, been the DC systems more commonly used for nano and pico grid systems run at low voltages (usually 12V), while on the other hand, the AC s are usually designed in higher voltages (24V,48V or 72V) in order to reduce conversion due lost (GIZ, 2017)

2.2.3. Off-Grids Systems

An Off-Grid system, or also called an isolated system, is a generation system that is not connected to the MG (which are called On-Grid systems) and thus focuses its design on generating 100% of the energy required by its users through the use of one or more generating stages that comprise it (SMA, 2019; IEA, 2017, IRENA,2019,GIZ,2017).

The vast majority of the systems identified during the review literature, allow to identify that these systems are composed of more than one distributed power generation component of reduced sizes such as DER (Sharma et al, 2007; Kanase-Patil et al, 2011; Herran, et al, 2012), as well as territorial dimensions of small area and installed capacities within the ranges established for small area power grids (Kumar, 2010, IRENA, 2018, Raman, et al, 2012) . This situation has caused these concepts to be used interchangeably. However, it was also possible to identify its use in smaller scale systems, with a single power generation stage and that do not strictly represent networks of diverse users, such as Solar Home Systems, or photovoltaic solutions to satisfy small-scale lighting (IEA , 2017; Shiroudi et al, 2013;SMA,2019) So it is possible to conclude that its terminology usage represents more a design paradigm, than a concept that indicates specific criteria in question to installed capacity, energy sources, power of use or construction topologies.

During the last decades, technological progress has allowed to reduce production costs and increase the generation capacity of various renewable technologies, making them attractive for their implementation in off-grid systems. This has occurred particularly with photovoltaic, biogas and micro wind technologies, given their ability to access energy sources in various areas of the world even if they are isolated from the main network, also resulting in cost reduction and dependence on fossil fuels (Gothwal et al, 2018; REN21, 2018; IEA, 2017; Chea, 2011). The following figure describes the number populations that has obtained energy access through the implementation of off-grid renewable system around the world in the last decade according to IRENA figures:

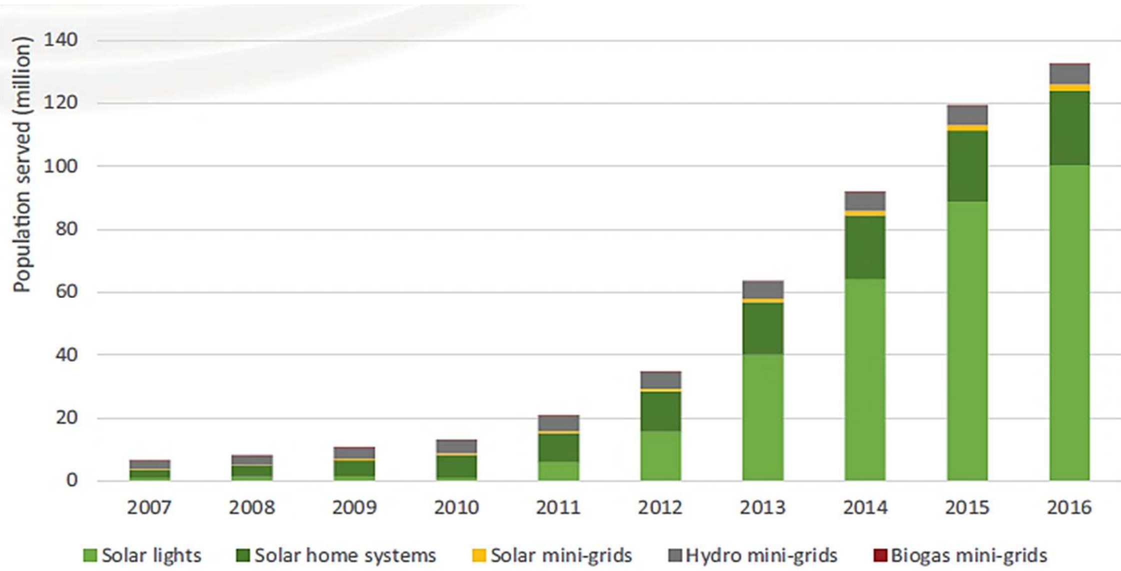

Figure 6 Population served by off-grid renewable energy solutions globally (Source: IRENA, 2018)

An Off-gird system is regularly composed of a main generation stage that provides the majority of the system's energy, a secondary generation stage that works on demand when the users' consumption exceeds the amount of energy that can be provided by the stage main generation, an accumulation system that allows to store energy generated from a requires energy accumulation systems, voltage regulation devices that are used mainly to rectify the energy supplied from the high fluctuation generating stages as renewable energy sources and the loading or consumption stage (SMA,2019; Cotar,2012)

This type of systems presents various barriers in technical and legal terms depending on the countries where they are implemented. On the one hand, from the technical point of view, Off-grid systems present complications to offer cost-feasible solutions for systems with high consumption profiles, such as satisfying the consumption demand of heating and cooling appliances in large communities.

On the other hand, the effect of the centralized paradigm, caused that the development of a large set of legal regulations which are strictly focused on concepts of the MG in terms of distribution, generation and transmission (Küfeoğlu et al, 2018) but leaving a large area to be covered in terms of liberalization and energy production and which currently restrict the implementation of off-grid systems in most areas of the world due to the lack of a correct definition of frameworks that favor the implementation of pricing, taxation, policy implementation, regulation and therefore restricting the increase of investment in the area as well as attraction of stakeholders (Chea, 2011).

2.2.4. Smart Grids

A Smart Grid can be understood as an electric power grid that incorporates the use of digital technologies in order to establish a bidirectional fluid communication between the power plant, the end user as well as other control devices in the network that measure performance and execute decisions about the use of resources of the network (Atheeq, 2018). In this any type of electrical grid that includes sensors, computers, automation and communication systems that allow monitoring and delivering real-time information and immediate react to balance loads in the system and achieve energy stability in terms of supply and demand is known as smart grid (DOE, 2010; Murphy,2010).

To do so, the smart grid devices monitor the consumption of loads in the network, allowing its value to be known at all times by incorporating an automated computer system capable of automatically responding to fluctuations in energy production, but also of demand through the use of tools like internet services, local networks, statistical approaches and informatics and home automation tools to respond firmly to the volatile demand for electricity (Afsar et al, 2015; Ataul et al, 2014). The main objective of these systems is to achieve a situation in which both the end user and the distributor have more information about consumption, and in which a more responsible and predictable use is made throughout the cycle: from the plants generators to the domestic system allowing a maintenance, projection of development of the network to in long term, as well as reduction of consumption of electrical resources when they are not necessary (U.S. DOE, 2010; Arbab-Zavar et al, 2019).

Among the main benefits obtained through the integration of Smart Grid technologies is the most efficient transmission of electricity, the reduction of operating costs, greater robustness of the service, more effective handling in the face of disturbance, reduction of demand peaks and better management of high fluctuation systems such as renewable energy systems (Siddiqua et al, 2018; Falvo et al,2013). From the point of view of the market, it allows the adjustment of consumption rates and the purchase of energy in real time (Küfeoğlu et al, 2018).

On a large scale, what converts a conventional network into a Smart grid is the inclusion of devices for methe following components:

Name	Description
Smart Meters	Are intelligent energy flow devices that improve the operation of the network by measuring the record voltage, current, and frequency and always provide reliable data about the network. (US DOE, 2010)
Grid Intelligence Components	It is a specific infrastructure of each network that allows its automated control, such as the connection or disconnection of resources to the network or the activation of some power generation resource in the network. (US DOE, 2010)
Smart Inverters	Devices that has the ability to operate efficiently and autonomously the AC/DC conversion of a system or vice versa, but also are programed to autonomously control de power flow, identify faults and disconnect with a particular node of the network if required without the need of an operator intervention. (Arbab-Zavar et al,2019)
Smart Energy Storage Systems	Technologies developed to transform and store the energy with high efficiency and high life cycle. The most common approach can be a battery bank that could measure it discharge level and disconnect to protect operation degrees that might be risky for its long life operation.(Falvo et al, 2013; Nishant et al, 2018)
Wired/Wireless Communication Technologies	Communication devices in charge of connecting the participants of the network through diverse protocols, like WAN, LAN or P2P. Wired Technologies are more immune to interferences and their operational dependency on batteries are less than with wireless technologies, but are restricted to physical limitations of the network. (Arbab-Zavar et al,2019)
IT Utilities	It is smart data management devices collected within the network, which allows both their distribution, access and the restriction of this information through security and encryption protocols. (Siddiqua et al, 2018)

Table 4. Smart Grid Main Components

2.3.Photovoltaic Concepts

2.3.1. Solar Irradiation

The solar resource is a function of solar radiation, which is the result of fusion reactions in the sun's atoms, which reaches the Earth in the form of photons. This radiation is the one that can be transformed directly into electricity by using photovoltaic and photo-thermal technologies or to heat by using thermo-solar technologies (Hersch and Zweibel, 1982).

The Solar radiation has two components:

- Direct radiation: comes directly from the solar focus, without reflections or intermediate refractions.
- Diffuse radiation: It is the one received through multiple phenomena of reflection and solar refraction in the atmosphere, in the clouds, and the rest of atmospheric and terrestrial elements.

Both types of radiation can be exploited through the use of active receivers, which use mechanisms to orient the receiver system towards the sun and better capture direct radiation, as well as Passive receivers remain static in a specific place and only gain advantages from radiation. direct they receive during the day (Cotar and Filcic,2012).

Solar radiation is usually measured in its amount of density over a specific area during a given time, been (kilo)watt per square meter per day or per year the most common unit of measure ($Wh/m^2/day$ or $kWh/m^2/a$) (Chea, 2011).

2.3.2. Photovoltaic Technologies

A photoelectric cell, also called photocell or photovoltaic cell, is an electronic device that allows electrical energy generation by taking advantage of the photoelectric effect (Hersch and Zweibel, 1982). When the electromagnetic radiation coming from the sunlight hits this kind of devices, an emission of electrons can be perceived, then under a constant and controlled exposure to this light it’s possible to control the flow of this free electrons to generate an electric current (Chea,2011; Markwart & Castaner, 2003).

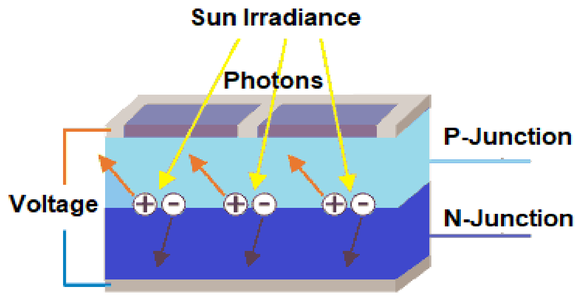

Figure 7. General principle of a PV cell

The photovoltaic panels or modules are structures composed of an array of photovoltaic semiconductors. Basically, these technologies are made-up semiconductor devices diode type which are excited by sunlight and generate a small difference in potential at their ends. To achieve higher voltages, several of these diodes are joined in series.

Figure 8 Photovoltaic Cell (Left) and Module components (Right)
(Source: Atersa,2019)

There are different elements that can be used to generate the photovoltaic phenomenon, but nowadays most PVs are composed from silicon (Si) a nontoxic element that can be found in abundance in the planet, been the next technologies the mores wide spread in the market (Askari et al, 2015; Cotar and Filcic,2012; Chea,2011):

- Monocrystalline: This type of cell stands out for being manufactured with very high purity silicon. They are the most efficient type of cells in terms of space and electricity generation, which translates into the practical implementation of smaller installations. They have a long useful life, with guarantees in many cases of 25 years and capacity to function up to 50 years. Due to their high composition of silicon they have a high price in comparison to other technologies and tend to yield less at higher temperatures. And one of its main problematics is the waste of material that is generated by during the cutting process of these cells. They are identifiable by their dark circular hexagonal or octagonal shape and by a single crystal of silicon sections.

- Polycrystalline: Its manufacture started in the eighties. Its biggest advantage with respect to monocrystalline cells is based on a lower cost production process, which pulls down the final price of these systems when they are manufactured by small crystallized particles. For its elaboration the silicon is melted and introduced in molds with which the cells are shaped. With this process not only a much smaller amount of this element is used, but losses in the production phase are avoided.

  The lower heat tolerance of these cells means that they have a lower efficiency than the monocrystalline alternative.

- Amorphous: This kind of technology is elaborated by setting a thin sheet of amorphous (non-crystalline) silicon covering a long surface. Are considered as the less effective of all PV technologies, however are the cheapest ones in the market too. As a result of its production process it owns particular property over the other technology of been folded, allowing it to cover particular areas that solid PV panels can’t. It main identified constrain is generated due its efficiency, because most of the power of this technologies tend to drop during the first months after production, to reach a point of stability. Can be made of elements junction of Cadmium and Tellurium (CdTe) or some mixes of Copper, indium, gallium and selenide (CIS, CIGS).

The maximum power that a panel can generate, is called peak power and is defined as: the maximum amount generated by a panel or set of panels in the hours of maximum insolation in a certain geographical area and is measured at 1000 w/m^2 (incident energy per square meter) and at 25º C of room temperature and currently average photovoltaic cell efficiency in the market is around 15%, owning an operation warranty of 25 years (Cotar and Filcic,2012).

2.3.3. Photovoltaic System

It is an electric power system formed by integrated functional blocks, with the purpose of providing the electrical energy necessary for the consumption of a facility, which can be from a house to an industry. It can be designed as an isolated system or to connected to the MG, it is mainly supported by electrical energy generated by solar panels, but can also include another backup generator stage (Cotar and Filcic, 2012). The biggest advantage of a PV system, it's the possibility of getting access to its main energy source for free, been just necessary to perform a correct assessment of the availability of this resource in the area to get benefit from it (Chea, 2011).

The following diagram illustrate a typical Photovoltaic system and its main components:

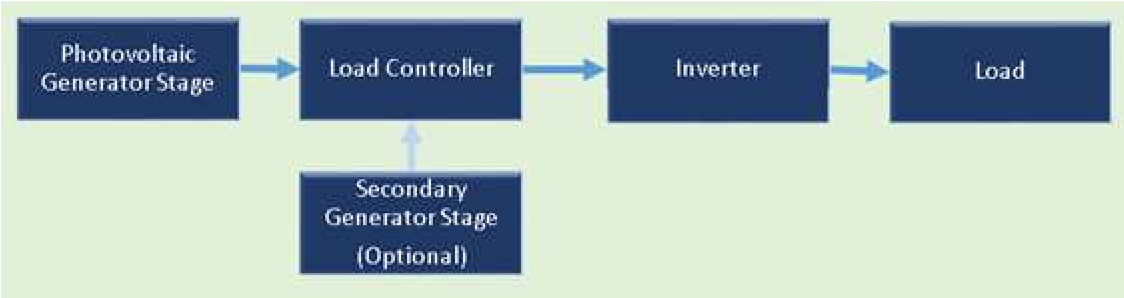

Figure 9 Typical Photovoltaic system
(Sorces: Elaborated from author with information from Cotar and Filcic, 2012; Alkhalidi and Hussain, 2018, ABM,2017)

In order to perform a correct definition of the requirement and size of a PV system in terms of are and installed capacity, the following characteristics need to be considered for the load Regime are listed in the following table (Ruralelec ,2014; Cotar and Filcic 2012; Colombo et al, 2016; Sivanagaraju and Sreenivasan , 2009):

Name	Description
Load Profile or Energy Consumption profile	It is an analysis that describes the amount of energy that is required to satisfy the energy demands. In a connected grid system, this can profile can be generated from the consumption measured during the last year. In the case of an off-grid system, it become more complicated due the lack of information, been necessary to define an estimation in order to design the system. Depending on the consumption, it will be measured in Wh / day or kWh / day
Use time	It defines the period of the day during which that energy will be used. This calculation is made, to evaluate the possible strategies to satisfy the energy necessities in accordance to the available irradiation values in the zone. If the system has usual night consumption or describes a consumption bigger that can be generated by the PV stage, the implementation in the market include a battery bank or a secondary power generation stage.
Maximum Load or Peak load.	The number of hours per day for each operating month that the irradiation values in the region can provide the peak hours (1000 w / m^2) To obtain it, the consumption pattern must be analyzed to determine if the load regime is constant, or if it has load

	peaks where several electrical loads must be fed simultaneously. Which must be satisfied, or the system will have an energy deficit.

Table 5 Requirements to define the characteristics and size of a PV system

2.4.Mexican Energetic Public Policies and its Regulatory Framework.

The current state of energy production in Mexico is the result of factors generated through the time as the result of the existence of fossil resources in the country, in conjunction with the development of a legal framework designed to promote the investment and develop of it relative supported technologies, developing gaps for the possibility of implementing alternatives solution as new technologies were developed.

In order to deeply understand how the current energetic legal framework in Mexico was developed, as well as identifying the legal restrictions and the administrative tools that allow the implementation of Mini grids in Mexican territory it is necessary to understand its origins and evolutions trough the time. Therefore, this section focuses on explaining the background of each of the changes in the policy framework since its origin up to date.

2.4.1. Origins of the Energetic Public Sector in Mexico (1937-1970).

In its origins, Mexico's electricity sector was made up of private companies comprised mostly of Mexican capital and, later, by a significant number of companies with foreign capital, whose operation was regulated by concessions. Then finally in 1937 the CFE was created with the objective of organizing and directing a national system of generation, transmission and distribution of energy and adapting it to the needs of the country's economic development, under the government of President Lázaro Cárdenas, marking the beginning of a tendency to establish the direct presence of the State in an activity that until then was in charge of individuals. A year later, in 1938, the now defunct Electricity Industry Law or "*Ley de la Industria Eléctrica*" as known in Spanish was enacted, which for the first time regulated everything related to concessions and permits in the field of electricity (SENER,2018).

The direct presence of the State was consolidated when in 1960, when Mexican government bought the "American and Foreign Power" company, as well as 90% of the shares of the Mexican "Luz y Fuerza del Centro" Company. Allowing the virtual nationalization of the Mexican electricity sector. Then as an immediate action the state was constitutionally established as the one holding the exclusive right to generate, conduct, transform, distribute and supply electric power for the provision of public service, constitutional approaches found in articles 25, 27 and 28 of the Political Constitution of the United Mexican States (Lopez, 2009)

2.4.2. The Public Electricity Service Law (1975 - 1992)

This legal system was maintained until 1975, when the Public Electricity Service Law or "*Ley del Servicio Público de Energía Eléctrica*" was issued, establish punctually that "the self-sufficiency of electric power to satisfy the demand of some users was not considered as a public service". This modification allowed one more time the participation of private investment in the electric power generation sector by holding a prior permit and the explicit condition that the proposed implementation was inconvenient or impossible to be provided by CFE In addition, in 1983, the Law was reformed to expand the self-supply framework, in order to allow cogeneration and generation of energy exclusively destined to emergencies derived from interruptions in the electric power service. And finally, in 1992 new amendments were made to this Law to allow private investment in the generation of electric power for exclusive sale to the CFE (Lopez, 2009; DOF,1993) .

Then after all these modifications, enabled the possibility that individuals generate electricity under the modality of independent energy producers under directives of the State. Other relevant characteristics to highlight that were created since the enactment of this law and given its amendments over the years are (Ramirez-Camperos, 2013):

- Figures with the purpose of generating self-supply, cogeneration, small production and independent production do not constitute as part of the public service sector.
- The concept of self-supply was expanded to include companies that have the objective of satisfying the energy demand of their partners.
- In the independent production mode, it is allowed to generate electricity for sale to CFE. The CFE has the legal obligation to acquire electricity through a specific contract.
- The mode of small production was created, which is similar to the independent production modality, with the restriction that its production capacity is limited to 30 MW. The production of electricity must be sold exclusively to CFE.

It is important to remark that the Public Electricity Service Law has keep in force since it´s promulgation and has continue till the moment when this report is generated. And although the energy monopoly for the provision of public service is preserved by the state, this legal framework is considered relevant because allows the current participation of individuals in the generation and importation of electricity. All these reforms were a first step to encourage private investment in electricity generation.

2.4.3. The Energy Regulatory Commission (1993-1995)

In 1993, the Energy Regulatory Commission (CRE) was formed as an advisory body in the field of electricity in order to promote the development of the gas and electric power sectors for the benefit of users (DOF, 1993). Then in 1995, the Law of the Energy Regulatory Commission was issued, transforming the CRE from a consultative body to a decentralized one, with technical and operational autonomy, in charge of the regulation of natural gas and electricity in Mexico (DOF,1995). The Law strengthened the institutional framework, made legal operative changes, and increased clarity, transparency and stability to the electric and (Edgar, 2009)gas and electric power and concentrated it powers that were dispersed in other systems, dependencies and entities.

2.4.4. Sectoral Energy Program (2000-2007)

At the end of the year 2000, the Sectorial Energy Program 2001 - 2006 (PSE) is published, which establishes that by 2006 at least 1,000 additional MW will have been added to the installed capacity of electricity generation, from renewable sources of energy (excluding the large hydroelectric plants programmed by CFE) (DOF,2001). Then, in December 2006 the initiative of the Law was approved in the Chamber of Deputies, which establishes the creation of a Program for the use of Renewable Energy Sources (SENER, 2006). In this Program, a minimum percentage of 8% with respect to total electricity generation of the country was proposed for the participation of renewable energies as the goal for 2012, excluding the large hydroelectric plants.

Similarly, for the year of 2007, the Energy Sector Program 2007-2012 is announced, where the main goal was to reach a percentage of electricity generation with renewable energy of 26% for 2012 (Presidencia de la Republica, 2007). As a result in 2008, a law proposal for renewable energies was performed, called the Law for the Exploitation of Renewable Sources of Energy or *"Ley para el Aprovechamiento de las Fuentes Renovables de Energía"* (LAFRE), that provided legal certainty to the use of renewable energies in the generation of electricity, establish rules regarding their use and recognize their benefits, with the purpose of supporting the generation of electricity produced by parastatal and private companies, in the case of small-scale generation and in isolated communities (Gaceta Parlamentaria, 2008). Main highlights were that a greater contribution from the private sector and the support of the CFE, in addition to making use of the different financing mechanisms, such as those developed by the Federal Government in conjunction with the Global Environment Facility (GEF), the World Bank (WBG) and the United Nations Development Program (UNDP) (Lopez, 2009).

2.4.5. Renewable Energy Transition (2008-2012).

On November 2008, the Law for the Use of Renewable Energy and the Financing of the Transition was approved. Containing of 31 articles distributed in four chapters, in addition to twelve transitory articles, was in accordance with Article 1: "to regulate the use of sources of renewable energy and clean technologies to generate electricity for purposes other than the provision of public electric power service, as well as establishing the national strategy and instruments for financing the energy transition " (SENER, 2018). The promulgation of this law was controversial, to the point of been considered by some Senators as unconstitutional due the strong modifications performed to the legal framework specially focused on changing the Law of the Energy Regulatory Commission (Lopez,2009).

A list of this modifications were: Reforms and additions in articles 1 and 2, mainly in fractions V, VI and VII; in article 3, in its fractions VII, VIII, IX, X, XI, XIII, XIV, XV and XXI; in the articles 4, 6 and 7 in their fractions VIII; and articles 10, 12 and 13, while at the same time derogate the section VIII of article 2.

2.4.6. Energetic reform (2013-2018).

In December 2013, the Energy Reform was approved by the Senate of the Mexican Republic, modifying the legal framework in hydrocarbons management laws, generation of electricity and use of geothermal energy. Among the objectives of the reform, it was sought to maintain the ownership of the Nation over the hydrocarbons that are in the subsoil and allow the modernization and strengthening of the national institutions focused on the energetic management of hydrocarbons and electrical distribution (Pemex and CFE) through the attraction of private investment in the energy sector that focused mainly on centralized control of government institutions (Presidencia de la Republica, 203.

The reform allowed to strengthen the regulatory bodies of the sector and assigned them new powers to regulate effectively public and private companies. In this regard, the Energy Regulatory Commission (CRE) obtained technical, operational, management and self-sufficiency autonomy and also built a long-term legal framework for private investment in the distributed PV solar generation sector (AMB, 2017). Specifically, in April 2017, the Federal Government approved the regulatory and public policy framework, in which incentives of various kinds are established in order to boost market growth, opening a new financing opportunity for the commercial Bank and national and international Investors in the area of renewable energy sources y DER schemes (CRE, 2016), allowing that by 2016, 25% of the generation capacity of electricity was produced in clean and renewable energy generators, although maintaining the installed capacity of photovoltaic technologies at a national level below 0.38% of the National production. (PROMEXICO, 2017).

2.4.7. Current State of the Energetic Public Policies and Regulatory framework in Mexico.

In terms of the regulatory framework, the amendments to the Public Electricity Service Law have favored the participation of private industry in the generation of electric power for activities that do not constitute a public service since 1992 (DOF, 1992), trough modalities like self-supply framework and cogeneration for the consumption of those involved in the project, as well independent energy production for projects whose purpose is to sell the electricity generated to the CFE.

When it comes to the area of electricity generation for the public service through the use of renewable resources, by constitutional mandate, the regulatory framework states that CFE would be the institution that should take advantage of the natural assets and resources available in the country, such as the existing large dams, as well as the nuclear energy, while the other forms of generation are allowed in the modalities authorized in the Electricity Public Service Law (SENER,2018) and will be the CRE the institution that would provide all the necessary regulatory instruments to allow individuals to develop renewable energy projects, such as the Interconnection Contract for Renewable Energy Source and the Interconnection Contract for Solar Energy Source in Small Scale (CRE,2016).

The main legal systems and the regulatory instruments through which the operations of the electricity sector are governed can be observed in the following diagram:

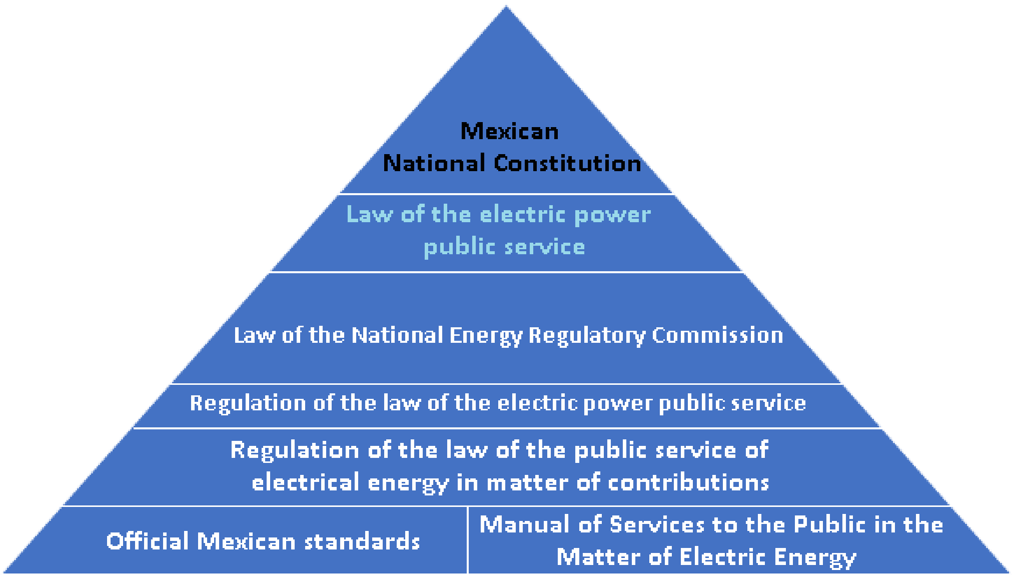

Figure 10 Legal systems that govern the activities of the Mexican electricity sector (Source: SENER, 2007)

As it is possible to observe, the regulatory framework of the Mexican electricity sector is based on the Political Constitution of the United Mexican States, in its articles 25, 26, 27 sixth paragraph, 28, 73, 74, 90, 108, 110, 123 and 134. Been the main legal systems derived from the fundamental norm that regulate the provision of the electric power public service:

- **Law of the Public Service of Electric Power:** Known as L*ey del Servicio Público de Energía Eléctrica* in Spanish. It act as the main order in the Electric power Sector, as well as the CFE structural constitution. It focusses on regulating the provision of the electric power public service as well as the operation and organization of the CFE.
- **Organic Law of the Federal Public Administration:** Known as *Ley Orgánica de la Administración Pública Federal* in Spanish. It mainly states the functions and faculties assigned to the Mexican State offices and

particularly to the Energy Secretariat. It reaffirms and recognizes the structural location of parastatal entities.

- **Law of the Energy Regulatory Commission**: Known as *Ley de la Comisión Reguladora de Energía* in Spanish, which regulates the activities and organization of CRE as well as its powers.

Beginning in 1995, through the issuance of the Law of the Energy Regulatory Commission. The CRE has established itself as an autonomous, technical and operational regulatory body which main objective is to promote the efficient development of the electricity industry, natural gas and LP gas. It aims to safeguard the provision of services, promoting healthy competition, protecting the interests of users, promoting adequate coverage national and address the reliability, stability and security in the supply and provision of services (DOF, 1995).

With the issuance of the LSPEE in 1975, it is established that the participation of individuals in the generation of electric power can be done, subject to prior permission and the opinion of CFE. Also, as result of its modifications in 1992, including cogeneration, independent producer, small production and export and import of electric power were incorporated (DOF, 1992). In other words, any type of project focused on the generation of electric power and distribution, is possible through the prior authorization of the CFE and CRE (CRE,2016).

2.5. Regulatory framework that covers the implementation of Mini grids in Mexico

As a facilitating mechanism for the participation of individuals in the generation of electricity, the Mexican regulatory framework has regulatory instruments that allow permit holders to request from suppliers the interconnection to the National Electric System. The following diagram illustrate the current modalities of permits and regulation instruments allowed by the Mexican Legal Framework:

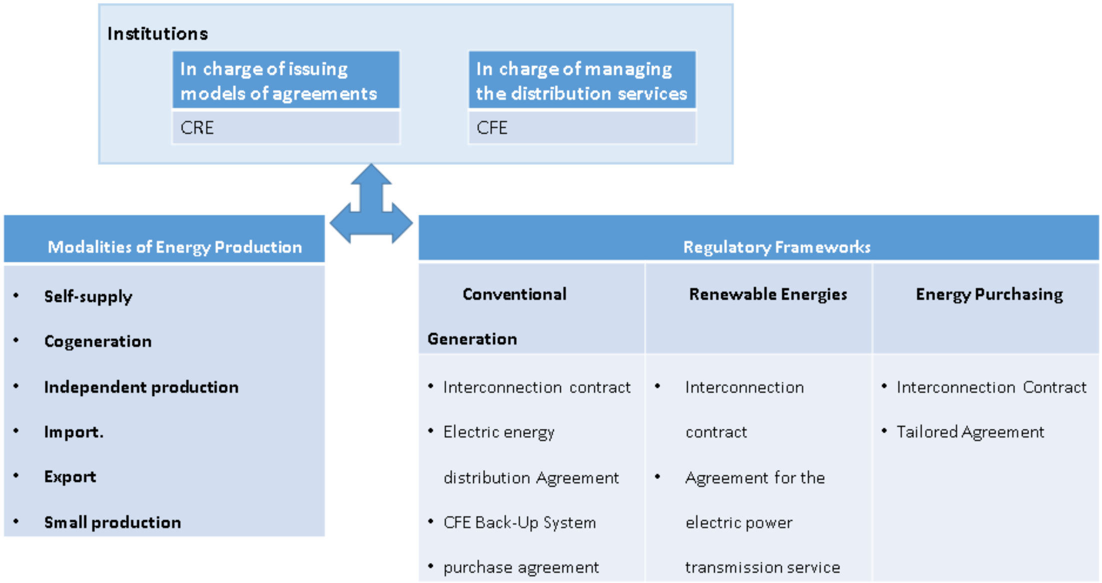

Figure 11 Modalities of permits and regulation instruments
(Source: Made by author from Lopez,2009;Ramirez-Camperos,2013; SENER,2007)

As can be observed, the only two possible ways that are possible to be implemented for Renewable energies are:

- Interconnection contract: It is the mechanism where terms and conditions are established for the necessary interconnection between the SEN, the renewable energy source and the permittee's consumption centers, so that this contract serves as a framework for all operations between the supplier and the permit holder.
- Agreement for the electric power transmission service: It allows transporting the electric power generated from the renewable energy source to where its consumption centers are located.

And from these types of contracts, it is possible to establish the following modalities the use of the generated energy (With Previous authorization of the CRE) (Ramirez-Camperos, 2013; CRE,2016; AMB, 2017):

- **Self-supply.** Generation of electrical energy for self-consumption purposes, provided that said energy is destined to satisfy the needs of natural or legal persons and is not inconvenient for the country.
- **Cogeneration.** Production of electrical energy together with steam or other secondary thermal energy, or both**.**
- **Independent production.** Generation of electricity from a plant with a capacity of more than 30 MW, exclusively for sale to the CFE or for export.
- **Import.** Acquisition of electric energy from generation plants established abroad through legal acts concluded directly between the supplier of electric power and the final consumer.
- **Export:** Generation of electrical energy to be used for export, through cogeneration, independent production and small production projects, which comply with the applicable legal and regulatory provisions, as the case may be. Permit holders in this modality cannot transfer the generated electric energy within the national territory, unless they obtain permission from the CRE to carry out said activity in the modality in question.
- **Small production**: It composed generation of electric power destined to:

1) The sale to the CFE of all the electricity generated, in which case the projects may not have a total capacity of more than 30 MW in a given area.
2) The self-sufficiency of small rural communities or isolated areas that lack electricity service, in which case the projects cannot exceed 1 MW.

3) Export, within the maximum limit of 30 MW.

In addition, since 2007, the interconnection contract for a small-scale solar energy source was generated, which is applicable to all generators with a solar energy source with a capacity of up to 30 kW, which are interconnected to the electricity grid of the supplier in voltages below 1 kV and that do not require the use of the supplier's system to carry power to their loads.

From here it is possible to identify that a mini grid system in Mexican territory could be implemented under a regime of an agreement for the electric power transmission service by means of a prior authorization from the government institutions (CRE and CFE) and to be executed in the modality of a small production regime while the project does not generate more than 1 MW.

2.6. Solar Energy Sector in Mexico

Historically, Mexico has been an extremely oil dependent country. Among the last decades, the Mexican national energy balance has shown a positive evolution through establishing most of its primary energy production through the consumption of hydrocarbons such oil and natural gas (SENER, 2018). It has been just until the last decade that renewable energies started to have a good degree of integration in the electric power production sector, through the use of biogas, wind generators, photovoltaic, and thermal technologies. Nevertheless, the use of renewable energies in the country has keep underutilized (ABM,2017).

The following figure describes the evolution of the composition of the internal energy supply in Mexico, and its respective distribution in renewable energies during the period of 2005 – 2015:

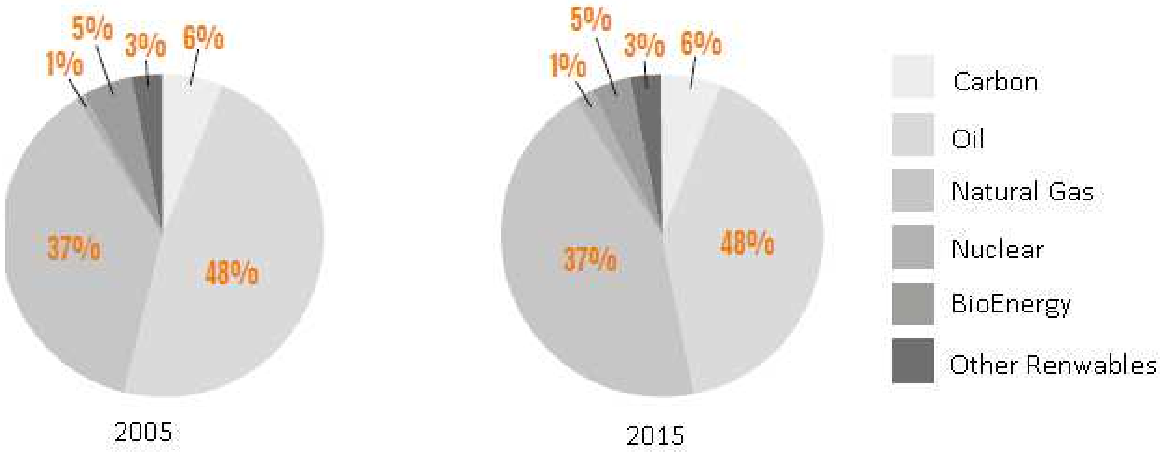

Figure 12 Composition of the internal energy supply in Mexico (2005 - 2015)
(Source: PROMEXICO, 2017)

By 2015, less than 3% of Mexico's energetic domestic production was generated from renewable energies. Representing a very small development, especially terms of implementation of photovoltaic solar energy contributing less than 0.12% of the total gross domestic energy supply, being overcome by the use of other renewable energies such as wind generators or thermal energy (PROMEXICO, 2017).

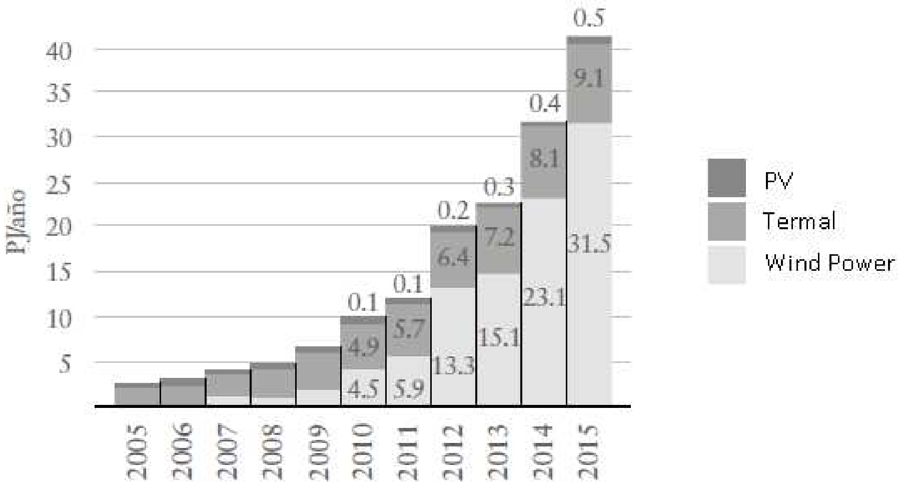

Figure 13 Composition of the renewable energy generated in Mexico (2005-2015)
(Source: PROMEXICO, 2017)

Even when Mexico has several regions where the values of solar irradiation exceeds by far the values of some countries around the world (And can be consulted in the Appendix I) where the solar resources has been already successfully implemented (CONAE,2007), the development of the photovoltaic sector has been limited by financial constraints, rather than by legal constraints, mostly because to the lack of experience of commercial banking in the sector, and the lack of knowledge of technology and its technical and credit performance, has generated a scenario where the majority of private commercial banks in the country perceive the photovoltaic investment as a high risk one (ABM, 2017).

As a result, most of the implemented photovoltaic generation plants in Mexico ware implemented in its origins as pilot projects or as part of international programs in collaboration with the Mexican government, causing that most of the implemented projects were oriented to mostly self-consumption proposes of small communities, rural schools and rural clinics (SENER,2018), like the Puerto Alcatraz Photovoltaic-wind-hybrid in Baja California (the first openly documented PV installation) performed in 1997 owning an installed capacity of 77.3kW. Formed by 3 wind turbines of 5kW, 2.30kW in photovoltaic arrays, 60kW diesel machine and 200kWh of a battery bank performed by the Non-Conventional Energy Area of the Electric Research Institute (IIE). From then other pilot projects were carried out in the cities of Mexicali, Baja California and Hermosillo, Sonora oriented to Solar Home systems and photovoltaic pumps (Lopez, 2009; SENER, 2018).

As a result of the implementation of the Energy Reform in 2013 and other tools in terms of regulatory framework and public policy established in 2017, the Mexican financial framework began to describe an environment of greater certainty for private investment in the distributed solar PV generation sector through the implementation of long-term financing models, fostering a paradigm shift in the focus of photovoltaic facilities in the country to open up large-scale installed capacity for generation proposes(AMB,2017; CRE,2017, DOF,2014).

The following figure describes the evolution of distributed installed capacity based on renewable energies during the period from 2007-2016 in Mexico:

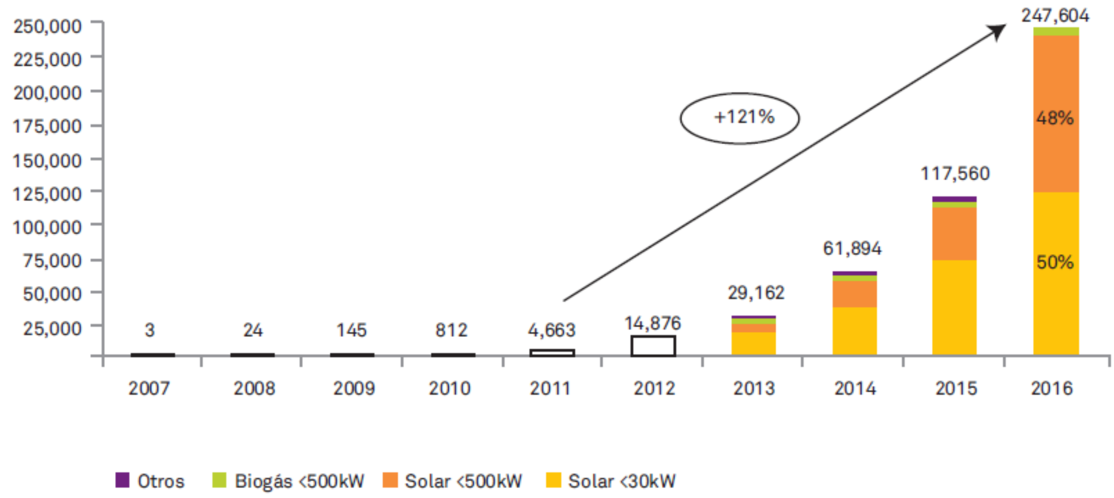

Figure 14 Evolution of renewable energies installed capacity 2007-2016 (kW) (Source: ABM,2017)

Currently in Mexico there are 23 registered generation plants distributed mainly in the north of the country, which are focused on self-consumption (11), Small production (3) and Generation (9), representing a total installed capacity of 214MW as described in the following picture:

Figure 15 Registered photovoltaic generation plants in Mexico (2018)
(Source: SENER, 2018)

3. Design Criteria's

3.1. Community Selection Criteria

The demographic distribution of the 3,5 million Mexican habitants that do not have access to any kind of electric power service can be described as follow (SENER,2015):

Number of inhabitants in the community	Number of communities	Representative percentage of total communities
0-19	3054	49.11
20-99	2950	47.44
100-149	113	1.82
150-199	47	0.76
200-249	20	0.32
250-299	10	0.16
300-349	4	0.06
350-400	3	0.05
401-449	3	0.05
450-500	6	0.10
501-549	1	0.02
550-600	4	0.06
600-1000	4	0.06
Total	***6219***	***100.00***

Table 6 Mexican communities without electricity connection sorted by population

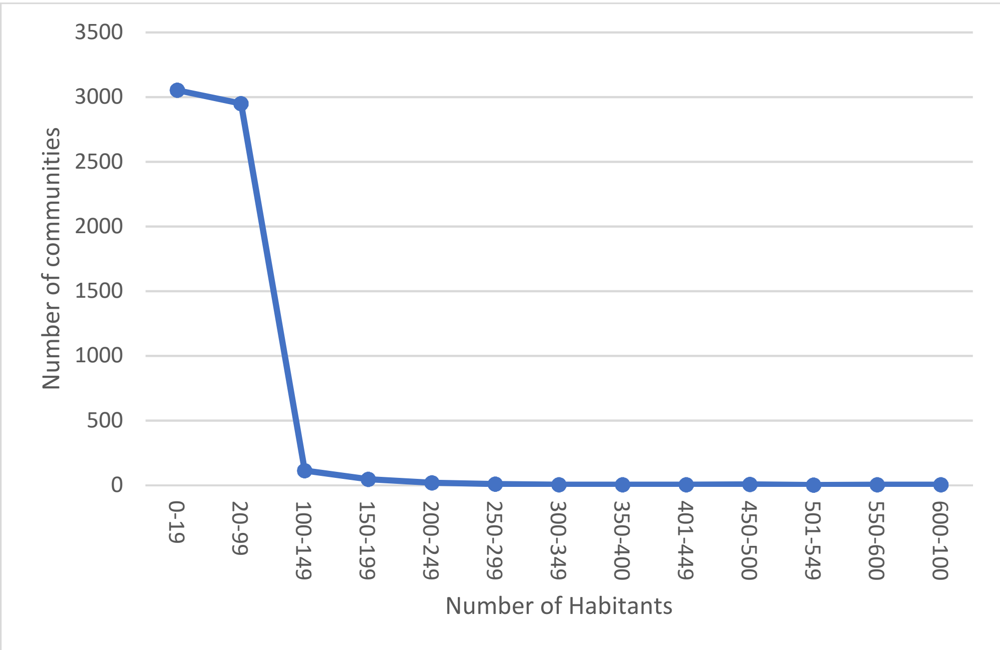

Figure 16 Communities without electricity access in Mexico given its number of habitants

As can be observed, of the 6000 communities without access to electric service distributed within the Mexican territory, approximately 96% of them have a population of less than 150 inhabitants. Being the main groups, populations owning less than 20 inhabitants (49.11%) and populations between 20 and 100 inhabitants (47.44%). from there, the communities of 100 to 500 inhabitants represent a lower incidence (3.32%) and populations with more than 300 inhabitants represent are very scarce event (0.14%). Therefore, its concluded that a technical implementation that could be proposed for the first two groups will allow to show relevant findings and design proposal that could be easily multiplied to solve the energetic issue in this communities.

For the scope of this investigation, the modeling of the system will be carried out using the community of San Pedro de Honor, located in the municipality of Acaponeta in the state of Nayarit, Mexico, as are reference.

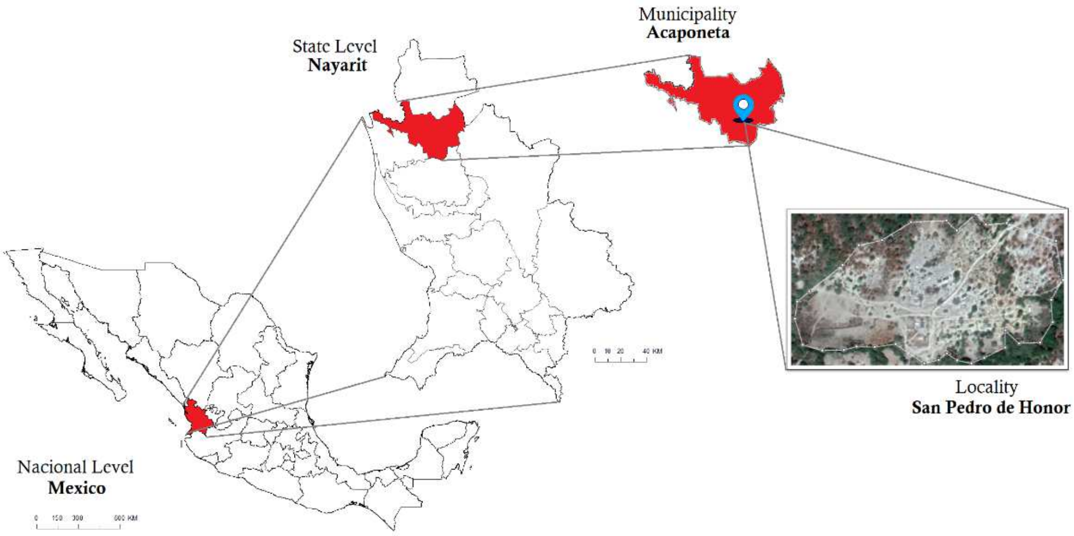

Figure 17Macro localization of San Pedro de Honor

This community was chosen because:

- It is considered to be a good representative isolated community due to its location of difficult access in the mountainous area of the country.
- Is located at a distance from the main network greater than that established in 2018-2032 Energy Development Plan.
- It owns a partially energized number of habitants by self-payed diesel generator systems which facilitates to obtain realistic reference costs, as lifestyles and consumption trends.
- The total population of the community is lightly over range of 100 habitants which is assumed to represent the maximum expected capital cost of the main two groups of communities.

The community of San Pedro de Honor owns a population of 117 inhabitants, of which around 50% of them decided to get self-energized through the acquisition's diesel generators. In order to do so, the diesel must be purchased and bring to the community through a distance of 53.7KM per dirt road area by the owners.

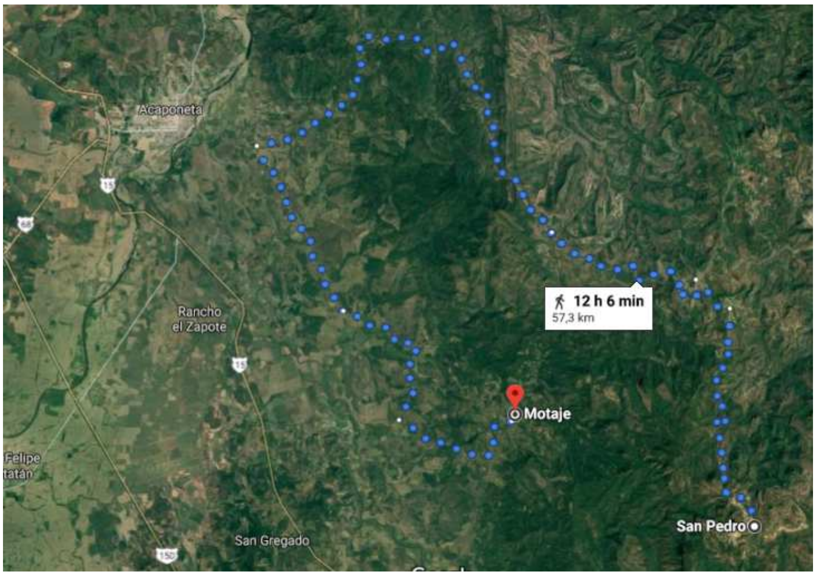

Figure 18 Distance that is necessary to travel to access the nearest community (Source: Made by the author using GoogleMaps. Google, 2019)

The community is geographically located at 924 meters above the sea level within the Sierra Madre Occidental mountain system in the coordinates [22.3656544, -105.1759338] making it difficult access. The closes point of the community to the main grid distribution lines is located at a distance greater than nine kilometers. As as can be observed in the following picture:

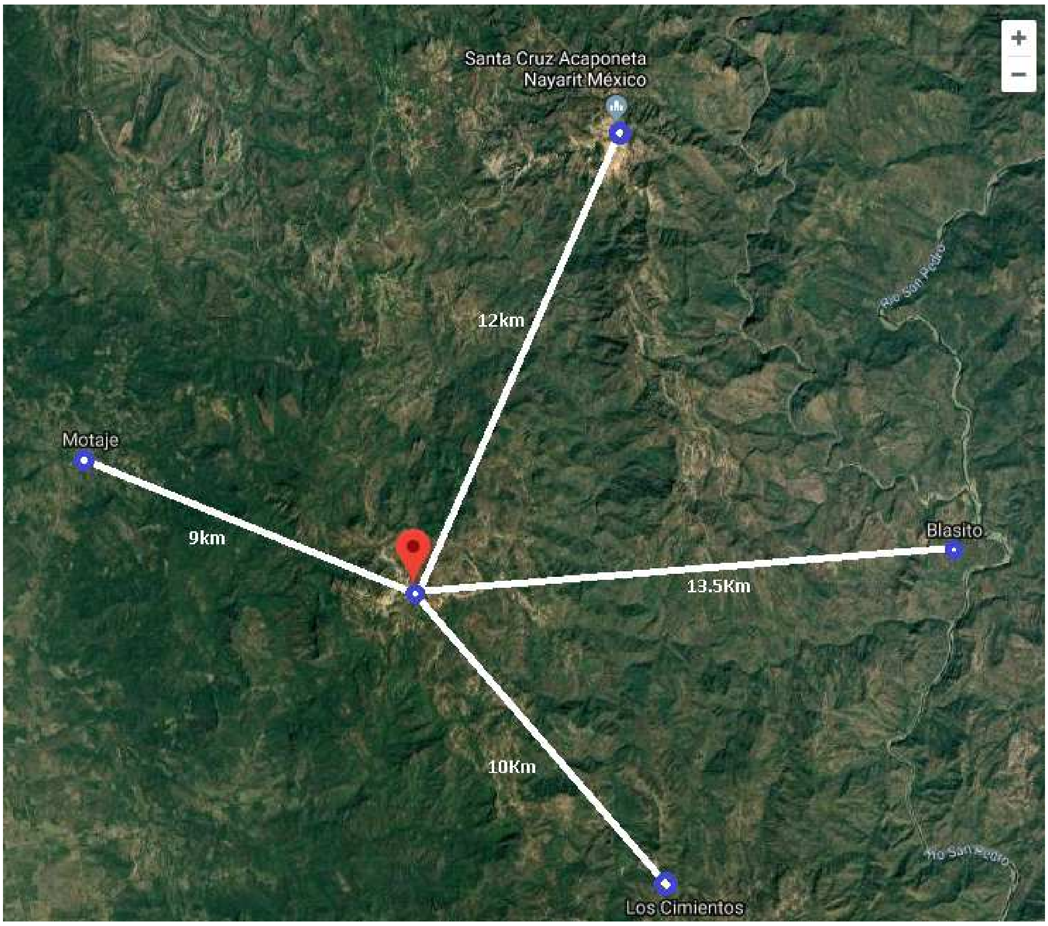

Figure 19 Distances of San Pedro de Honor from the closest main grid access point (Source: Made by the autor using GoogleMaps. Google, 2019)

It is important to remark that although the distances used in the map describe a straight distance as a reference, in the practice this is not possible due to geographical and environmental issues, so in a real implementation an even greater distances should be expected.

The following table shows the more representative demographic information of the population:

Characteristic	Description
Total population	117
Population composition	65 men / 52 women
Ratio women per men	0.8
Fertility rate	3.15
Indigenous population	5.98%
Number of households	25
Access to electricity	50% (Supported by diesel generators)
Access to piped water service	87.5%
Access to own sanitary infrastructure	8.33%
Owns a radio receiver	29.17%
Owns a televisión	20.83%
Owns a fridge	4.17%
Owns a washing machine	4.17%
Owns a car	12.5%
Owns a Mobile Phone	12.5%
Owns internet Access	0%
Economically active inhabitats	29.917%
Educational Institution	1 (Elementary School)

Table 7 Demographic information of San Pedro de Honor
(Source: Author made from statistical data provided by Pueblos America, 2018)

Regarding its Solar resource potential, the average irradiation value of San Pedro de Honor during the year is estimated at 5.91 $kWh/m^2/d$ with an average temperature of 22.4 °C, that varies from 19°C degrees to 25°C degrees in a normal day. It owns a relative humidity of 60.3% and a clearness index of 0,632 that represents low precipitations during the year, mainly in summer during the months of June, July and August (NASA,2017), describing a mostly sunny region with moderated warm temperatures that allow the proper operation of the Photovoltaic cells.

Regarding to the distribution and type of housing, it is possible to identify single-level homes, composed typically by up to 3 rooms, a kitchen, a bathroom and a common space area. The following figure describes the Households distributions in San Pedro de Honor, making distinctions between the main buildings used for living and some secondary structures that owns a rooftop.

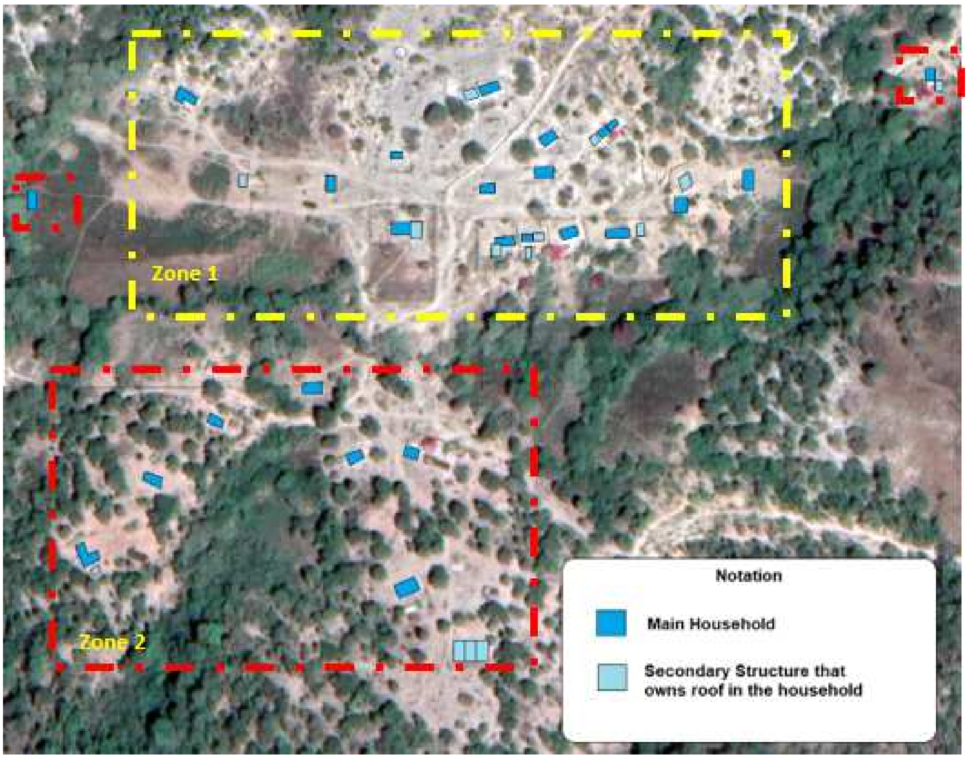

Figure 20 : San Pedro de Honor´s Households distribution
(Source: Elaborated by the author using GoogleMaps Satellite view)

As can observed, the distribution of households in the community describes a concentration in the center of the community (Zone 1) and followed by a lower concentration of housing in the southern zone (Zone 2). Finally, it is possible to identify two isolated houses far from the center. Metrics elaborated by satellite approximations suggest that the household mostly owns a build area dimension between 40m^2 and 50m^2 and mostly do share physical connection with other houses of the community as sounded by large back/front yard space.

3.2. Solar Irradiance profiles.

In order to determine the solar resource profiles in the region that can be used for the power generator stage of the photovoltaic systems the following databases were used:

- The National Aeronautics & Space Administration's (NASA's) global weather database: that includes the surface meteorology and solar energy data set observed for every month in the period 1983 to 2005 from years through the use of 200 space satellites.
- The data base provided by the NREL's Electric Systems Center and the National Solar Radiation Data Base (NSRDB): A data base that contains the data files for the typical meteorological year during the years of 1961 to 2016.

The databases were access by the using the official software oriented to design PV systems: PVSol (Version) and PVSyst (version 6.79). From these databases, it was proceeded to identify the values of solar irradiance and average peak solar hours per day during each month in the community. For reasons of space, the analysis per day is not included in the body of this document. However, representative figures of each month were generated and included as references and can be found in the Appendix III.

The following table illustrates the most representative values per month that are used in further calculations.

Month	Average Temperature (°C)	Relative humidity (%)	Daily solar radiation (horizontal) / Daily Peak Sun Hours (kWh/m2/d)	Clearness index
January	19	50.80%	4.43	0.618
February	19.8	47.30%	5.65	0.68
March	20.8	42.80%	6.62	0.698
April	23	42.50%	7.24	0.69
May	24.9	48.00%	7.4	0.673
June	24.7	69.50%	6.51	0.586
July	24.6	79.00%	6.52	0.591
August	24.5	79.00%	6.36	0.596
September	23.9	78.70%	5.77	0.585
October	23.6	71.70%	5.48	0.63
November	21.1	61.10%	4.85	0.65
December	18.9	53.60%	4.07	0.599
Annual	22.4	60.30%	5.91	0.632

Table 8 Monthly average weather and irradiation values of the selected site
(Source: Made by author from data collected from NASA and NRLE database in PvSyst version 6.79)

3.3.System Design Criteria

In order to define a robust system capable of satisfying the community energy demand, its mandatory to focus not just on the technical design, but also to understand and correctly predict the socioeconomic, environmental and cultural community drivers and its consumption tendencies. Lessons learned from various implemented off-grid electric systems demonstrates that ignoring those factors might result in incorrect sizing and bad performance of the system (Ruralelec ,2014).

Firstly, studies suggest that the energy consumption of an inhabited household is described by a range of consumption oriented to cover the daily needs of the house and that is shared by the inhabitants of the home. This value, tends to be maintained independently in family or individual household, and is associated with the construction characteristics of the house and not the number of its total residents. From this point, the energy consumption in the house will tend to increase given the habits of consumption for each resident (Gonzáles and Durán, 2015). This allow to conclude the existence of similar minimum consumption per household, which summarized will describe the minimum consumption expected in the community.

In this context, the energy consumption has been defined by some authors as a commodity with an elasticity close to zero, pointing that the economic income of the users will not produce significant changes in the household's electric consumption (Medina and Vicéns, 2011). However, some empirical studies performed in Mexican communities has shown that this is not necessarily true, and reveals that the energy consumption per capita increases as the age of the head of the household increase and it’s not likely to decrease during time, mostly as a result of factors like the increment of the economic income through their lifework period that allows to purchase more commodities trough the time, as well as the development of a family and the time in which the inhabitants are in the house after retirement (Sánchez, 2012a; Sánchez 2012b).

This suggesting that the energy consumption and the appliances of a Mexican household have a direct relationship with the socioeconomic level of the users and imply that when the economic income of a given user increases its energy consumption demand will also increase, as a result of the acquisition of new appliances and comfort products (Maqueda and Sánchez, 2011), showing that far from what can be initially considered, the consumption increase in the household seems to not be directly related to the number of habitants. Given that such studies, regarding energy consumption have not been able to correlate population growth and energy consumption in an evident way, and rather support the theory that there exists a closer relationship between rates of economic growth and/or higher incomes and the growth of energy demand (Darmstadter, 2004).

In Mexico, the economic income is measured in minimum wages, that is the minimum amount of remuneration that an employer is obliged to pay to its employees for their work during a given period and cannot be reduced either by virtue of a collective agreement or an individual agreement. Currently, the minimum wage is set at 102.68 Mexican pesos per day or 5.38 USD (CONASAMI, 2018). Empirical studies focused on energy consumption behavior and its correlation with the economic income per household in Mexico in terms of its minimum wages seem to support the theory that, as the income of a given household increase, so does its consumption (Sánchez, 2012a). This behavior is described in the following figure, that shows the consumption per household in a given quarter of the year against the income in the household given in minimum wages:

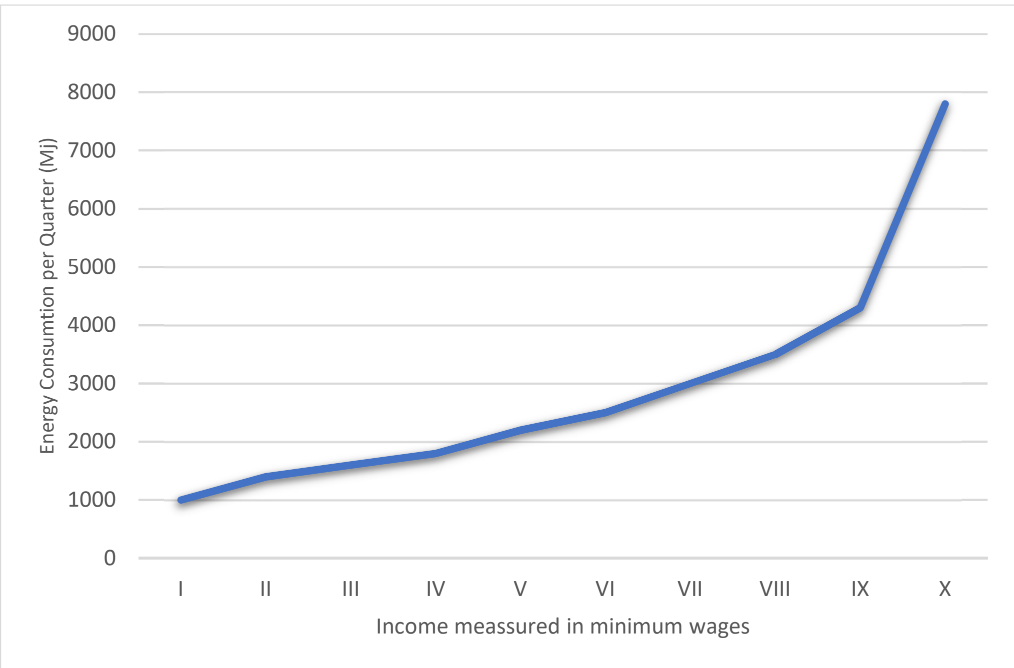

Figure 21Energy Consumption Per capita per household according to their Income (Source: Own figure based on Sánchez, 2012a)

As can be observed, the figure describes tree different behaviors depending on the income of the household. First, in the range composed from one to four minimum wages, it is possible to identify consumption values that increase slowly under values of 2000MJ, then a greater disparity is observed with a with a more accelerated slope growth from values from 2000MJ to 4000MJ, finally the consumption slope drastically changes to show a more aggressive values for houses with an income higher than the eight minimum wages.

The reasons for this behavior seem to not be conclusive yet, and are probably related to factors like the climate, lifestyles, cultural patterns of the region, consumption patterns, area of residence, age structure and composition of the household (O'Neill and Chen 2002, Pachauri, 2004), however, it is a behavior that must be taken into consideration to implement an isolated system that could satisfy the energy demand in the community for a long time.

An example of this phenomenon is the energy consumption of cooling devices in Mexico. According to INEGI statistical data, more than 50% of the low-income population does not own cooling devices, such as fans or air conditioning, while population groups with more than five and up to ten minimum wages spend a significant portion of their electricity demand for cooling (INEGI, 2017). Interesting findings also shown that households that earn more than then minimum wages owns heating appliances, even when for most of the population do not considered it as a real necessity (Gonzáles and Durán, 2015). This allow to show that some appliances, like the cooling or heating devices, can represent the behavior of an elastic commodity, and might be acquired by the habitants of a house in the community if their economic income allows it, generating drastic changes in their energy consumption habits. Hence, the private household energy consumption must be considered a dynamic factor with changing consumption values over time based on available factor income (Ndeye et all, 2007).

The following table summarize the more representative issues identified in the lesson learned minutes of different Off-Grid systems implemented around the world. It describes the type of off-grid system, its design criteria and the more relevant problems that were identified during the off-grid system operation.

Places	Type Of System	Designed Approach	Real Profile Found After Implementation
Rio Negro, Argentina	Off-Grid Village	It was designed to run during two or three punctual times at day a basic load composed of two lights (4h) and a small radio (2h)	Even when 66% of the population operated under the designed load profile. It was possible to identify systems where the consumption level was never suspended (Radio was used during the whole day) It was also found that some of the habitants that could afford it even added new appliances like small televisions and VCRs.
Puerto Plata, Dominican Republic	Medium SHS Profile	It was designed to run a television (3-4h), a light system (4h) and a radio (the day)	It was found that habitants used television from 8 to 10 hours per day
Lime Village, Alaska, United States	Off Grid Village	It was designed as a Pilot program to proposed to satisfy the electric consumption a small community till 100 people. The system was implemented to in a population of 65 people.	The original system was insufficient and was irreversibly damaged due overconsumption. Complete substitution of battery banks was required and an upgrade of the numbers of the Photovoltaic panels was also needed.

Alaminos, Philippines	Off Grid Village	Load Profile was designed for 60 households with and estimated consumption of 2000 Wh/day per home. The proposed load profile was composed by a light system, a radio tape recorder, a television and a VCR. No autonomy days were considered during the design and it was suggested to the users to suspend Television usage during the rain.	Habitants experienced periodic load disconnections during normal operations. It was found that users do not suspended the use of television during the rain and the battery bank was damaged in less than 2 years. It was found also that Television consumption was increased on weekends and the radio was used for the majority of the day.
Hyderabad, India	Off Grid Village	Designed to satisfy 60 households and 300 people with a consumption of 2000 Wh/day per home.	The real consumption profile was duplicated from the original estimations. As a solution the habitants gathered to watch television in common areas in order to avoid electric power disconnections.
San Juanico, Baja California, México	Off Grid Village	The load profile was designed to satisfy 3 schools, a hospital, 2 restaurants and 400 residents distributed in 30 households. The load was composed of a television (3-4h), a light (4) system and a radio. To avoid parasite consumptions, the power provided to the appliances were controlled by implementing On/off switches (There was no standby Consumption appliances, and the	Result shows that even when the school and the hospital met the designed consumption profile. The consumption profile in the house holds reflected profiles bigger than expected as a result of leisure activities. It was also found that the load described three periodic peaks during the day. A morning peak: where lights and radio are used while preparing breakfast. An afternoon peak: where the load reflected lunch preparation appliances, the

		consumption of each load would be either zero or its nominal consumption)	radio usage and in some cases the television as well. An evening peak: where the load was characterized by meal preparation appliances, leisure activities after sunset that included the use of all lights, television and the radio turned on. It found that television was used 8 to 10 hours and sometimes together sometimes with a VCR system. Some of the villagers purchased satellite dishes reinforcing the importance of television viewing.

Table 9 Lesson learned minutes of implemented Off-Grid systems around the world
(Source: Elaborated by author from Minutes provided at Ruralelec, 2014 and Ndeye et all, 2007)

The information gathered allows to identify that the main problematics were generated by the

- Load profiles were not realistic and were designed considering ideal static scenarios,
- Some design assumed a zero consumption that is very unlikely to happen,
- Design do not considered protection against incorrect usage,
- It was assumed that habitats will not increase it load profile over time,
- It was assumed that users will follow strictly the design consumption criteria.

In fact, most of the documented designs were not designed considering a static load, that achieved to satisfy basic consumption patterns, but failed as result of not considering a future electricity demand, the increase of consumption due realistic users patters as well as not considering development of income. Perhaps the most valuable lesson learn that could be get from these minutes is that the real consumption in an off-grid system tend to be bigger than the original load profile estimation, and has a constant tendency to increase (Ndeye et al, 2007) reason why the design of the system should consider the possibility of expansion according to the household consumption.

Similarly, it is important to do not underestimate the usage of the loads oriented to leisure during the daily usage, that according to the findings tend to get a priority for their residents over other appliances and lead to a higher daily consumption. This is supported by information in the minutes that state that some families within these implemented projects decided to suspend the usage of the lighting system in order to extend the usage of appliances like the television (Ruralelec, 2014). An even more drastic founding suggested that some of the user would like to run television during the whole day if possible (Ndeye et al, 2007). This is an undoubtedly relevant finding in the Mexican context where it load profiles and consumption surveys conducted by INEGI in households supported the notion that the highest electricity consumer (not necessary the highest load) is generally the television (used from 5 to 8 hours per day), followed by washing machine, radio and refrigerator bearing in mind that the cooking equipment predominantly is operated by LPG (INEGI,2017).

Lastly, it is necessary to consider the current population trends in the communities of Mexico as well as its composition structure. The standard consumption profile reveals that couples without children as well as non-family households, which are increasing in numbers, are associated with highest per capita consumption based on their higher free income while couples with children have the lowest energy consumption per capita (Sánchez, 2010).

Based on the foregoing, the following design criteria have been decided to develop the designs of the isolated electrical system of the community:

- A similar daily consumption must be supplied for all households in the population, supported by theories that households with a similar economic income generate a similar daily consumption.
- A standard Mexican load profile should be proposed as a minimum daily consumption and not a restrictive consumption profile. Therefore, it is recommended that the load profile reflect the daily consumption habits in terms of the use of devices and ranges of operation of the Mexican population mean.
- The design of the network should consider the possibility of extending its installed capacity, given that consumption per household can increase based on economic income.
- The inclusion of smart devices should be included in the network in order to allow the daily monitoring of the load, protection of the devices, identification of excessive consumption load, well as the consumption identification of necessary upgrades in the system.

And in accordance with the guidelines established in the "2018-2032 Energy Development Plan"

- The proposed system should generate as much as possible (economically and technically) the greatest amount of energy through the use of photovoltaic technologies and minimize dependence on fossil fuel.

3.4.Load Profile Design Criteria

Predicting the profile of an off-grid system is not an easy task as in most cases, no previous relevant consumption information is existing (Ndeye et all, 2007). Therefore, researchers have followed develop diverse approaches to formulate possible loads that could be used in for the design of the PV systems.

The most recurrent approaches used to formulate a Load Profile that were identified during the literature review can be summarized as:

1) Arbitrary Generation (The load profile was suggested without providing a specific formulation) (Bala and Siddique, 2009; Nandi et al, 2010).
2) Use of a Similar Context load profile (The selected load profile was selected from a similar community, economic income household, similar region, ect) (Nfah and Ngundam, 2009, Nfah and Ngundam,2012; Phrakonkham et al., 2012; Semaouiet al., 2013).
3) Electric Appliance and consumption habits assumption (The load profile is generated from a selection of electric appliances and its calculated by using proposed use periods) (Al-Karaghouliand Kazmerski, 2010;Bekele and Tadesse, 2012)
4) Stochastic methods (The load profile is generated by by probability distribution functions) (Colombo et al, 2016)

Given that there are no consumption profiles that can be used as a reference, for the present investigation it was decided to carry out a mixture of third and fourth approaches. By selecting devices that can be found in the average Mexican household and suggesting a consumption time reflecting the time distributions reported by the average population.

Firstly, regarding the appliance selection. It was considered that the best alternative identified to parameterize the load characteristics in a faithful way with the Mexican sociodemographic consumption was the usage of the information provided by the National Household Income-Expenditure Survey prepared by the INEGI which includes data on the expenditure that households make on energy including electricity and fuels, together with an extensive database of sociodemographic information. In addition, other information identified in research was used as well (INEGI, 2016; INEGI, 2017; INEGI, 2018; González and Durán, 2012).

The following table describes the main electrical appliances that are commonly counted in households in Mexico according to the data obtained by the surveys conducted at the national level (INEGI, 2016; INEGI, 2017; INEGI, 2018). These data were used to define which and how many devices are more likely to be acquired by the houses of the community and thus achieve the parametrization of the load profile used for the community as follows:

Number of appliances per households in Mexico				
Appliances	**0**	**1**	**2**	**3**
Televisions	7,66	**54,01**	**25,1**	**9,25**
Stoves	11,88	**87,3**	0,78	0
Blenders	15,69	**81,7**	2,43	0,16
Refrigerators	18,17	**80,46**	1,29	0,3
Irons	20,22	**76,32**	3,03	0,29
Washing machines	29,1	**69,67**	1,21	0,02
DVDs	51,24	**42,25**	5,02	1,07
Fans	**53,01**	27,48	11,96	4,93
Stereos at home	**54,44**	**43,19**	2,06	0,25
Microwave	**56,77**	**42,69**	0,49	0,01
Computers	**69,89**	24,48	3,42	1,58

Radio Recorders	**76,6**	22,49	0,71	0,18
Radios	**82,14**	16,66	0,17	0,04
Toaster	**85,45**	14,43	0,11	0,01
Printers	**85,8**	13,29	0,8	0,1
Video game Console	**89,39**	9,02	1,11	0,45
VCRs	**91,17**	8,4	0,3	0,13
Vacuum cleaners	**92,33**	7,55	0,17	0,03

Table 10 Number of appliances per households in Mexico
(Source: Generated from INEGI,2016; INEGI,2017; INEGI,2018; González and Durán, 2012)

From this information it's possible to note that more than 80% of Mexican households owns at least one refrigerator in their home being one of the main purposes of energy use in Mexican households, however is not expected to owns more than one. Regarding entertainment appliances, it was found that around the 91% of households have at least one television, and owning two or more of these devices is an expected practice as the economic income increase. In contrast to what was observed in the load profiles of the systems used for reference, there is a tendency on the reduction of musical players like radio, radiocasted recorders and stereo appliances showing a behavioral change in the last decades. Regarding computers, even there exist a tendency on purchasing this type of appliance, its identified that less than 28% of the total household owns one.

Regarding the availability of other household appliances for general use, it is possible to observe that almost all homes have at least one blender, washing machine or iron, but devices such as microwave, toaster, printers, video game consoles, VCRs and vacuum cleaners are items not likely to be found in all homes, not been clear if this is a result of cultural practices or purchasing power. In terms of food cooking, 87.30% of households have at least one stove, and is not expected to own more than one of these appliances. From these stoves more than 99.4% use LP gas for this practice, less than 0.06% use electric stoves. (INEGI 2018; Díaz and Mansera 2002; Sheinbaum et al, 1996).

In relation to the ambient temperature appliances, it was identified that about 96% of households do not own cooling or heating appliances, 87.63% does not have air conditioning, and 53.01% of households do not have fans in their home. From, those household owning a fan, data suggest that 60% of it owns just one, 30% two and 10% rest 3 or more, distributed between mounted fans and portable fans (INEGI,2018).

Finally, regarding to the lighting service, it is possible to identify a central trend in the number of spotlights per household, as can be seen in the following figure:

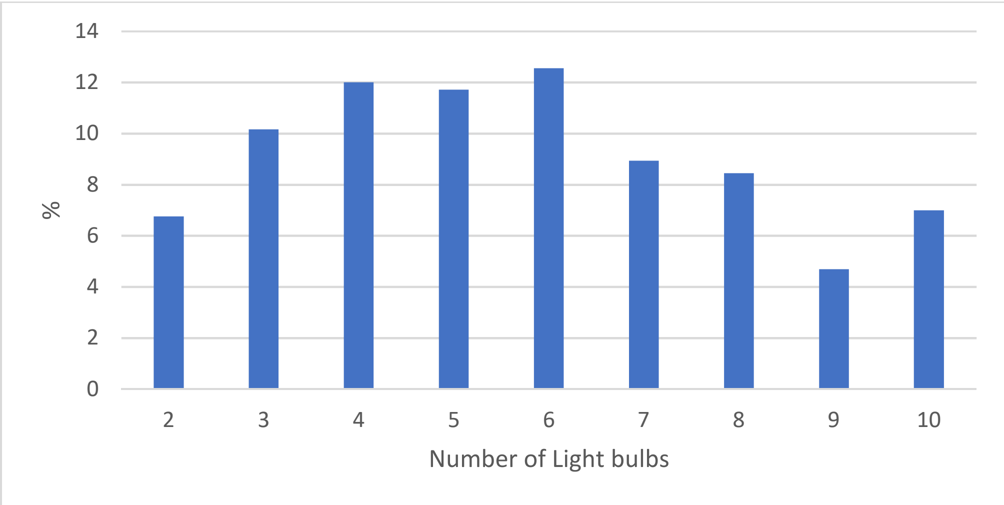

Figure 22Numbers of Lightbulbs per households In Mexico
(Source: INEGI, 2018)

However, it's possible to determine that two to ten illumination lamps per household are used more frequently, representing indoor and outdoor ones. Been two or three bulls the representative value in small residences like single apartments, and four to eight the average number in a normal residential house. The main technology used for this propose is fluorescent bulbs representing a 72% of the total population, then traditional incandescent bulbs with a 16% and finally LED technologies with 12% (INEGI, 2018). It is observed that 12.55% of households use six bulbs, close to 5% use nine bulbs; Households using more than ten are 3% and lower. Supporting the theory exposed in last section, and showing that the number of bulbs per household is affected by housing characteristics and the household income, rather than the number of inhabitants per household (Sánches, 2012; Cruz and Durán, 2015).

The following figure illustrates the common location and hours use of light bulbs in the Mexican households:

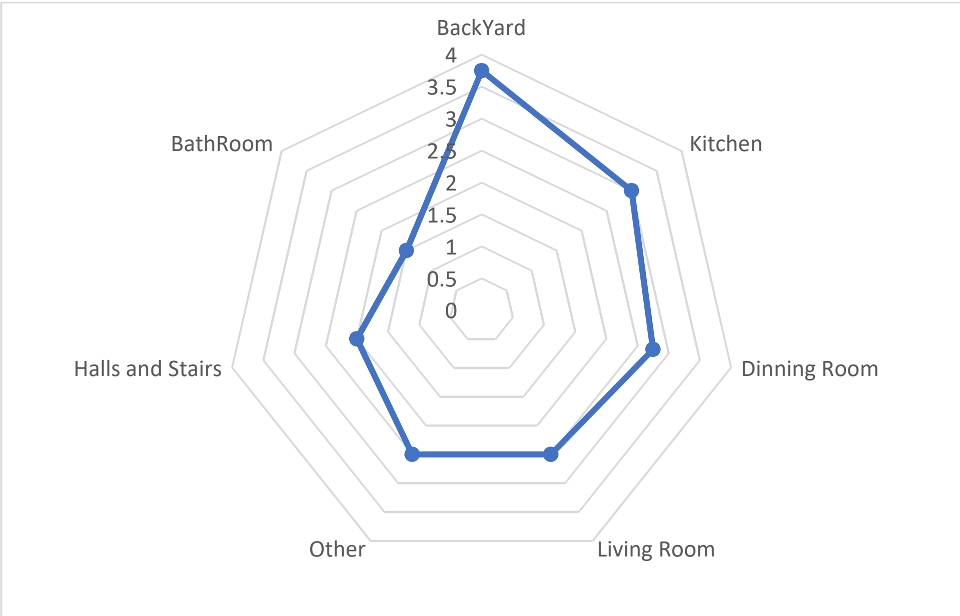

Figure 23 Usage time and place of electric bulbs in the Mexican Households (Source: INEGI, 2018)

Regarding the parameterization of the consumption of the refrigerator appliances, it was decided to use the daily average consumption value established by the manufacturer as reference, given that being a device that works by cycles, an analysis of its consumption profile in time lapses does not represent a reliable value that can be used as a reference. It is important to note that this value changes radically depending on the technology and size, so it was decided to use the distribution profile shown below for the selection of devices of the types of refrigerators used:

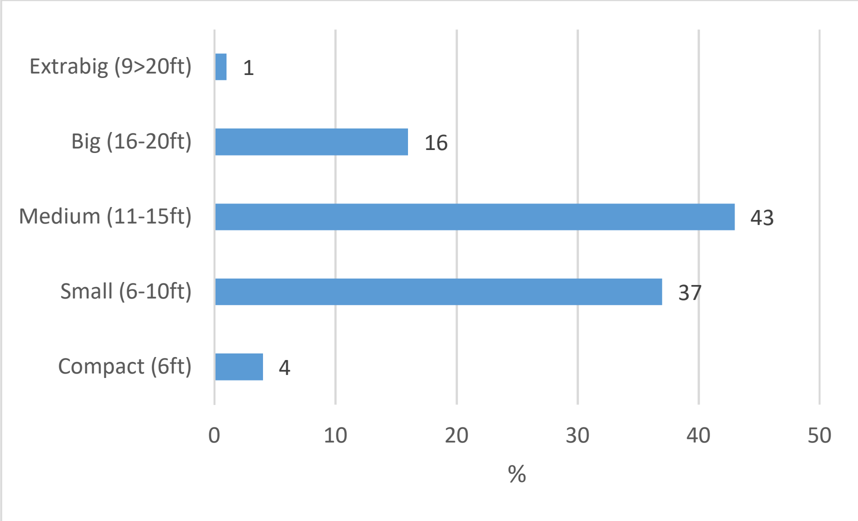

Figure 24Percentage distribution of refrigerator size per Household (Source: INEGI, 2018)

Pointing that small and medium size refrigerators are likely to be found in the standard Mexican Household.

Finally, it is important to note that the database indicates the existence of electric efficiency appliances in the average Mexican household, given the current regulations in Mexico. Based on these figures it is possible to identify that 72% of the refrigerators, 65% of the washing machines and 56% of the air conditioners used in the households are characterized as high energy efficiency devices (INEGI , 2018), reason why it was decided to include this kind of devices in the characterization data base used for the simulations.

Another demographic information used to perform the Load Profile calculation that was not included in this section due space proposes is included for conveniences in the Appendix I.

3.5.Main Grid Extension Criteria

As described in the last section, the selected community is located inside the mountains, having the closest main grid distribution line in a distance over 9 Km. As a result, the extension of the main grid was designing considering the use of several transformers that allows to reduce the losses through long distances. Similarly, the use of robust concrete structures that can handle the mountainous environment, humidity and vegetation was selected, as well as special cables that could prevent the easy corrosion or get damaged by the existing trees.

The technical design of the Main grid extension is not covered technically, given that its implementation was already discarded by the government authorities due its distance to the main grids access point over 5Km (SENER, 2018) However, its empiric design is included in order to perform economic comparison of the proposed mini-grid systems.

The proposed investment and system design were generated by using the costing and dimensioning tools provided by the CFE company on its website, that are used in order to request permits for the extension of the current main grid (CFE, 2019). As a result, a given static system selected from the CFE database was used as reference for the current investigation which is defined as "1C-3F-3H 13 KV 1/0 AWG AAC-PC RURAL" that is the technical mane for an aerial line distribution system composed by a three-phase (3 cables / 3 phases) and is made of concrete poles designed for rural areas, operating voltage of 13V and uses aluminum cable size 1/0 known as AAC.

This kind of system is able to provide a voltage of up to 220V to the designed residential area and its costs without taxes are tabulated below:

Concept	Cost per km (MXN)	Total cost per concept (MNX)
Cost for line connection	-	2053.42
Initial Deposit	-	35,681
Permanent installation materials and equipment	160,939	1,448,451
Civil and electro-mechanical work	101,241	911,169
Project design	2,627	23,243
Supervision	5,325	47,925
	Total Cost (9km)	2,466,469

Table 11 Main grid extension costs not including taxes
(Source: Elaborated by the author from cost provided by CFE,2019)

As it is possible to observe the cost of the system is calculated per kilometer. Since the nearest access point of the main network to the community of San Pedro de Honor are within an approximate distance of 9Km this value was decided to be used in order to parameterize the costs. However, it is necessary to point out that given the mountainous geographical conditions a real implementation of this project will represent further distance.

Hence, the necessary investment for the main grid connection would sum up to a minimum of 2,466,469 Mexican Pesos or an equivalent of 128.685,55 USD. Given the geographical area and temperatures in the site the applicable tariff is likely to be type 1 as shown in table (A short description of Mexican tariff is included in Appendix 4). These values will be the used ones for the levelized cost of energy in the further scenario's analysis. Hence, the designated PV mini-grid system could be determined as economically attractive if the LCoE is below the reference values of the grid connection.

Concept	Description	Cost
Basic consumption	For each of the first 75 (seventy-five) kilowatts-hours.	0.814
Intermediate consumption	For each of the following 65 (sixty-five) kilowatt-hours.	0.984
Excess consumption	For each additional kilowatt-hour to the previous ones.	2.879

Table 12 CFE energy cost for electric Tariff 1
(Source: Elaborated by the author from cost provided by CFE,2019)

3.6.Optimization Criteria

Given the design guidelines established by the “2018-2032 Energy Development Plan "established by SENER. The design scenarios considered for the development of the network are reduced to the use of photovoltaic energies, which given their inability to satisfy electrical energy during the night need to use a secondary generation stage, such as a bank of batteries or diesel generators. Other technologies of a renewable nature are not considered given to the scope of this proposal.

Therefore, the suggested scenarios can be described as

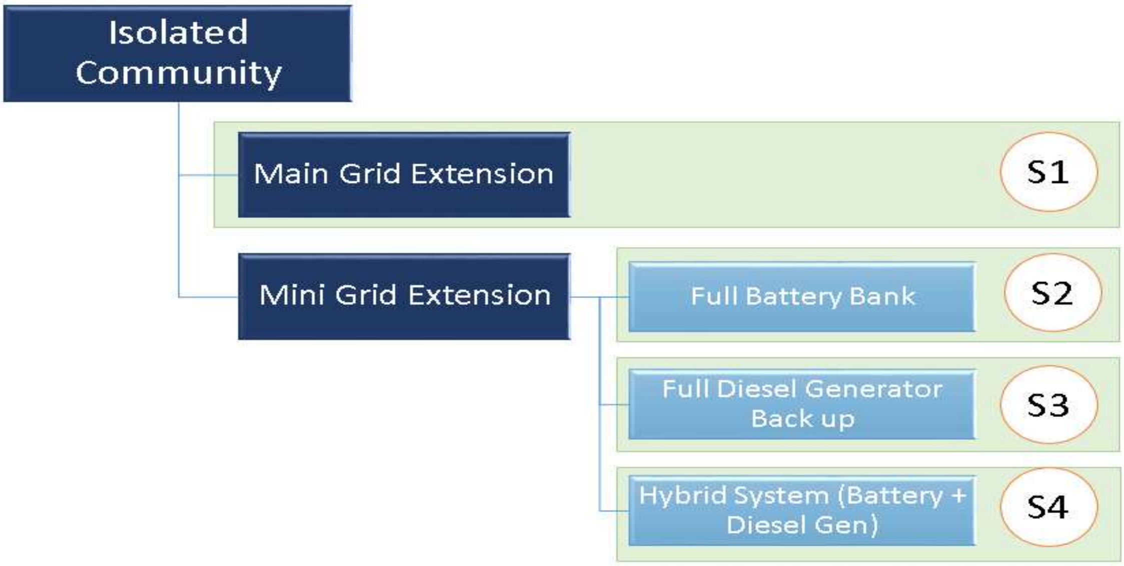

Figure 25Scenarios proposed for the current investigation

ID	Scenario	Description
S1	Main Grid Extension	Provide electrification to the isolated rural community by extending the Main Grid
S2	Full Photovoltaic System with 100% Battery Back Up	Provide electrification to the isolated rural community by using a Full Photovoltaic Mini Grid Systems and a Battery Bank
S3	Full Photovoltaic System with Diesel Generator Back Up	Provide electrification to the isolated rural community by using a Full Photovoltaic Mini Grid Systems and a Diesel Generator for back up energy.
S4	Full Photovoltaic System with Hybrid Back Up	Provide electrification to the isolated rural community by using a Full Photovoltaic Mini Grid Systems, a Battery Bank and a Diesel Generatorfor back up energy.

Table 13Proposed Scenarios.

For each scenario the following constrains was defined to evaluate the implementation of the Photovoltaic Mini grid solution:

ID	Constrain Profile	Criteria and Performance implications
Q1	Full Energy Security	The energy should be secured at all the time (No Black outs allowed), ignoring Economic or Social implications.
Q2	Economic Optimum	A middle point between cost and energy security if desired (blackouts are tolerated).
Q3	Load Restrictive	There exist a restriction of consumption profiles or appliances allowed in homes. This might affect life style in the community.
Q4	Upgradable	A homogenous load is provided for all users. But the system might be upgradable as needed per household but owner must absorb the cost.

Table 14Proposed Constrains used for the Scenario Simulation

3.7.Economic Evaluation Criteria

The economic comparison between the proposed systems are made by using the Levelized Cost of Energy (LCoE), given it allows to perform comparison of all costs involved in each given design and compare in terms of it cost of production.

For the purposes of this investigation the LCoE is be calculated by using the NPV method, that allows to discount the expenses required for the investment, the payment flows of revenues and all the expenditures coming forward during the whole power plant lifetime by referencing a given date. In this way, the LCoE can be described as the follows (Konstantin, 2013):

$$\mathrm{LCoE} = \frac{\mathrm{I_0} + \sum_{t=1}^{n} \frac{\mathrm{A_t}}{(1+\mathrm{i})^{t}}}{\sum_{t=1}^{n} \frac{\mathrm{M_{t,el}}}{(1+\mathrm{i})^{t}}}$$

Equation 1 Levelized Cost of Energy General Formula

Where LCoE represents the levelized cost of electricity given in MXN/kWh, $\mathrm{I_0}$ represents the investment expenditure given in Mexican peso, $\mathrm{A_t}$ represents the annual total cost per year in a given t, $\mathrm{M_{t,el}}$ represents the produced amount of electricity in kWh per year, i represents the real interest rate ratio and finally n represents the economic lifetime in years.

In a more general context, the LCoE can be also described as:

$$\mathrm{LCoE} = \mathrm{I} + \left(\sum_{t=1}^{n} Income - \sum_{t=1}^{n} Costs\right)$$

Equation 2 LCoE general Formula

Where I represents the investment cost of a given scenario (CAPEX), $Income$ represents the incomes generated by the generation plant measured during a given time (Represented by the amount of generated electricity), and $Costs$ represents the operational cost (OPEX such insurances, labor cost and maintenance) during a given time.

All the cost used for the economic calculations are obtained from the cost in the Mexican market, and were imported in the simulation software to perform the optimizations.

4. Design of the Photovoltaic Smart Mini Grid System

4.1. Load Profile Formulation

Based on the previous findings, an appliance database was created from the selection of common devices and brands available in the Mexican market. Load profiles used in the present investigation and a consumption time was generated dynamically during the period based on the probability functions established for each of the devices. To do so, first a selection of the components that are statistically found in the Mexican households was created in an excel file and were separated in 3 main categories:

- Basic necessities appliances: Are those considered a essential to be included in each household or are statistical included in most of the Mexican Households according to the statistical analysis of the Mexican appliances, like a lighting system, a refrigerator, television or clothes washing machine.
- Standard necessities appliances: Are those that can be found in a standard Mexican household (earning from 3 to 6 minimum wages), but might vary according to personal preferences like a second television, a fan, a computer, an electric stove or a microwave, and are randomly generated according to the statistical information explained in Appendix IV.
- Luxury necessity appliances: Are those devices that according to the national surveys, are held by high income users (earning from 6 to more minimum wages), like an air conditioner system or an electric heater.

Then in order to simulate the different income profiles 3 main different Load profile criteria was defined:

- Basic Load Profile (BLP): Is a load profile composed just by the basic necessities appliances and reflect the current status quo in the population at the moment of setting the mini grid without considering a change in the appliances due the income.
- Standard Load Profile (SLP): Is a load profile that include the basic necessities appliances, in addition to random ones added from the standard list. It aims to represent the changes from BLP to the SLP due a possible an economic income increase in the household.
- High Income Load Profile (HLP): It's a load profile that include the SLP appliances plus random ones selected from the luxury category. It emulates high income in the household

Each load profile was generated by using Excel Macros functions that allowed the random selection of the profiles and devices. Then its load consumption and use time was generated according to the statistical usage time profiles reported in the national surveys. Finally, the total consumption of the community was generated by adding the 25 generated load profiles during a desire time.

For the purpose of presenting the load profile data in a format that could be used by a photovoltaic systems design software, the designed Excel Macros were generated the load profile output in a time measurement interval that was formulated in a discrete manner representing each hour of the day in 15 minute periods, as a that each load profile per household would allow to generating a set of 96 values per day. In such a way that the load profile that represents the daily consumption per household would be determined by the following equation:

$$\mathrm{TL}(\mathrm{t},\mathrm{n})_{\mathrm{day}} = \sum_{\mathrm{t}=1}^{\mathrm{T}=96} \sum_{\mathrm{n}=1}^{\mathrm{n}=\mathrm{N}} \mathrm{L}(\mathrm{n}) * \mathrm{P}(\mathrm{n},\mathrm{t})$$

Equation 3. Formula of total daily consumption per Household

Where $\mathrm{TL}(\mathrm{t},\mathrm{n})_{\mathrm{day}}$ represents the total load per day generated by all appliances in an discrete time composed from a measured period from t to T, n represents a given item in the designed appliance list composed by N components of a given generated Load Profile, $\mathrm{L}(\mathrm{n})$ represents the hour consumption of the appliance n in Wh divided by four and $\mathrm{P}(\mathrm{n},\mathrm{t})$ represents a probability function of the device n to be operating in a given value of time t.

Then the total consumption per day of the community per time can be determined as the following formula:

$$\mathrm{TL}(\mathrm{t},\mathrm{n},\mathrm{H})_{\mathrm{day}} = \sum_{\mathrm{H}=1}^{\mathrm{H}=25} \sum_{\mathrm{t}=1}^{\mathrm{T}=96} \sum_{\mathrm{n}=1}^{\mathrm{n}=\mathrm{N}} \mathrm{L}(\mathrm{n}) * \mathrm{P}(\mathrm{n},\mathrm{t})$$

Equation 4 Total consumption per day of the community

Where $\mathrm{TL}(\mathrm{t},\mathrm{n},\mathrm{H})_{\mathrm{day}}$ represents the total load per day generated by all appliances in all households given in a discrete time composed from a measured period from t to T amd H represents the number of households in the community.

The following figures illustrate the common output of the load profile elaborated buy the excel Macros functions:

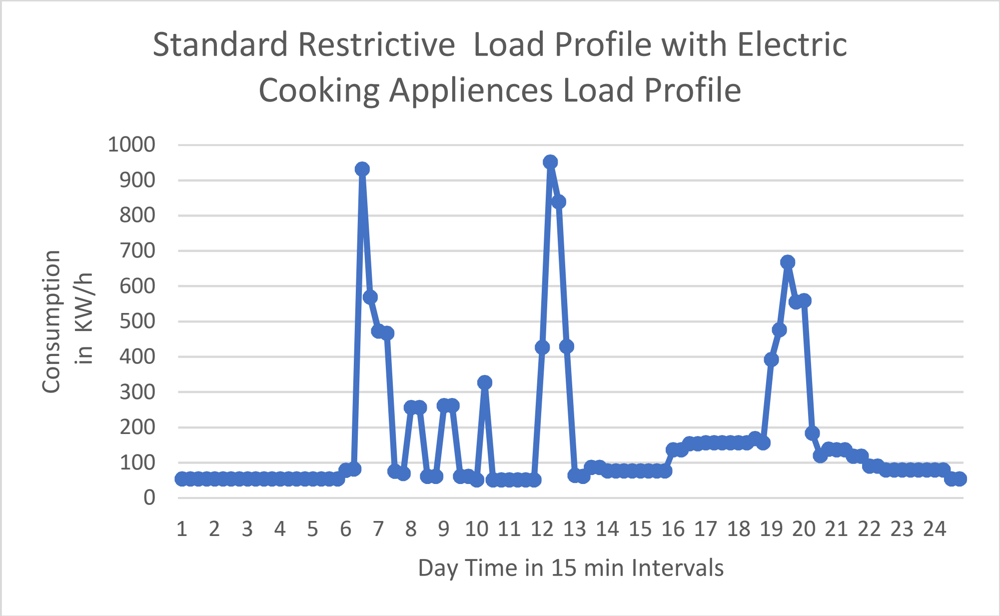

Figure 26 Standard Load Profile

Similarly, the generated list of appliances was generated as follow:

Appliance	Consumption Used For Calculation (Wh)	Work Hours per Day	Quantity	Total Energy Consumption Wh/day
Frontyard Lighting	23	4,5	1	103,5
Backyard Lighting	23	4,5	1	103,5
Kitchen Lighting	13	3	1	39
LivingRoom Lighting	13	3	3	117
DinningRoom Lighting	23	2,75	1	63,25
BathRoom Lighting	13	1,5	1	19,5
Fan (Portable)	50	9,5	2	950
Radio	40	4	1	160
30" LCD TV	60	6	1	360
DVB Digital receiver	25	24	1	600
Game Console/ DVD Player	180	3	1	540
Mobile phone charger	6	3,25	4	78
Tablet Computer	10	5,25	1	52,5
American-style Fridge Freezer	180	24	1	4320
Blender	450	0,75	1	337,5
Bread toaster	900	0,5	1	450
Coffee Machine	1000	0,25	1	250
Electric stove / Cooktop (Medium)	1500	3	1	4500
Microwave	1200	0,5	1	600
14-15" Laptop Computer	70	5	1	350
Inkjet Printer	30	0,25	1	7,5
Projector	270	1	1	270
Scanner	18	0,25	1	4,5
Curling Iron	35	0,25	1	8,75
Electric iron	1100	0,5	1	550
Clothes Washing machine	800	0,5	1	400
Water Pump	746	0,5	1	373
ADSL / Wifi router	10	9	1	90
				15697,5

Table 15 Standard Load Profile

4.2. Photovoltaic Mini Grid Stages.

As explained in the past chapters, the general structure of a Photovoltaic Mini grid system is composed of the following elements:

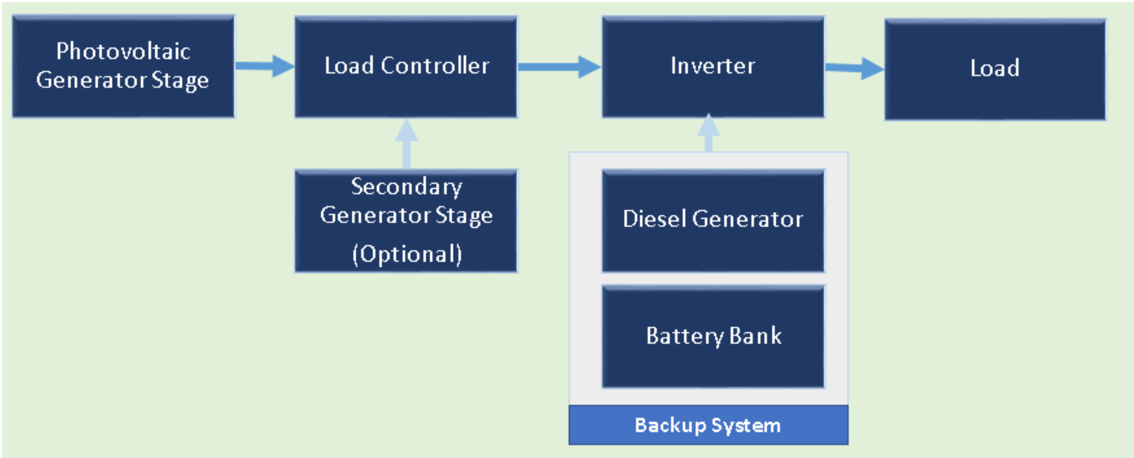

Figure 27 Photovoltaic Mini grid system Block Diagram

The load profiles generated last section are used as input in order to determine the sizing of the Photovoltaic mini grid network.

4.2.1. Sizing of the PV Generator Stage

The general relation of power that should be provided by the arrangement of solar panels per day to the community is defined as:

$$\text{Total Power}_{\text{PV}} \geq \frac{(\text{Total Load}_{\text{Wh}})}{\text{Peak Sun Hours}}$$

Equation 5 Minimum power relation that should be provided by a PV generator

Where "Total Power $_{\text{PV}}$" represents the total power consumption generated by the photovoltaic generator stage array, the"Total Load$_{\text{Wh}}$"indicate the total power generation day required by the community per day and the "Peak Sun Hours" represents the peak sun hours that are provided at the community. In order to ensure the energy satisfaction of the community throughout the year, the sizing of the PV generation stage should be made by using the irradiance values of the less favorable month. As a result, the minimum power that should be provided per day by the PV generator step in the community grid can be obtained by the following equation:

$$P_{G_{Min}} = \frac{(W_d)(G_{CEM})}{(G_{dM})(PR)}$$

Equation 6 Minimum power that should be provided per day by the PV stage

Where $P_{G_{Min}}$ indicates the minimum total power of the photovoltaic generator phase in Watts. W_d represent the total energy consumption load in the community per day in Wh, G_{CEM} represents the irradiance constant under Standard Test Conditions (STC), that is referred as the value of 1000 W/m^2 at 25C and 1.5 AM. G_{dM} represents the average irradiation value of th worst month given in Wh/m^2, finally the PR represents the performance ratio of the system. Even when the value of a PR ideally should be 1, in the case of the current design a value of 0.06 as is suggested for off-grid systems composed by a load control system, an inverter and battery bank (Kumar and Sudhakar, 2015). Then the number of Photovoltaic panels required to satisfy the minimum of the community will be given by:

$$N_{PV} = \frac{P_{G_{Min}}}{P_{Max}}$$

Equation 7 Number of required PV panels

Where N_{PV} indicates the total number of modules needed to provide the minimum consumption in the installation, $P_{G_{Min}}$ indicate the minimum power of the Photovoltaic generator phase in Watts and P_{Max} indicate the maximum power that can be provided by a given commercial photovoltaic panel technology available in the market in Watts. In order to not oversize the number of panels, the following relation is used to calculate a more precise fit from the number of panels in the database.

$$P_{G_{Min}} \leq P_G \leq 1.2\ P_{G_{Min}}$$

Equation 8 Sugested production range of PV pannels.

Once the number of panels needed to satisfy the daily consumption of the community is identified, it would be necessary to determine a back-up generator that could provide energy to the community grid in case that the photovoltaic generator stage cant provide enough power, as it might happen during partially cloudy seasons, presence of rain or unexpected peaks of consumption in the community.

4.2.2. Sizing of the battery bank stage

Under the criterion of reducing the use of diesel fuel to the lowest possible, it is suggested the implementation of a bank of batteries, whose size is determined by the equations presented in the current section. Firstly, in order for the battery bank to satisfy the community's energy consumption, the authors suggest its design considering the maximum current that is necessary to maintain in the system during the peak power consumption of the community (Nishant et al, 2016). In this way, the general equation to calculate the maximum current required in the network to define the battery bank will be determined by:

$$I_{Max} = \frac{W_d}{V_{Syst}}$$

Equation 9 Maximum current required to be provided by the battery bank.

Where I_{max} represents the maximum operating current that must be provided by the system, W_d represents the total power consumption required by the community per day in Wh and V_{Syst} indicates the nominal voltage used for operation in the system of a given 12V, 24V and 48V system. However, in practice, its mandatory to consider in addition to the nominal voltage of the system further technical specifications. Allowing to rewrite the maximum current required to be provided by the battery bank system as:

$$I_{Syst} = \frac{(A_d)(I_{Max})}{\delta} (L_f)$$

Equation 10Maximum current required to be provided by the battery bank.

Where I_{syst} represents the Maximum operating current that must be provided by the system, A_d represents the days of autonomy, in other words the days that the battery should provide energy to the system in case that there is no sunlight source, which according to the atmospheric performance in the data base is usually less 2 days. I_{Max} represents the maximum operating current that could be required by the system, δ represents the depth of discharge recommended for the given battery, which must be respected in order to correctly use and maximize the useful life of the battery bank and avoid reducing as was pointed previously in the section, that for deep cycle battery systems is usually recommended in the range value of 0.6. And L_f represents the performance factor, including some factor like losses by yield, increase of temperature and yield of materials, and are provided for each given battery in its specification sheet.

From the identification of the necessary current, there are several possible combinations of battery arrays in different voltage ranges, in parallel or in series, which can be satisfied with the existence of various commercial brands. For the present investigation we proceeded to determine the different scenarios and look for the maximization of cost-benefit in a more efficient way by using the database and calculation software included in the PVSol and PVSyst design softwares (version 6.79).

4.2.3. Load Regulator

Once the current is identified, the maximum current of the system and the number of batteries for the system need to be determined as well as the necessary system load regulator. According to the recommendations of several authors, the selected Load controller must be able to:

- Resist a simultaneous overload without risk of damage at standard temperatures.
- Be able to handle at a short-circuit current with a nominal value of at least 25% higher than the short-circuit of the given PV generation stage at STC.
- Produce a minimum current with a nominal value of at least 25% more current than the maximum consumption current in the network.

In this way, the input or load current of the regulator is defined as:

$$I_{In} = (I_{sc})(N_{PV}) * 1.25$$

Equation 11 Load Regulator Input current

Where I_{In} represents the input current to which the charge controller must be selected from the options in the market, I_{sc} represents the short circuit current that can be provided by the given solar panel selected for the system and is indicated in the manufacturer's data sheet, finally N_{PV} represents the number of panels in the system. Similarly, the intensity of the regulator output will be determined by a value in a range of 20% to 25% of the maximum peak current consumption calculated for system loads and that was defined in the calculation of the load profile.

Similarly, the output current will be determined as:

$$I_{Out} = (I_{Syst}) * 1.25$$

Equation 12 Load regulator output current

Where I_{Out} represents the minimum output current that should be provided by the selected load regulator and is indicated in the provider datasheet specifications, I_{Syst} represents the maximum current required in the system according to a given operational voltage and was calculated in accordance to the load profile and the battery bank in the last sections. It is concluded that the selection of the device will be determined directly to the nominal data of the intensity of input and output of the regulator defined by the manufacturer.

4.2.4. Sizing of the Inverter stage

Given that the vast majority of the appliances available in Mexico operate under a voltage regime of 120V in alternating current, it is mandatory to include an inverter stage for the transformation of continuous to alternating current. The general equation of the output power relation of an inverter is determined by:

$$P_{Out} = \frac{(W_{Max})}{C}$$

Equation 13 Output power relation of an inverter

Where P_{Out} represents the output power of the inverter that is necessary to satisfy the energy demand in a given household and is provided in the characteristics of a given Inverter, W_{Max} represents the maximum peak power that may be required provide during a normal day, and finally C the coefficient of simultaneity of the devices usage in the given home.

From a design point of view, assuming a scenario where all devices are executed at the same time is unrealistic, which is why the following design criteria are suggested.

- The sum of the powers of the equipment in the household operating simultaneously must not exceed 80% of the nominal power of the inverter.
- The Inverter must be able to work at a minimum efficiency of 90% nominal 24 hours/day.
- The input voltage of the inverter must be selected in accordance with the nominal direct current voltage established in the network for other elements in the network like the battery bank or the load control stage (12v, 24V or 48V)

The installed power required for the inverter under simultaneity of 90% will be defined by:

$$P_{Out} = \frac{(W_{Max})}{.90}$$

Equation 14Installed power required for the inverter under simultaneity of 90%

P_{Out} represents the output power of the inverter that is necessary to satisfy the energy demand in a given household. W_{Max} represents the maximum peak power that may be required during a day.

From the obtained value it is possible to choose a suitable inverter available in the Mexican market. For the research paper, it has been decided to use the existing components in the database of the official software PVSol and PVSyst (version 6.79).

4.2.5. Sizing of the Diesel Generator Stage

For the economic comparisons of different mini-grid configurations, it is necessary to consider the inclusion of a diesel generator which can function as a secondary energy source replacing the battery bank. The selection process was carried out following the methodology used by other authors (Cota et al, 2016; Becerra Lopez, 2011). As expected, the optimal design suggested in the reviewed literature focuses on the dimensioning of a community generator with the ability to meet the needs of the community during periods when energy demand cannot be met by the PV generation stage (Cota et al, 2016). Similar to the PV generation stages, the minimum power that must be provided by the diesel generator are determined by the following equation:

$$\text{Min Power}_{\text{D}} \geq (\text{Load}_{\text{Wh}})$$

Equation 15minimum power that must be provided by the diesel generator

Where “Total Power $_{\text{D}}$” represents the minimum power that should be generated by the diesel generator and ”Total Load$_{\text{Wh}}$"indicate the load of consumption that must to be supplied to the community in a given time. It is important to note that the electric power with is referenced in their apparent power measured in kVA, within their spreadsheets.

Where the ratio of kVA and kW are defined by the following relationship:

$$\text{kVA} = \frac{\text{KW}}{\text{Cos } \varphi}$$

Equation 16 Apparent power measured in kVA

These values can be found in the specifications of each generator provided by the manufacturer. Then the amount of energy supplied by the diesel generator can be described on time as:

$$P(k)_{Out} = (P_G)(Q)(H(k)) \quad \text{(Nfah EM, 2007)}$$

Equation 17 Amount of energy supplied by the diesel generator

Where $P(k)_{Out}$ represents the amount of energy supplied by the diesel generator, P_G is the nominal rated power of the generator, Q represent the constant load fraction at which the diesel generator is operated, finally $H(k)$ represents the constant of time that the diesel generation is operated.

For the present investigation it was proceeded to determine the different scenarios and look for the maximization of cost-benefit in a more efficient way by using the database and calculation software included in the PVSol.

Among the design criteria, it is considered that the generator must have the capacity to supply parameters of a partial to total demand in the community, focusing its selection on a greater efficiency factor in fuel consumption. Its selection is reduced to models of three-phase character allowing to feed the equipment of these characteristics in scenarios that include elements such as air conditioning.

4.3.Description of the Selected smart components

The components used for the proposed Photovoltaic Smart Mini Grid (PSMG) was chosen focusing in a balance between functionality, quality and cost. A 48V voltage components was selected for the operation of the system, as showing better results (in terms of relation of cost, energy production and capacity storage) according to the size of the system. All selected components have a warranty of up to 25 years, with the exception of batteries that have a warranty of up to 10 years.

The following table describes the selected components that were used in the networks:

Component	Descripton
Bauer Polycrystalline Panel Solar (330W, 24V, 8.7A) 	It consists of 72 cells of polycrystalline silicon. It owns a power capacity of 330W with a maximum short circuit current (Isc) of 9.3A, a voltage at maximum power (Vm): 37.95V and a maximum current intensity at maximum power (Im) of 8.7A
Fronius Primo 3.8-1 208-240 Smart Inverter 	The device was selected due its property of been able to be connected with another 3 Inverters and operate in Master-Slave configuration, allowing to share the surplus of energy of a particular PV generation stage to other inverters in the same topology. This enable to efficiently distribute the available energy in the grid without the need to request the usage of a secondary generation stage until the Master inverter requires it. It includes a communications card that support ethernet and Wireless connection that allow to monitor the solar installation through the WAN or LAN. It also includes a MPPT controller that allow to identify the balance between voltage and current of

	several solar panels connected in serial configuration and operate them at their maximum power removing the need to acquire additional load controllers.
Three-phase inverter Fronius Symo Hybrid 5kW 	This device is specialized in the handling of batteries. Having the technical characteristics similar to Primo Smart Inverter, is selected as slave investor, for price question. An inverter of three-phase characteristics was selected, foreseeing the use of devices such as water pumps or air conditioners that may require it.
Fronius Three-phase Smart Meter 50KA-3 	It is a consumption measuring device to be installed in the house. It allows to measure consumption statistics, as well as to configure and dynamically control the power supplied to the home provided from the PV stage. It allows to observe instant energy consumption in a web portal of the manufacturer, as well as consumption graphs throughout the 24 hours a day.

Table 16Selected Components for the Smart Mini Grid Configuration

The Smart inverter devices was selected due its property of been able to be connected to other Inverters (In Master-Slave configuration) allowing to share the surplus of energy between different points of the PV generation stage, as well as allowing to expand the smart mini grid dimension by connecting new inverters to the connection points operated by the master inverters. Another practical property identified on this technology is the existence of two MPPT lines that allow to operate the voltage and current input of several PV connected in Serial configuration by just one device. Similarly, the slave inverters designed to operate a battery bank allows the possibility of distributing the energy surplus during the day.

All the Smart devices in the network (inverters and meters) allows to be remote monitored by the use of web services, allowing to know the consumption profiles of the community, similarly the smart meters allow to restrict the peak and maximum consumption per household in case the configurations require it. This allow to develop direct functionalities in the normal operation of the grid:

- The possibility of identifying when it is necessary to increase the installed capacity in the network,
- To monitor the consumption per household, creating the possibility of developing a tariff system to pay for the electric service if it is appropriate.
- Identify load profiles that are excessive in the network
- Limit the consumption of households on the bank of batteries and ensure its maximum useful life.

For the design of the proposed networks, the photovoltaic generation stage was designed in a concept of star topology, which consists of generation nodes composed of a smart inverter (master) operating centrally up to three other inverters (slaves). Meanwhile the slave inverters are responsible for managing the banks of batteries distributed in the community from the energy surplus generated during the day. Finally, all the master inverters are connected to the electric distribution bus that reaches the homes through an access point delimited by the smart meter.

5. Simulation Results and Analysis

5.1. Installed Capacities of the Mini Grid

The optimization was realized by using the official software oriented to design PV systems: PVSol (Version) and PVSyst (version 6.79). During the process several architectures are tested, to provide of those that represent to be more feasible to be implemented in accordance to the design criteria.

The following table describe the three system configurations and its respective required installed capacity in kW for each proposed scenario:

		Required Installed Capacity (kW)		
	ID	PV Panel Stage (Flat Panels)	Disel Generator	Lead Acid Battery
BLP	S2	92.86	-	167.14
	S3		187.71	-
	S4		55.71	167.14
SLP	S2	157.14	-	628.57
	S3		314.29	-
	S4		94.29	282.86
HLP	S2	250	-	1,000
	S3		500	-
	S4		150	167.14

Figure 28 System architecture and its required installed capacity

5.2. Economic analysis

The Economic analysis consisted on a comparison of the LCoE during the 20 years of expected life of the proposed Mini-Grid systems. The analysis includes a cash flow during the including the life time of the project considering different type of cost like the replacement cost, diesel fuel costs, operating cost and capital cost in its NPV.

At the moment of performing this investigation the diesel cost in Mexico is 20.85 Mexican pesos (MXN) per liter, in comparison with the rest of the world that describe an average value of 26.21 MXN (GlobalPetrolPrices, 2019), the Investment cost of Diesel generators was estimated at $500,000.00MXN, the annual inflation rate in Mexico is considered as 5%, and conservative value of interest rate of 10% and a weighted average cost of capital of 20% is used reflecting the values used by the average of Mexican banks (Banco de Mexico, 2019). By using this parameter, the lowest possible initial capital costs, operating costs, net present costs, and cost of per unit electricity.

The results of the economic evaluation are shown in the following table:

		Investment Cost	Operation and Mantainance	Net Present Value	LCoE (MXN/kWh)
BLP	S1	2,466,469.00	485,894.39	3,206,409.70	6.39
	S2	7,184,861.10	5,747,888.88	15,088,208.32	19.53
	S3	500,000.00	12,922,857.14	16,928,942.86	13.98
	S4	4,671,211.03	2,802,726.62	8,922,013.07	9.91
SLP	S1	2,466,469.00	485,894.39	3,206,409.70	3.77
	S2	12,158,995.71	9,727,196.57	25,533,891.00	12.91
	S3	500,000.00	13,887,142.86	18,192,157.14	8.87
	S4	7,558,972.51	4,535,383.51	14,664,406.67	6.26
HLP	S1	2,466,469.00	485,894.39	3,206,409.70	2.37
	S2	19,343,856.82	15,475,085.45	36,946,766.52	9.64
	S3	500,000.00	15,250,000.00	19,977,500.00	6.12
	S4	11,730,183.54	7,038,110.13	22,756,556.07	4.56

Table 17 Economic Evaluation

As can be observed, each of the suggested configuration has its own advantages and disadvantages for the community. First, the Main Grid extension describe an expected behavior displaying a more attractive LCoE as the consumption in the Household increase distributing in a faster way the cost of investment and maintenance. It still is important to remind that in this calculation the distance for the main grid extension was assumed as 9km, however, in a real implementation the implementation would likely represent a least 3 times the proposed distance due geographical conditions.

Regarding the smart mini grids implementation, is possible to observe that even when the investment cost associated to the BLP represent the lowest cost, it still reflects the highest higher LCoE, then the implementation of the smart mini grid suggests an inconsistency, since the implementation of the network would suggest the creation of new expenditures, in a sector with already restricted economic income. This suggest that the consumption profiles do not justify the investment in infrastructure like the suggested devices (smart devices, a battery bank or a high capacity diesel generator) and therefore a simpler grid might result a more feasible implementation in terms of cost, sacrificing the benefits on functionality and upgradability of the design. An interesting characteristic identified during the design, is that the system sizing allow to satisfy most of the consumption of the BLP by the use of the PV during the day hours for 9 of the 12 months of the year, been just the rainy seasons of the year(June, July and August) and in night, when the system requires the use of the battery bank. Regarding the diesel configuration, it is observed that even when the consumption profile does not suggest a strong usage of the diesel generator during the not rainy seasons, the capital cost of the diesel generator heavily impact in the LCoE, similarly to the battery bank.

On the other hand, HLP suggest the lowest LCoE due its high energy consumption, however this is translated in an oversizing of the system translated in the biggest investment cost. It is observed that particularly the use of devices with high consumption per hour (like the air conditioner) is translate to a huge increase of the run-cost generated during the rainy months, that are also the hottest of the year, suggesting a biggest consumption of diesel usage. Interestingly the consumption habits of this profiles during the rest of the year allow to cover the battery system and the diesel generator capital cost in a faster way during the not rainy months' period, however, in a realistic approach, it is not expected that the economic income in the community currently represents profiles like the HLP. It is important to remark that the run-cost generated of this profile were the highest ones when comparing the S3, particularly during the rainy season that are also related to the hottest month, suggesting a more usage of air-conditioner appliance that is mostly covered by the diesel fuel investment cost.

Finally, it was concluded the SLP configurations as the more cost-effective ones (Particularly those in the range of 15kWh to 20kWh, that represented a more conservative consumption habits) that allowed better LCoE than the BLP ones and less investment cost than the HLP. In terms of design, the LCoE and NVP calculations, a tariff implementation allows to suggest the implementation of the smart devices and the second power generation stages, that are also justified by the consumption habits of the middle-income load profiles that tend to stay stable under the expected consumption estimations allowing a more suitable sizing of the PV generation stage, and reducing the run cost related to the diesel generator. It is considered that this might be mostly related to the absence of devices of high consumption like air conditioner o extra leisure devices that tend to generate more consumption during the rainy season and during the times of the day where the irradiance do not provide enough energy to satisfy high consumption load (evening/night), suggesting that restrictive load profile in terms or appliance might perform more effectively. From the social point of view, the SLP design allows the integration of a greater range of devices useful for daily life, such as washing machines, refrigerators, some power tools, a second television or computer, satellite internet services and even replacing the gas stoves, by electric stoves, representing as the only identified restriction of design the non-inclusion of air conditioning (profiles of >3h of usage per day) or electric heaters in general, that according to the statistical figures explained in the load profile design criteria, are not likely to be purchased by the Mexican mean.

Regarding to the comparison of the four scenarios, the NPV shows the hybrid mini grid system as the most viable implementation, followed by the PV Diesel variation and letting the Full Battery and PV as the less feasible scenario, one of the biggest reason that was identified performing the cost analysis was the necessity of substituting the whole bank of batteries in 10 years, when the diesel generator was expected to last more than 20 years given its low usage.

It is important to point out that each mini grid implementation represents different characteristics and therefore the results of that each grid are not decisive to perform comparison with other communities' implementations. For example, while the cost of extending the electric grid to an isolated community increases according to the distance, the performance and cost of mini grids and the diesel generator will depend on the location of the community and its consumption habits. Particularly in the proposed hybrid design (SLP and SLP), a very reduced use battery bank and the diesel generator is observed during the daytime, suggesting that the consumption was mostly covered by the

PV generation stage reducing the run cost of fuel use during not rainy days.

5.3.Photovoltaic Smart Mini Grid Line Diagram

The following diagram illustrate the Line diagram of the proposed SLP mini grid generated in PvSol:

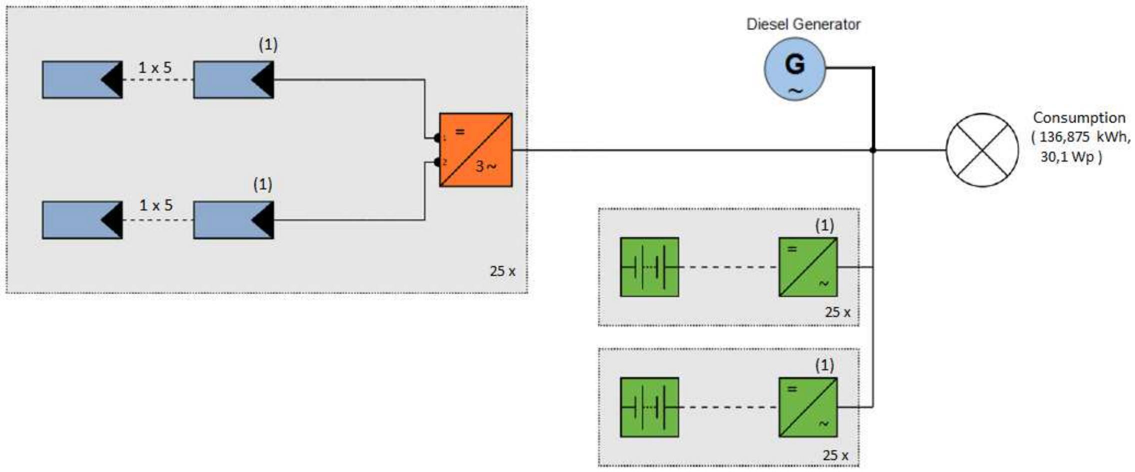

Figure 29 SLP Single Line Diagram

6. Conclusions

The use of photovoltaic technologies in smart mini-grids, undoubtedly represents a feasible strategy to provide energy security to the 3,5 million people living in isolated villages within Mexico and that still lack of electric service. This is because the irradiation values that exist in most of the Mexican territory allows to establish power generation designs without having to depend on the main distribution network, relaying in the use of photovoltaic modules as its main energy generation resource.

The main reason for not extending the main network to these communities is their high investment cost and loss factors that results of the distribution stage in the Main Grid. The use of isolated photovoltaic mini-grids allows the implementation of self-sufficient systems that are able to satisfy the consumption needs of its users, while at the same time avoid the production of emissions attributed to the use of fossil or nuclear resources that are currently widely spread in the conventional centralized system around the world.

By the use of mini grids, it is allowed to establishing a wide range of possibilities for the benefit of isolated communities. In the social terms, the availability of energy easy to access allow to improve their lifestyles and allow its integration. Examples of this is the access to cheaper lighting services, the possibility of using refrigerators to extend the useful usage of food or even eliminating the dependence on the use of fossil resources or biomass for food cooking activities through the integration of electric stoves and reducing in this way the concerning related to the difficulty accessing to this type of fuels or the harmful side effect associated to the exposure of its missions. Similarly, mini grids can also enable the use of communication technologies, which can open new opportunities for improvement in education and knowledge access, economic development, or ensure the requirements for better quality of health-oriented technologies. Last, but not least, it could allow the integration of electronic devices for entertainment proposes.

The access to a large number of electrical appliances represents a great advantage from the social point of view, but in the same way, it represents an increase in the costs and in the complexity of the installed capacity required to satisfy its functions. Because the number of devices in the household and it hours of use (also known as load profile), will be reflected differently between each household within the community and its nominal value will tend to increase over time, more in relation to the economic income of the members that live on it, than in terms of the number inhabitants. This generates a crucial factor in terms of network design, in such a way that it becomes meritorious to foresee the possibility of its expansion in order to avoid the obsolescence of the system or the damage of its components.

From the point of view of design, this problematic can be solved in two ways, the first one, by implementing a restrictive system in terms of the technologies allowed to be used in the mini grid and the time of use allowed or each appliance, leading to restrictive repercussions on the lifestyles of it users, or by the second way, through the implementation of systems that allow to satisfy this demand levels by means of other components in the mini grid, like a secondary energy generator stage that works on demand or due the increase of capacity in the grid.

On the one hand it has been demonstrated through several implementations, that the restrictive profiles tend to be insufficient to satisfy their users demands and its consumption habits and end up negatively impacting the network components generating economic losses due highest operating and maintenance cost. However, on the other hand, proposing an oversized network tends to represent a high capital cost, which investors generally do not consider attractive.

From the technological point of view, this research chose to make a disruptive implementation and tried to find a middle point, through the improvement of the traditional components used in the current PV mini grid system by the addition of smart devices (such as the use of smart meters and smart inverters) that autonomously control the distribution of current and voltage in the network, while at the same time allows to monitor the consumption of each household in the community in real time, and even remotely through the use of connections to LAN or WAN communication networks. This allow to foresee the development or expansion of the network as users increase its energy consumption habits, as well as the establishment of a tariff system, if considered viable, which can be implemented by a governmental or private instance, allowing to establish a restrictive design for a community in a certain time, but that allows to develop with the consumption of the population and with its economic income.

To this end, the design and proposal of various networks were developed, which were designed using load profiles that reflect the lifestyles of homes with a low, medium and high income. These profiles were generated randomly from the statistical data of the Mexican population generated through the national censuses, under the premise that the network should be able to provide a fair lifestyle for its users compared to the styles of life of the main network users. The profiles were designed under design constrains that focused on the maximization of energy security (no blackouts), economic maximization (lower LCoE possible), possibility of being expanded (selection of components and topologies that allow adding new installed capacity and users) and restrictive profiles (focused on including or discarding specific technologies of high consumption, or consumption habits that would affect the other design criteria as well as increase the costs), then load profiles was chosen aiming to use those that were representative for each social sector (low, medium and high economic income)

Finally, the proposed loads profile was simulated and optimized through the use of professional software focused on the implementation of photovoltaic systems (PvSol and PVSys). The criterion of positive comparison between the proposed systems was its LCoE, which allowed to identify that the PV smart mini grid systems were economically feasible and possible for its implementation.

The results allowed to point out the hybrid mini grid design, oriented to middle income users and made of PV technologies, a diesel generator and a battery bank, as the most propitious to be implemented in terms of cost and design criteria. Mainly because it represents a balance point between investment cost, presenting a NPV more competitive than the other systems and a competitive LCoE, that allows to satisfy the capital investment through the consumption habits of the users, in conjunction with a design that supports the possibility of use of a great variety of devices that can be found among the average Mexican mean, being restricted only the use of air conditioning for more than 3 hours as well as the use of electric heaters.

From the economic point of view, this presents the possibility of providing, not just the social benefits to the population, but also the establishment of new market models, where the implementation of the mini grid can be payed dynamically by the consumptions of users without the need that some other institution has to absorb the investment costs.

As expressed during the analysis of the Mexican legal framework, Mexico has a regulatory framework that allows the implementation of a smart mini grid system under a regime of an agreement with the electric power transmission service and by a prior authorization from the government institutions (CRE and CFE), that will allow it to be executed in the modality of a small production regime while the installed capacity does not generate more than 1 MW.

In fact, the Mexican regulatory framework has allowed the implementation and distribution of decentralized energy facilities since 1992, however the proliferation of electric generation projects that do not follow the conventional centralized paradigm were not possible till the last decade, as a result of the establishment of a centralized control regime regulated by the Mexican government that promoted the usage of fossil fuels. Generating the development of economic incentives and legal tools that encouraged the investment and development of the Main grid and decreased the competitive advantages of most of the decentralized and renewable systems. The result of this practices has prevailed to date, generating a perception that investment in renewable energy technologies, such as the photovoltaic sector, represent unattractive investments and high-risk among the banking institutions. It was until the establishment of the energy reform in 2013 and the consolidation of its legal reforms on 2017, that finally longer loan periods was allowed for this type of technologies, allowing the development of renewable energy projects with greater installed capacity, as represented by a mini grid.

However, to date, it is still necessary to attenuate certain barriers that exist in the

Mexican sector to achieve the consolidation of renewable energy systems such as smart mini grids. First, it is necessary to develop policies oriented to the development business models for decentralized and isolated generation systems, given that currently, the regular framework established by the Mexican regulatory institutions (CRE and CFE) is strictly focused on centralized paradigms, which allow the creation of capital through the sale of the energy resource through its provision to the main grid or through modalities of self-consumption, however, it does not make clear the guidelines for the creation and development of tariff systems that could create competitive costs for users not connected to the main grid. This greatly restricts the attraction of investment in the sector and reduces the possible implementation of photovoltaic projects to a very specific systems, like setting PV to attenuate the high consumption regimes, or like the development of photovoltaic generation plants oriented to provide energy to the main grid. As a result, it generates that most projects oriented to the energy security of isolated communities need to be self-financed or to be provided by a governmental organization or a non-profit institution.

In this context, the combined participation of researchers, transnational institutions, market leaders and the governments of the countries is of crucial importance, in order to establish consensus on terminologies, characteristics and frames of reference on decentralized technologies that allow to create a clear context that could be used for the development of policies and legal tools.

It is suggested too, to stablish policies that encourage and raise awareness about the protection of resources and better energy consumption habits in the Mexican population, as well as the establishment of a framework of understanding between the government, the educational institutions and the Mexican citizens, in order to strengthen the proliferation of sustainable energy consumption habits. Similarly, it is recommended to establish a great policy control over the quality and the energy efficiency of the electric devices and the current housing standards available in the country. Because as was observed in the consumption rates of the houses, it is up to them to achieve the development of more efficient and sustainable systems.

Finally, it is necessary that the electrification and credit strategies provides achievable guidelines to plan and implement decentralized systems in realistic time frames, and not just focus on investment and inflation rates, in order to establish an a more attractive market for the private investment, and develop a framework where the geographical location would be no more a restriction to have access to electric service.

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I. Appendix I distribution and time of use of main appliances in Mexican households

In the current appendix are included the percentage distributions and appliance usage time statistics used for during the load profile generations. The figures were generated from the information gathered from INEGI (INEGI,2017)

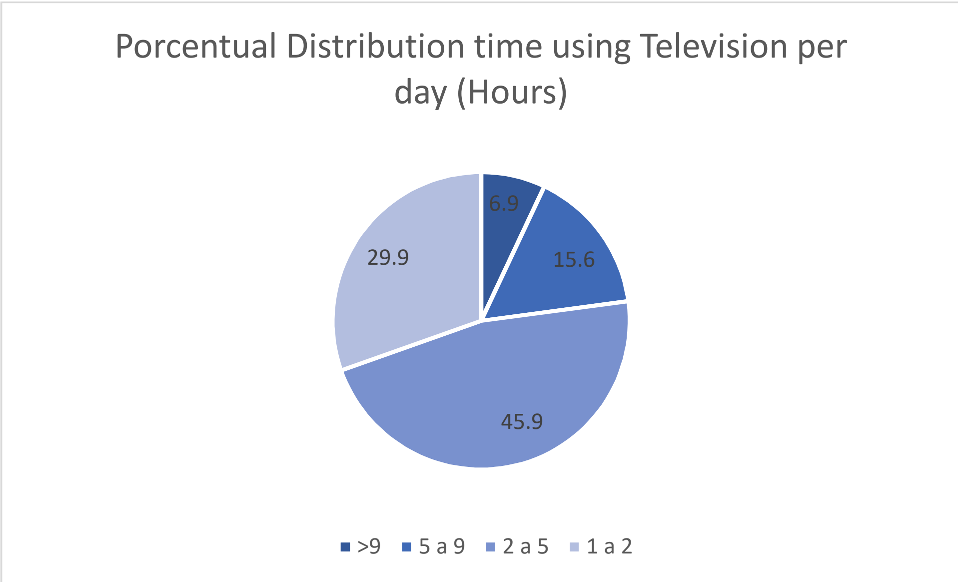

Figure 30Porcentual Distribution time using Television per day (Hours)

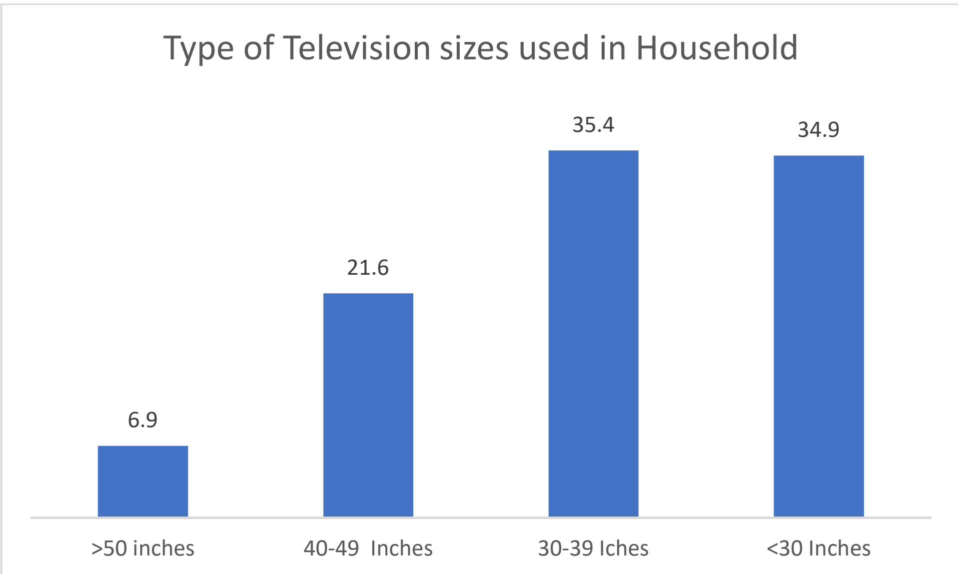

Figure 31 Type of Television sizes used in Household

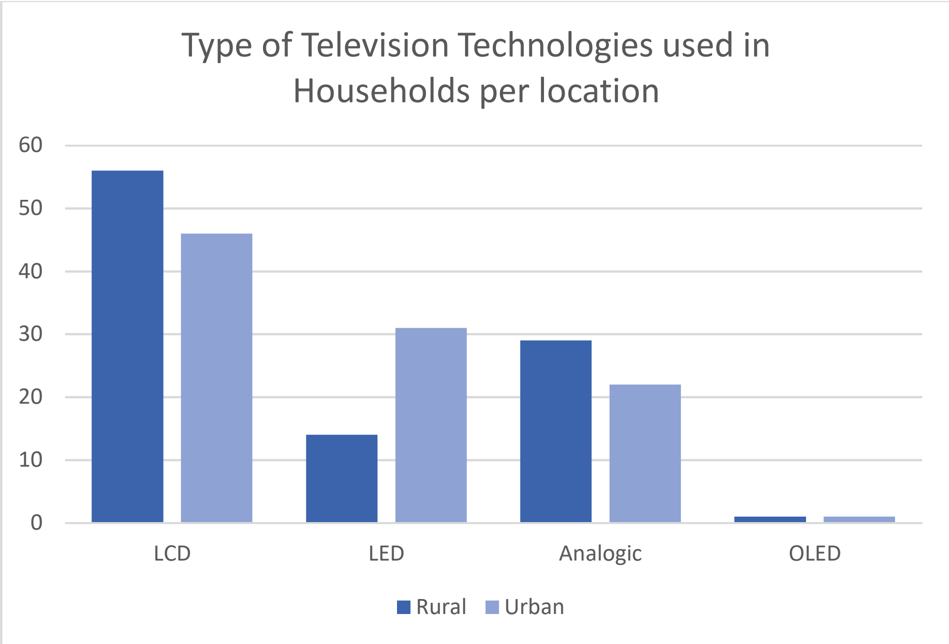

Figure 32 Type of Television Technologies used in Households per location

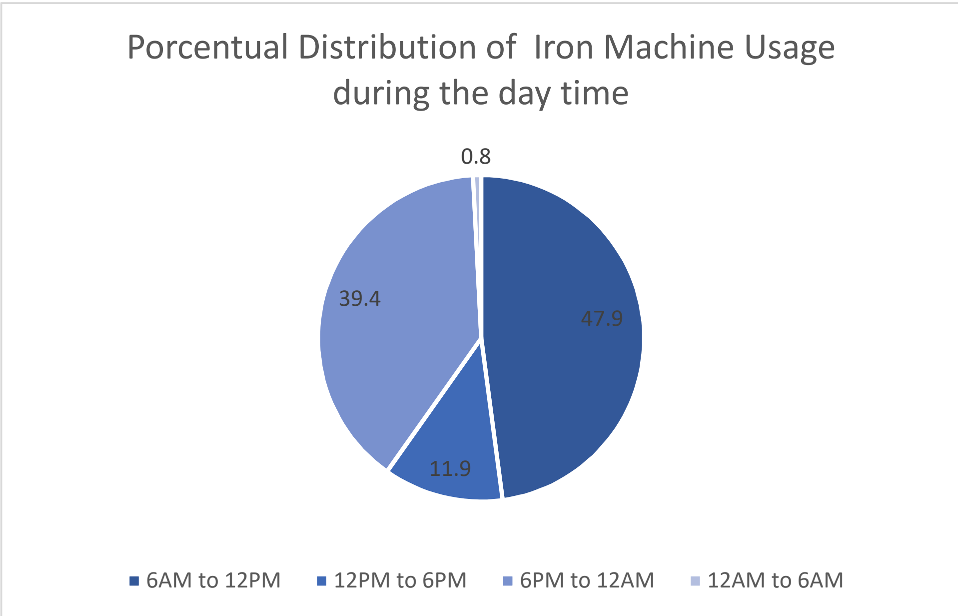

Figure 33 Percentual Distribution of Iron Machine Usage during the day time

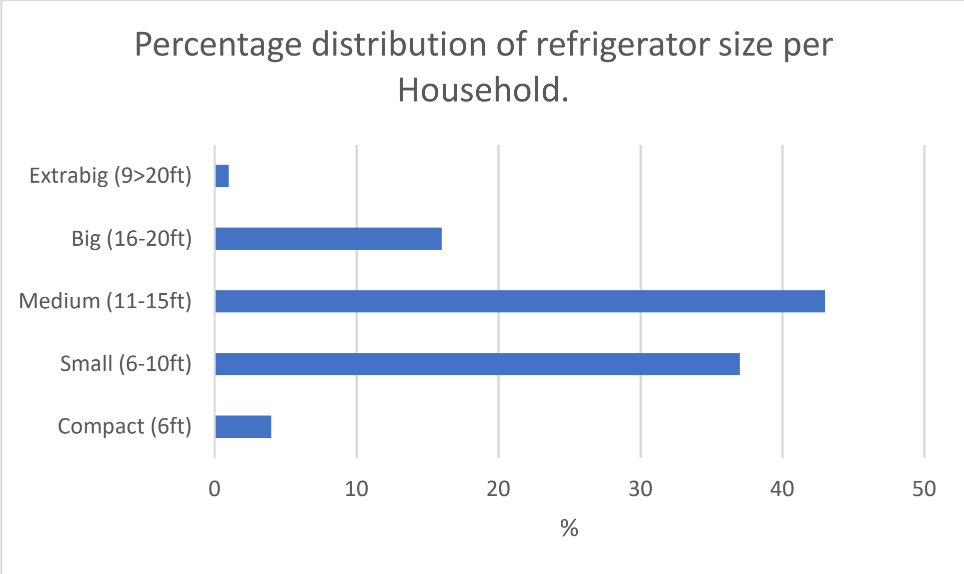

Figure 34 Percentage distribution of refrigerator size per Household

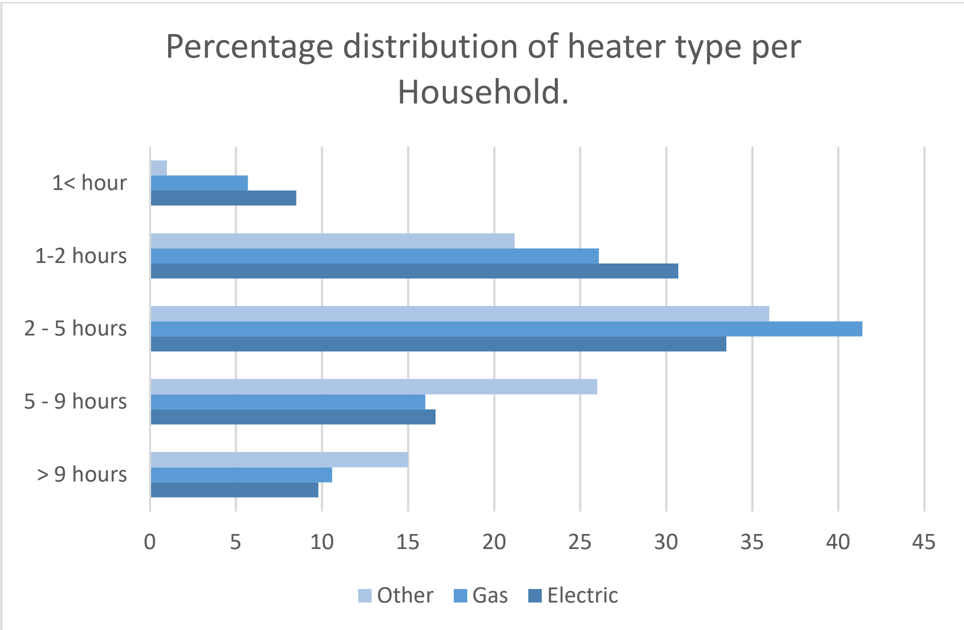

Figure 35 Percentage distribution of heater type per Household

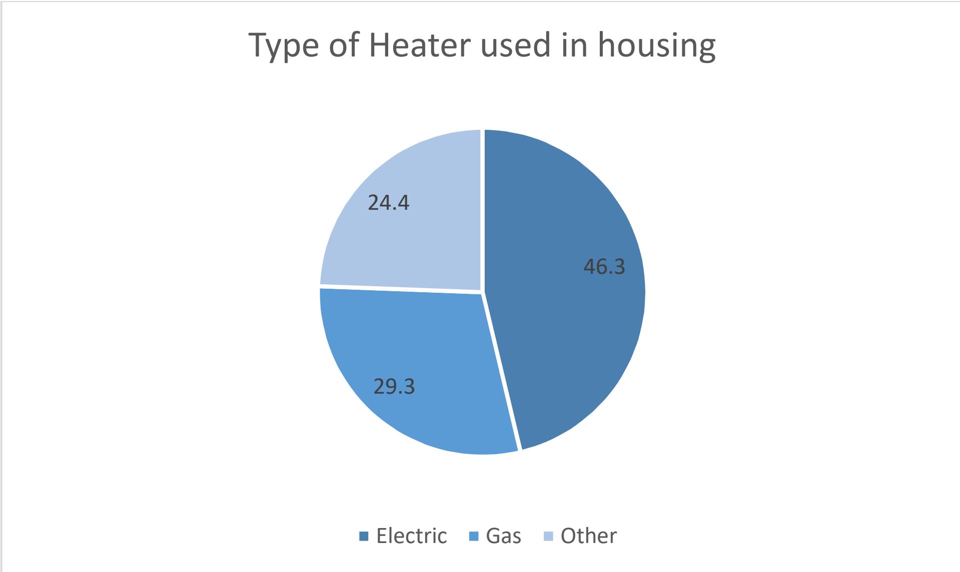

Figure 36 Type of Heater used in housing

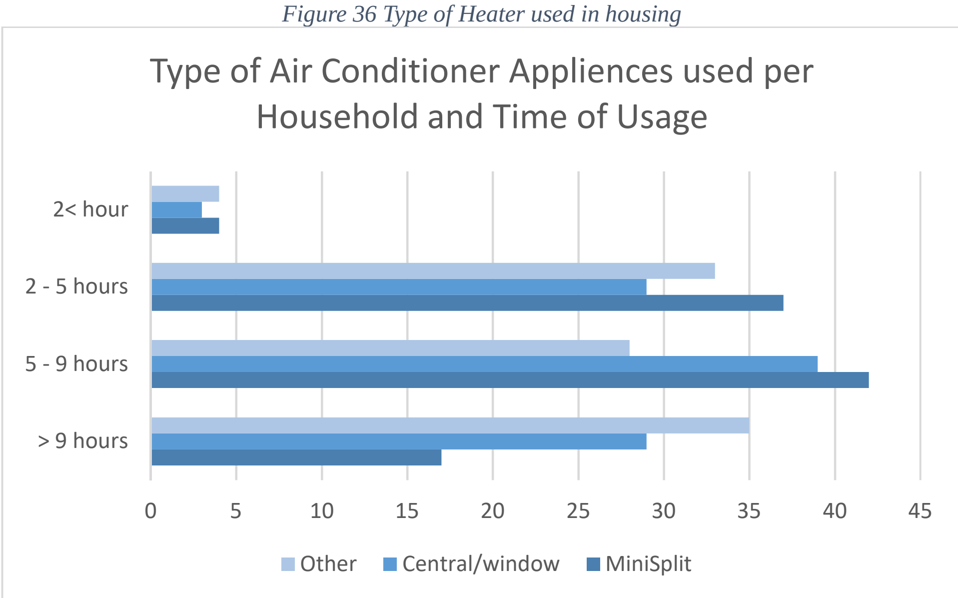

Figure 37 Type of Air Conditioner Appliences used per Household and Time of Usage

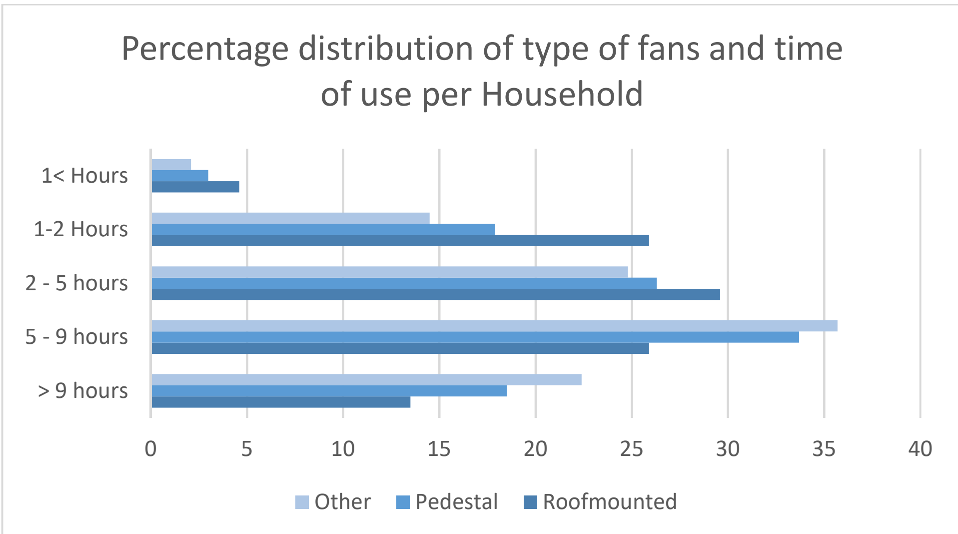

Figure 38 Percentage distribution of type of fans and time of use per Household

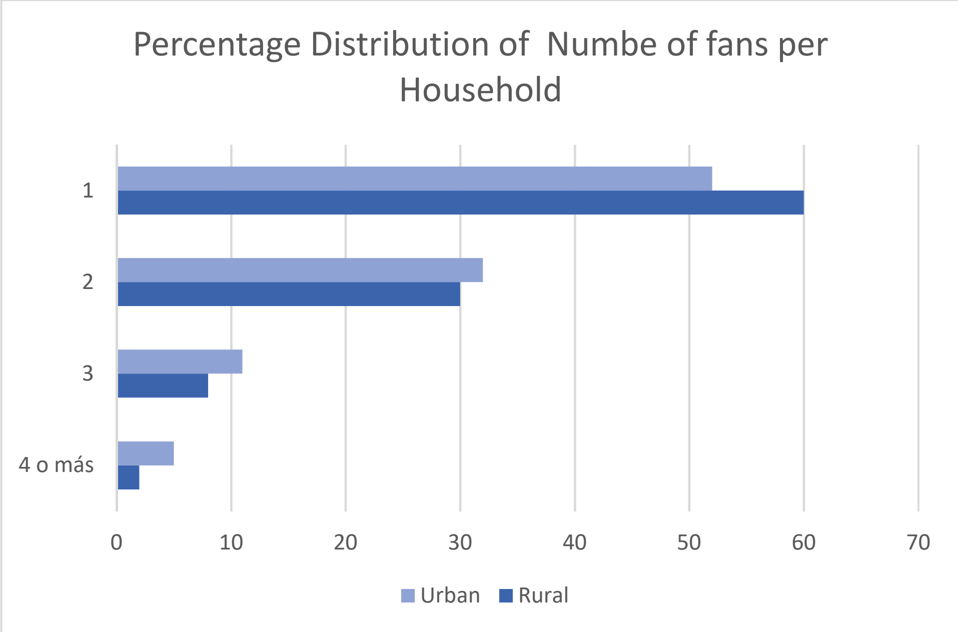

Figure 39 Percentage Distribution of Numbe of fans per Household

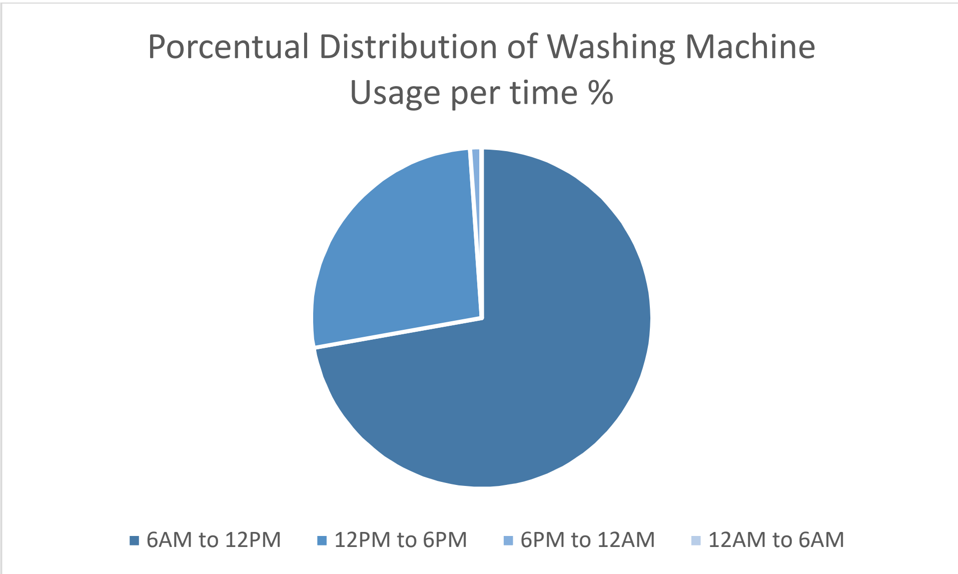

Figure 40 Porcentual Distribution of Washing Machine Usage per time %

II. Appendix II Special load Profiles

During the trade-off analysis, several variations of the BLP, SLP and HLP were created in order to represent different design criteria and user consumption patterns. Those profiles were used to observe the economic, social and design implications that could result of introducing particular appliances in the load profiles or because implementing design restriction criteria, such as the use of air conditioning in homes, the substitution of the use of gas stoves for electric stoves, several televisions in a household, high consumption profiles, the inclusion of power tools and the use of electric heaters. Those loads list appliances are not included in the main body of the current investigation due space reasons but are included here for illustrative purposes. The following table describe the criteria used to formulate the variation in the BLP, SLP and HLP:

		Main Profile Category										
		BLP			SLP				HLP			
		BLP_Gas	BLP_Base	BLP_H	SLP_Gas	SLP_Base	SLP_AirCon	SLP_H	HLP_Gas	HLP_Base	HLP_AirCon	HLP_Full
Desing Criteria	BLP Appliances	X	X	X	X	X	X	X	X	X	X	X
	SLP Appliances		X	X	X	X	X	X				X
	HLP Appliances							X	X	X	X	X
	Light Efficiency	X	X	X	X	X	X	X	X	X	X	X
	Electric Cooking		X		X	X		X		X	X	X
	Not Electric Cooking	X			X	X			X			
	Air Conditioner						X	X	X		X	X
	Hight Profile Usage			X							X	X
	Restrictive		X		X	X			X	X		
	Not Restrictie			X				X				X
	Electric Heating											X

Table 18 Criteria used to formulate the variation in the Load profiles used in the trade-off analysis.

From this it was possible to estimate the consumption and maximum power ranges required to be met in each Household, which were used to calculate the total consumption of the community. The total energy consumption (Wh/day) and the peak consumption (W) of the more representative load profiles that were used during the decision of the design of the load profile are shown in the following table:

Main Profile Category		Load Name	Maximum Peak Power (W)	Total Consumption Per Day (W)	Description
Main Profile Category	BLP	**Basic Income Load Restrictive with Gas usage for Cooking**	677.25	10,006.75	BLP Appliances and use of LP Gas
		Basic Income Load Restrictive With Electric Cooking	713.75	13,006.75	BLP Appliances and Electric Stove
		Basic Income Load Status Quo	528.75	10,186.00	BLP and SLP Appliances
	SLP	**Standard Restrictive Income Load Profile**	6,182.00	10,097.50	SLP Appliances and use of LP Gas
		Standard Restrictive Income Load Profile with Electric Cooking Appliances Income Load Profile	8,882.00	15,697.50	SLP Appliances and Electric Stove
		Standard Income Load Profile	1,076.25	20,587.50	SLP Appliances and Air Conditioner (3-9h)
		Standard High Income Load Profile	1,076.25	29,242.50	SLP, HLP Appliances and Air Conditioner (3-9h)
	HLP	**High Income Load Using Gas for cooking**	1,026.25	25,141.75	HLP Appliances and use of LP Gas
		High Income Load Restrictive Mexican Mean	1,500.25	31,441.75	HLP apliances in the Mexican High Income mean (Use of Electric cooking and Air conditioner 3-9h) Load Profile
		High Income Load using Gas For Cooking and Heating Restrictive	1,026.25	35,041.75	HLP Appliances and Air Conditioner (3-9h)
		High Income Load Gas For Heating	1,750.25	45,241.75	HLP Appliances and Air Conditioner (3-9h), Electric Heater, and others

Table 19 Load Profiles consumption comparison according to it design criteria

From the elaborated load profiles, it is possible to identify consumption ranges that are tentatively presented due to consumption habits or increase of income per household. Indicating a consumption of up to 11k W/h in BLP, up to 29kW/h for SLP and values above 45kW in HLP.

It was observed that the ranges of variation tend to remain within an expected range regardless of consumption habits within the same load profile category, however, as new appliances were added, consumption per household presented a greater range of variation that depended directly on consumption habits in housing (hours that each user watched TV for example) making difficult to parameterize the consumption ranges as the profiles with a bigger income was introduced to the simulations. Being the devices like the control of temperature, the dryer of clothes, clothes washing machine, the electric stoves, the vacuum and the dish washing machine that generated biggest changes in terms of peak consumption required in the household, and that supposed an increase of the capacities of the devices required in photovoltaic network.

It was observed that even though the substitution of gas stoves in the home for electric stoves represented an increase in the daily and peak consumption of the house, they represented a predictable consumption behavior that allowed to establish specific design criteria to cover it in terms of daily consumption. However, in terms of entertainment devices such as computers, radio or television, it was observed that the wide range of possible consumption habits (ranging from 2 to 9 hours per household) makes difficult to establish an equitable pattern of consumption among all the households.

For the purpose of network design, it was decided to establish an average expected consumption per household as follows:

	Average consumption per day (W/day)	Peak consumption (W)
BLP	11,000.00	600.00
SLP	25,000.00	1,100.00
HLP	35,000,00	2,000.00

Table 20 Average consumption Values used to design the PV Mini grids.

The following figure describe the comparison of consumption per day per household according to each proposed:

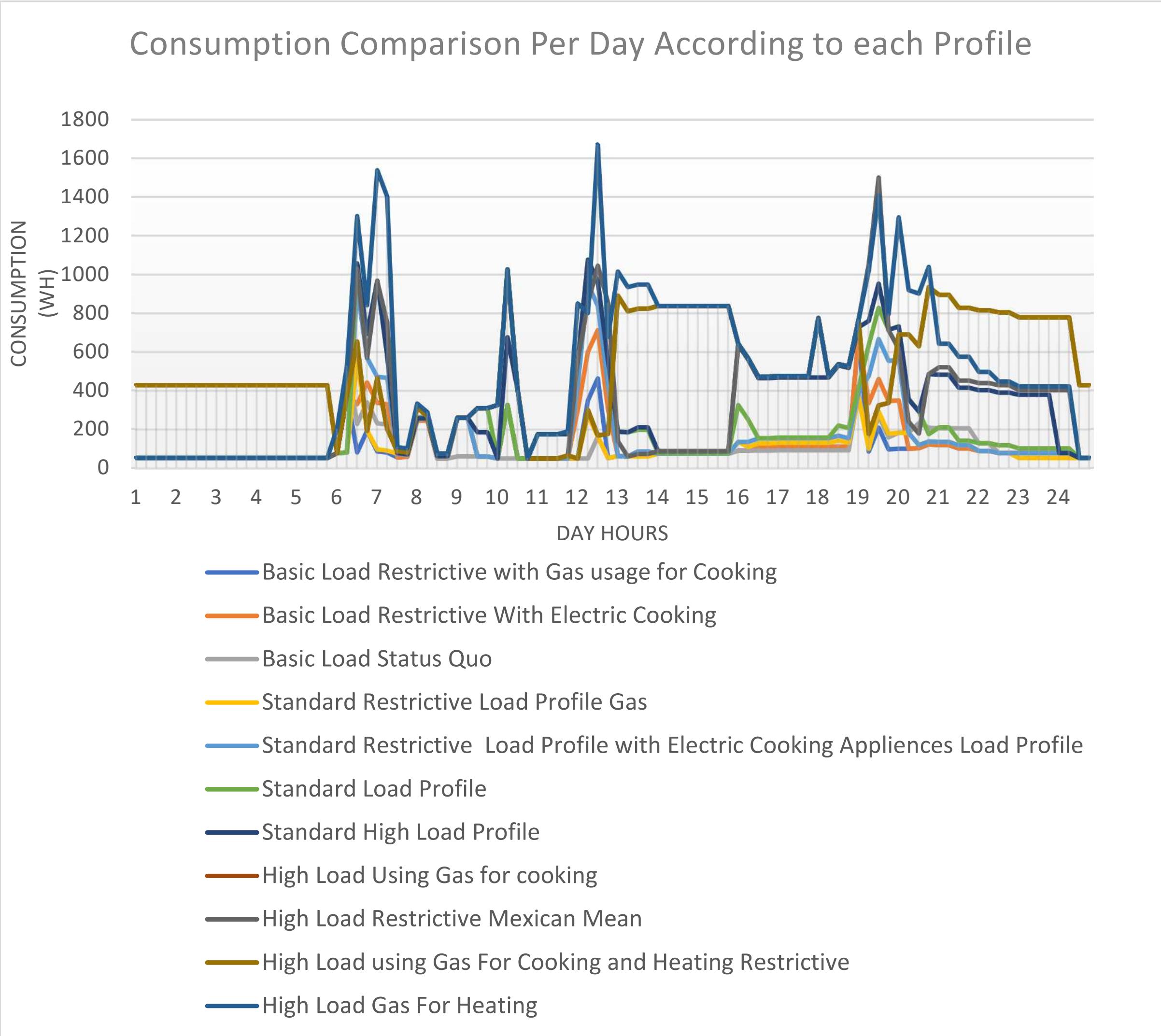

Figure 41 Consumption Comparison Per Day According to each Profile

Similarly, each load profile appliance list can be found in the next pages:

Basic Load Restrictive with Gas usage for Cooking

Appliance	Consumption Used For Calculation (W)	Work Hours per Day	Quantity	Total Energy Consumption Wh/day
Frontyard Lighting	23	4,5	1	103,5
Backyard Lighting	23	4,5	1	103,5
Kitchen Lighting	13	3	1	39
LivingRoom Lighting	13	3	3	117
DinningRoom Lighting	23	2,75	1	63,25
BathRoom Lighting	13	1,5	1	19,5
Fan (Portable)	50	9,5	2	950
Radio	40	2	1	80
30" LCD TV	60	0	1	0
DVB Digital receiver	25	24	1	600
DVD Player	60	3	1	180
Mobile phone charger	6	3,25	4	78
Tablet Computer	10	5,25	1	52,5
American-style Fridge Freezer	180	24	1	4320
Blender	450	0,75	1	337,5
Electric Stove (Small)	1000	3	1	3000
Microwave	1200	0,5	1	600
Kettle - Electric	1200	0,5	1	600
14-15" Laptop Computer	70	5	1	350
Electric iron	1100	0,5	1	550
Clothes Washing machine	800	0,5	1	400
Water Pump	746	0,5	1	373
ADSL / Wifi router	10	9	1	90
				13006,8

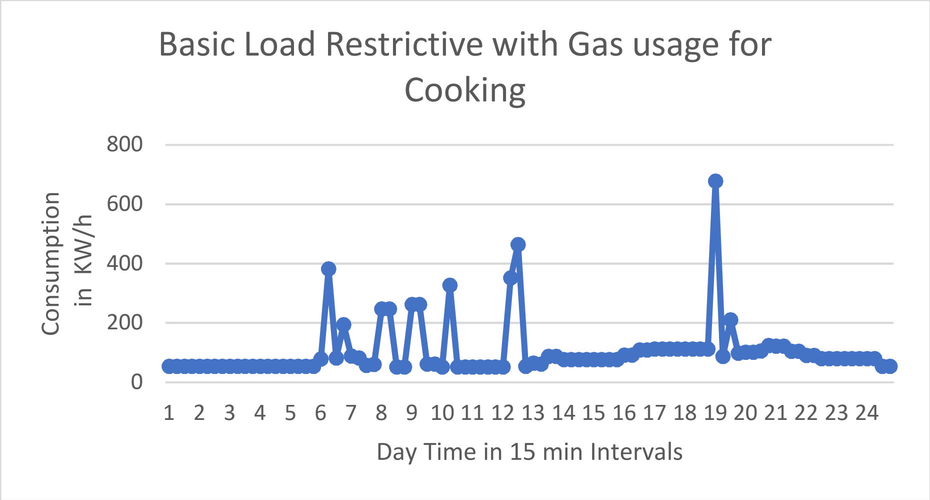

Figure 42 Basic Load Restrictive with Gas usage for Cooking

Basic Load Restrictive With Electric Cooking

Appliance	Consumption Used For Calculation (Wh)	Work Hours per Day	Quantity	Total Energy Consumption Wh/day
Frontyard Lighting	23	4,5	1	103,5
Backyard Lighting	23	4,5	1	103,5
Kitchen Lighting	13	3	1	39
LivingRoom Lighting	13	3	3	117
DinningRoom Lighting	23	2,75	1	63,25
BathRoom Lighting	13	1,5	1	19,5
Fan (Portable)	50	9,5	2	950
Radio	40	4	1	160
30" LCD TV	60	6	1	360
DVB Digital receiver	25	24	1	600
Game Console/ DVD Player	180	3	1	540
Mobile phone charger	6	3,25	4	78
Tablet Computer	10	5,25	1	52,5
American-style Fridge Freezer	180	24	1	4320
Blender	450	0,75	1	337,5
Bread toaster	900	0,5	1	450
Coffee Machine	1000	0,25	1	250
Electric stove / Cooktop (Medium)	1500	3	1	4500
Microwave	1200	0,5	1	600
14-15" Laptop Computer	70	5	1	350
Inkjet Printer	30	0,25	1	7,5
Projector	270	1	1	270
Scanner	18	0,25	1	4,5
Curling Iron	35	0,25	1	8,75
Electric iron	1100	0,5	1	550
Clothes Washing machine	800	0,5	1	400
Water Pump	746	0,5	1	373
ADSL / Wifi router	10	9	1	90
				15697,5

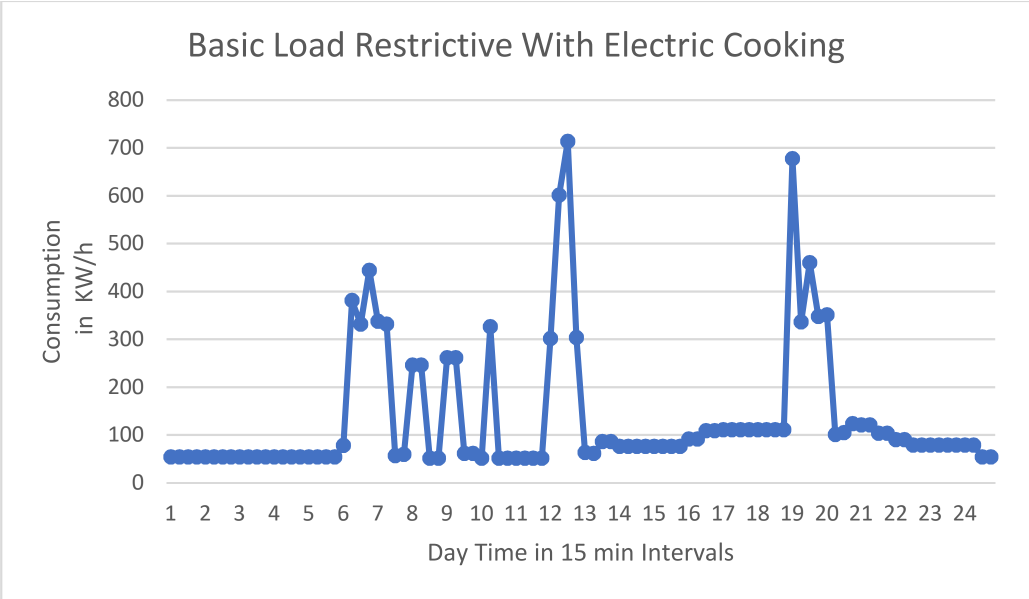

Figure 43Basic Load Restrictive With Electric Cooking

Basic Load Status Quo

Appliance	Consumption Used For Calculation (Wh)	Work Hours per Day	Quantity	Total Energy Consumption Wh/day
Frontyard Lighting	100	4,5	1	450
Backyard Lighting	100	4,5	1	450
Kitchen Lighting	100	3	1	300
LivingRoom Lighting	100	3	3	900
DinningRoom Lighting	100	2,75	1	275
BathRoom Lighting	100	1,5	1	150
Fan (Portable)	50	9,5	2	950
Radio	40	2	1	80
25" colour TV Generit CRT (2000)	150	0	1	0
DVB Digital receiver	25	24	1	600
DVD Player	60	3	1	180
Mobile phone charger	6	3,25	4	78
Tablet Computer	10	5,25	1	52,5
American-style Fridge Freezer	180	24	1	4320
Blender	450	0,75	1	337,5
Kettle - Electric	1200	0,5	1	600
Water Pump	746	0,5	1	373
ADSL / Wifi router	10	9	1	90
				10186

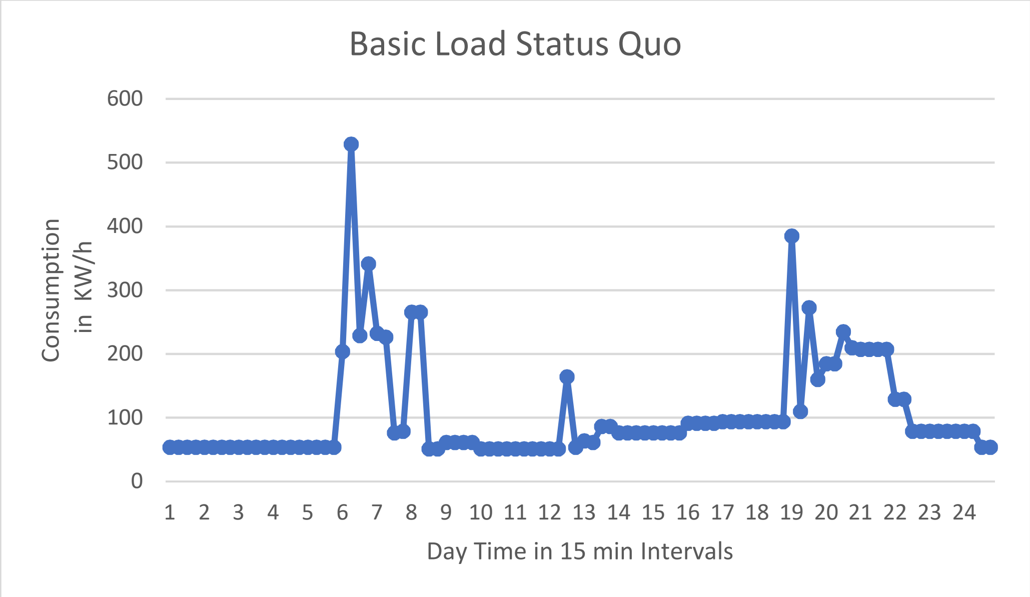

Figure 44 Basic Load Status Quo

Standard Restrictive Load Profile with Gas For Cooking

Appliance	Consumption Used For Calculation (Wh)	Work Hours per Day	Quantity	Total Energy Consumption Wh/day
Frontyard Lighting	23	4,5	1	103,5
Backyard Lighting	23	4,5	1	103,5
Kitchen Lighting	13	3	1	39
LivingRoom Lighting	13	3	3	117
DinningRoom Lighting	23	2,75	1	63,25
BathRoom Lighting	13	1,5	1	19,5
Fan (Portable)	50	4,5	2	450
Radio	40	4	1	160
30" LCD TV	60	6	1	360
DVB Digital receiver	25	24	1	600
Game Console/ DVD Player	180	3	1	540
Mobile phone charger	6	3,25	4	78
Tablet Computer	10	5,25	1	52,5
American-style Fridge Freezer	180	24	1	4320
Blender	450	0,75	1	337,5
Bread toaster	900	0,5	1	450
Coffee Machine	1000	0,25	1	250
14-15" Laptop Computer	70	5	1	350
Inkjet Printer	30	0,25	1	7,5
Projector	270	1	1	270
Scanner	18	0,25	1	4,5
Curling Iron	35	0,25	1	8,75
Electric iron	1100	0,5	1	550
Clothes Washing machine	800	0,5	1	400
Water Pump	746	0,5	1	373
ADSL / Wifi router	10	9	1	90
				10097,5

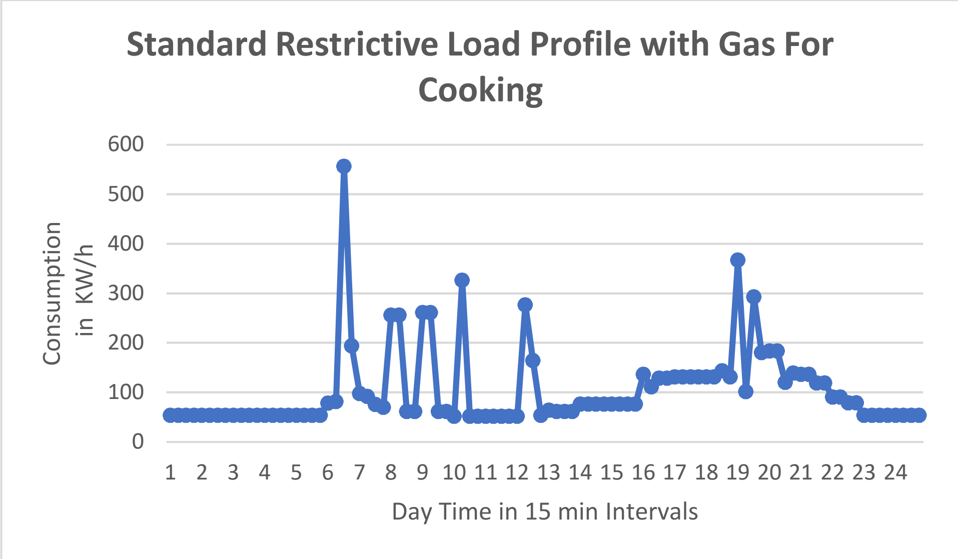

Figure 45Standard Restrictive Load Profile with Gas For Cooking

Standard Restrictive Load Profile with Electric Cooking Appliances Load Profile

Appliance	Consumption Used For Calculation (Wh)	Work Hours per Day	Quantity	Total Energy Consumption Wh/day
Frontyard Lighting	23	4,5	1	103,5
Backyard Lighting	23	4,5	1	103,5
Kitchen Lighting	13	3	1	39
LivingRoom Lighting	13	3	3	117
DinningRoom Lighting	23	2,75	1	63,25
BathRoom Lighting	13	1,5	1	19,5
Fan (Portable)	50	9,5	2	950
Radio	40	4	1	160
30" LCD TV	60	6	1	360
DVB Digital receiver	25	24	1	600
Game Console/ DVD Player	180	3	1	540
Mobile phone charger	6	3,25	4	78
Tablet Computer	10	5,25	1	52,5
American-style Fridge Freezer	180	24	1	4320
Blender	450	0,75	1	337,5
Bread toaster	900	0,5	1	450
Coffee Machine	1000	0,25	1	250
Electric stove / Cooktop (Medium)	1500	3	1	4500
Microwave	1200	0,5	1	600
14-15" Laptop Computer	70	5	1	350
Inkjet Printer	30	0,25	1	7,5
Projector	270	1	1	270
Scanner	18	0,25	1	4,5
Curling Iron	35	0,25	1	8,75
Electric iron	1100	0,5	1	550
Clothes Washing machine	800	0,5	1	400
Water Pump	746	0,5	1	373
ADSL / Wifi router	10	9	1	90
				15697,5

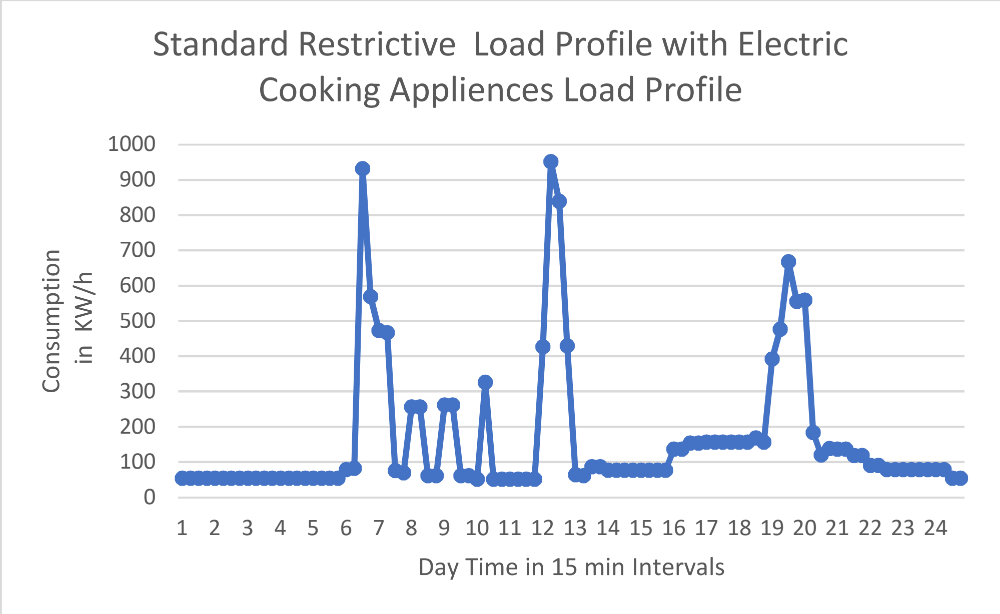

Figure 46 Standard Restrictive Load Profile with Electric Cooking Appliences Load Profile

Standard Load Profile

Appliance	Consumption Used For Calculation (Wh)	Work Hours per Day	Quantity	Total Energy Consumption Wh/day
Frontyard Lighting	23	4,5	1	103,5
Backyard Lighting	23	4,5	1	103,5
Kitchen Lighting	13	3	1	39
LivingRoom Lighting	13	3	3	117
DinningRoom Lighting	23	2,75	1	63,25
BathRoom Lighting	13	1,5	1	19,5
Fan (Ceiling)	75	3,5	2	525
Fan (Portable)	50	9,5	1	475
Radio	40	2	1	80
30" LCD TV	60	9,5	1	570
DVB Digital receiver	25	24	1	600
Reader-CD / DVD Player	60	3	1	180
Game Console	180	3	1	540
Mobile phone charger	6	3,25	4	78
Tablet Computer	10	5,25	1	52,5
American-style Fridge Freezer	180	24	1	4320
Air extractor (bell)	500	5,5	1	2750
Blender	450	0,75	1	337,5
Bread toaster	900	0,5	1	450
Coffee Machine	1000	0,25	1	250
Electric stove / Cooktop (Medium)	1500	3	1	4500
Microwave	1200	0,5	1	600
14-15" Laptop Computer	70	5	1	350
Desktop Computer (Standard)	200	3	1	600
Inkjet Printer	30	0,25	1	7,5
Projector	270	1	1	270
Scanner	18	0,25	1	4,5
Curling Iron	35	0,25	1	8,75
Electric iron	1100	0,5	1	550
Electric Shaver	20	0,25	1	5
Hair Dryer	1500	0,25	1	375
Drill - 1/2"	750	0,25	1	187,5
Hedge Trimmer	450	0,25	1	112,5
Strimmer	500	0,5	1	250
Weed Eater	500	0,5	1	250
Clothes Washing machine	800	0,5	1	400
Water Pump	746	0,5	1	373

ADSL / Wifi router	10	9	1	90
				20587,5

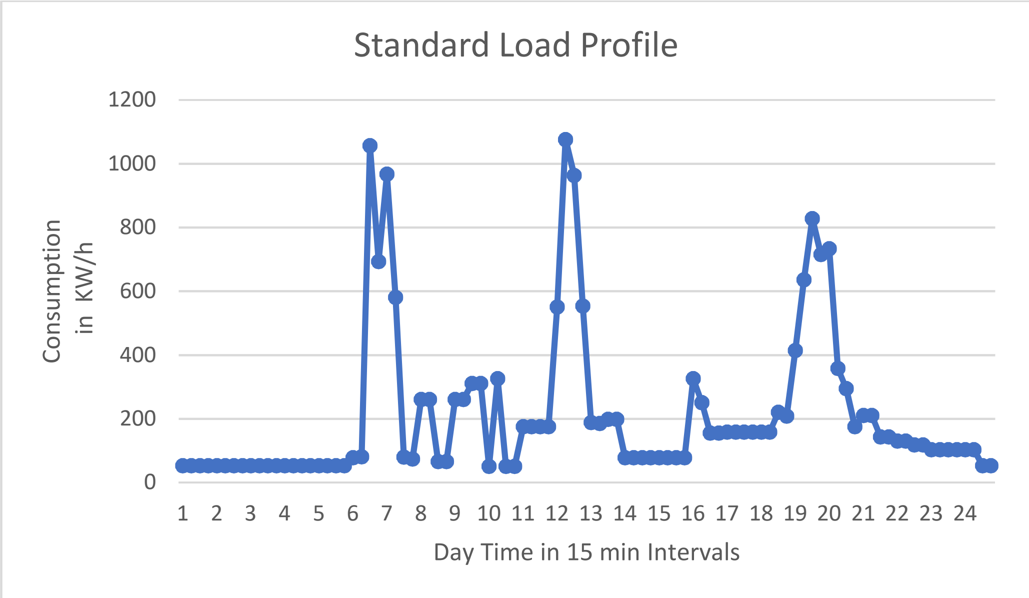

Figure 47 Standard Load Profile

Standard Appliances High Load Profile

Appliance	Consumption Used For Calculation (Wh)	Work Hours per Day	Quantity	Total Energy Consumption Wh/day
Frontyard Lighting LED Bulb - 100 Watt Equivalent	23	4,5	1	103,5
Backyard Lighting LED Bulb - 100 Watt Equivalent	23	4,5	1	103,5
Kitchen Lighting	13	3	1	39
LivingRoom Lighting	13	3	3	117
DinningRoom Lighting	23	2,75	1	63,25
BathRoom Lighting	13	1,5	1	19,5
Window Air Conditioner 12,000 BTU NA	1200	6,25	1	7500
Fan (Portable)	50	9,5	2	950
Radio	40	2	1	80
42" LED TV	50	9,5	1	475
DVB Digital receiver	25	24	1	600
DVD Player	60	3	1	180
Game Console	180	3	1	540
Mobile phone charger	6	3,25	4	78
Tablet Computer	10	5,25	1	52,5
American-style Fridge Freezer	180	24	1	4320
Air extractor (bell)	500	5,5	1	2750
Blender	450	0,75	1	337,5
Bread toaster	900	0,5	1	450
Coffee Machine	1000	0,25	1	250
Electric stove / Cooktop (Medium)	1500	2,5	1	3750
Microwave	1200	0,5	1	600
Microwave oven	2000	0,5	1	1000
Kettle - Electric	1200	0,5	1	600
14-15" Laptop Computer	70	5	1	350
Desktop Computer (Standard)	200	3	1	600
Inkjet Printer	30	0,25	1	7,5
Projector	270	1	1	270
Scanner	18	0,25	1	4,5
Curling Iron	35	0,25	1	8,75
Electric iron	1100	0,5	1	550
Electric Shaver	20	0,25	1	5
Hair Dryer	1500	0,25	1	375
Drill - 1/2"	750	0,25	1	187,5
Hedge Trimmer	450	0,25	1	112,5
Strimmer	500	0,5	1	250
Vacuum cleaner	1400	0,5	1	700

Clothes Washing machine	800	0,5	1	400
Water Pump	746	0,5	1	373
ADSL / Wifi router	10	9	1	90
				29242,5

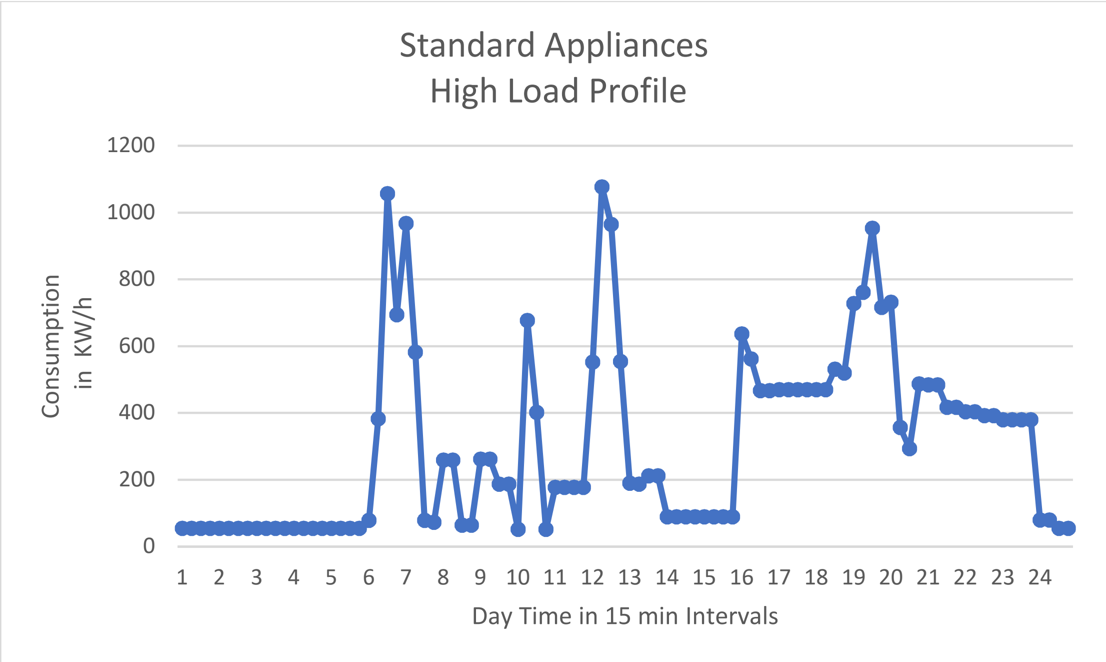

Figure 48 Standard Appliances

High Load Restrictive with Gas for Heating

Appliance	Consumption Used For Calculation (Wh)	Work Hours per Day	Quantity	Total Energy Consumption Wh/day
Frontyard Lighting	23	4,5	1	103,5
Backyard Lighting	23	4,5	1	103,5
Kitchen Lighting	13	3	1	39
LivingRoom Lighting	13	3	3	117
DinningRoom Lighting	13	2,75	1	35,75
BathRoom Lighting	13	1,5	1	19,5
Window Air Conditioner 12,000 BTU NA	1200	6,75	1	8100
Fan (Ceiling)	75	3,5	2	525
Fan (Portable)	50	9,5	1	475
Radio	40	2	1	80
50" LED TV	100	9,5	1	950
DVB Digital receiver	25	24	1	600
Reader-CD / DVD Player	30	3	1	90
DVD Player	60	3	1	180
Game Console	180	3	1	540
Mobile phone charger	6	3,25	4	78
Tablet Computer	10	5,25	1	52,5
American-style Fridge Freezer	180	24	1	4320
Air extractor (bell)	500	0,75	1	375
Blender	450	0,75	1	337,5
Bottle warmers	330	0,25	1	82,5
Bread toaster	900	0,25	1	225
Coffee Machine	1000	0,5	1	500
Dishwasher	1800	1	1	1800
Electric can opener	60	0,5	1	30
Electric Stove (Small)	1000	3	1	3000
Electric stove / Cooktop (Medium)	1500	3	1	4500
Microwave	1200	0,5	1	600
Microwave oven	2000	0,75	1	1500
Pressure Cooker	700	0,5	1	350
Rice Cooker	500	0,5	1	250
Kettle - Electric	1200	0,5	1	600
14-15" Laptop Computer	70	5	1	350
Desktop Computer (Standard)	200	3	1	600
Inkjet Printer	30	0,25	1	7,5
Projector	270	1	1	270
Scanner	18	0,25	1	4,5
Clothes Dryer - Electric	3000	3	1	9000

Curling Iron	35	0,25	1	8,75
Electric iron	1100	0,5	1	550
Electric Shaver	20	0,25	1	5
Hair Dryer	1500	0,25	1	375
9" disc sander	1200	0,25	1	300
Chain Saw - 12"	1100	0,25	1	275
Drill - 1/2"	750	0,25	1	187,5
Hedge Trimmer	450	0,25	1	112,5
Lawnmower	1400	0,25	1	350
Strimmer	500	0,5	1	250
Weed Eater	500	0,5	1	250
Electric blanket	180	1	1	180
Humidifier	26	0,5	1	13
Sewing machine	125	0,25	1	31,25
Vacuum cleaner	1400	0,5	1	700
Clothes Washing machine	800	0,5	1	400
Water Pump	746	0,5	1	373
ADSL / Wifi router	10	9	1	90
				45241,75

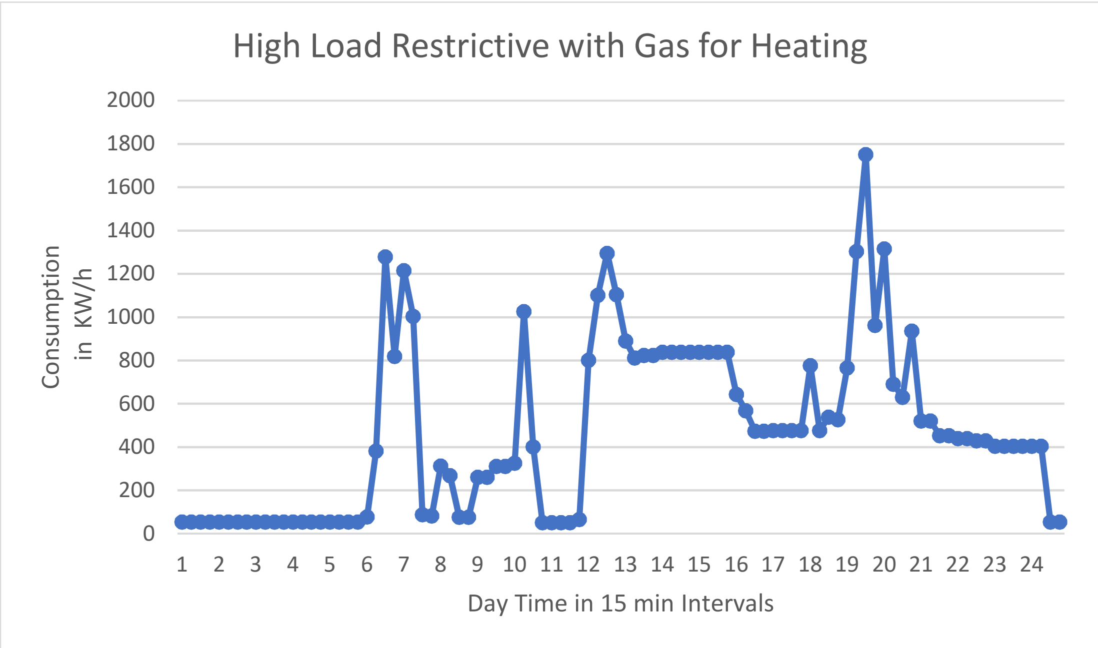

Figure 49 High Load Restrictive with Gas for Heating

HLP Using Gas for cooking

Appliance	Consumption Used For Calculation (Wh)	Work Hours per Day	Quantity	Total Energy Consumption Wh/day
Frontyard Lighting	23	4,5	1	103,5
Backyard Lighting	23	4,5	1	103,5
Kitchen Lighting	13	3	1	39
LivingRoom Lighting	13	3	3	117
DinningRoom Lighting	13	2,75	1	35,75
BathRoom Lighting	13	1,5	1	19,5
Window Air Conditioner 12,000 BTU NA	1200	6,75	1	0
Fan (Ceiling)	75	3,5	2	525
Fan (Portable)	50	9,5	1	475
Heater (resistors)	1500	9	1	0
Radio	40	2	1	80
50" LED TV	100	9,5	1	950
DVB Digital receiver	25	24	1	600
Reader-CD / DVD Player	30	3	1	90
DVD Player	60	3	1	180
Game Console	180	3	1	540
Mobile phone charger	6	3,25	4	78
Tablet Computer	10	5,25	1	52,5
American-style Fridge Freezer	180	24	1	4320
Air extractor (bell)	500	0,75	1	375
Blender	450	0,75	1	337,5
Bottle warmers	330	0,25	1	82,5
Bread toaster	900	0,25	1	225
Coffee Machine	1000	0,5	1	500
Dishwasher	1800	1	1	0
Electric can opener	60	0,5	1	30
Kettle - Electric	1200	0,5	1	600
14-15" Laptop Computer	70	5	1	350
Desktop Computer (Standard)	200	3	1	600
Inkjet Printer	30	0,25	1	7,5
Projector	270	1	1	270
Scanner	18	0,25	1	4,5
Clothes Dryer - Electric	3000	3	1	9000
Curling Iron	35	0,25	1	8,75
Electric iron	1100	0,5	1	550
Electric Shaver	20	0,25	1	5
Hair Dryer	1500	0,25	1	375
9" disc sander	1200	0,25	1	300
Chain Saw - 12"	1100	0,25	1	275

Drill - 1/2"	750	0,25	1	187,5
Hedge Trimmer	450	0,25	1	112,5
Lawnmower	1400	0,25	1	350
Strimmer	500	0,5	1	250
Weed Eater	500	0,5	1	250
Electric blanket	180	1	1	180
Humidifier	26	0,5	1	13
Sewing machine	125	0,25	1	31,25
Vacuum cleaner	1400	0,5	1	700
Clothes Washing machine	800	0,5	1	400
Water Pump	746	0,5	1	373
ADSL / Wifi router	10	9	1	90
				25141,75

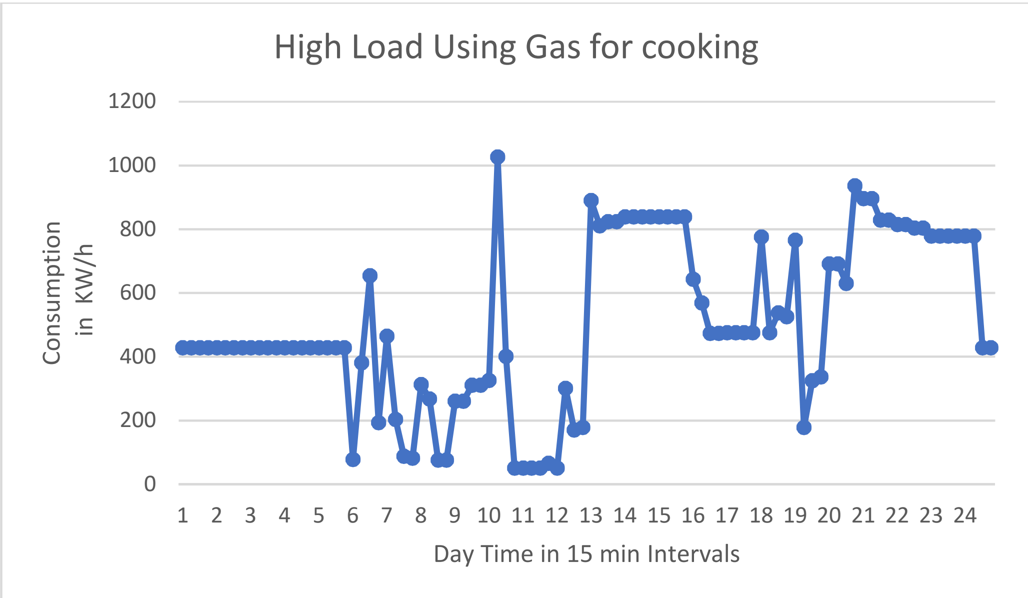

Figure 50 High Load Using Gas for Cooking

HLP Restrictive (Mexican Mean)

Appliance	Consumption Used For Calculation (Wh)	Work Hours per Day	Quantity	Total Energy Consumption Wh/day
Frontyard Lighting	23	4,5	1	103,5
Backyard Lighting	23	4,5	1	103,5
Kitchen Lighting	13	3	1	39
LivingRoom Lighting	13	3	3	117
DinningRoom Lighting	13	2,75	1	35,75
BathRoom Lighting	13	1,5	1	19,5
Window Air Conditioner 12,000 BTU NA	1200	6,75	1	8100
Fan (Ceiling)	75	3,5	2	525
Fan (Portable)	50	9,5	1	475
Radio	40	2	1	80
50" LED TV	100	9,5	1	950
DVB Digital receiver	25	24	1	600
Reader-CD / DVD Player	30	3	1	90
DVD Player	60	3	1	180
Game Console	180	3	1	540
Mobile phone charger	6	3,25	4	78
Tablet Computer	10	5,25	1	52,5
American-style Fridge Freezer	180	24	1	4320
Air extractor (bell)	500	0,75	1	375
Blender	450	0,75	1	337,5
Bottle warmers	330	0,25	1	82,5
Bread toaster	900	0,25	1	225
Coffee Machine	1000	0,5	1	500
Electric can opener	60	0,5	1	30
Electric stove / Cooktop (Medium)	1500	3	1	4500
Microwave	1200	0,5	1	600
Microwave oven	2000	0,75	1	1500
Pressure Cooker	700	0,5	1	350
Rice Cooker	500	0,5	1	250
Kettle - Electric	1200	0,5	1	600
14-15" Laptop Computer	70	5	1	350
Desktop Computer (Standard)	200	3	1	600
Inkjet Printer	30	0,25	1	7,5
Projector	270	1	1	270
Scanner	18	0,25	1	4,5
Curling Iron	35	0,25	1	8,75
Electric iron	1100	0,5	1	550
Electric Shaver	20	0,25	1	5

Hair Dryer	1500	0,25	1	375
9" disc sander	1200	0,25	1	300
Chain Saw - 12"	1100	0,25	1	275
Drill - 1/2"	750	0,25	1	187,5
Hedge Trimmer	450	0,25	1	112,5
Lawnmower	1400	0,25	1	350
Strimmer	500	0,5	1	250
Weed Eater	500	0,5	1	250
Electric blanket	180	1	1	180
Humidifier	26	0,5	1	13
Sewing machine	125	0,25	1	31,25
Vacuum cleaner	1400	0,5	1	700
Clothes Washing machine	800	0,5	1	400
Water Pump	746	0,5	1	373
ADSL / Wifi router	10	9	1	90
				31441,75

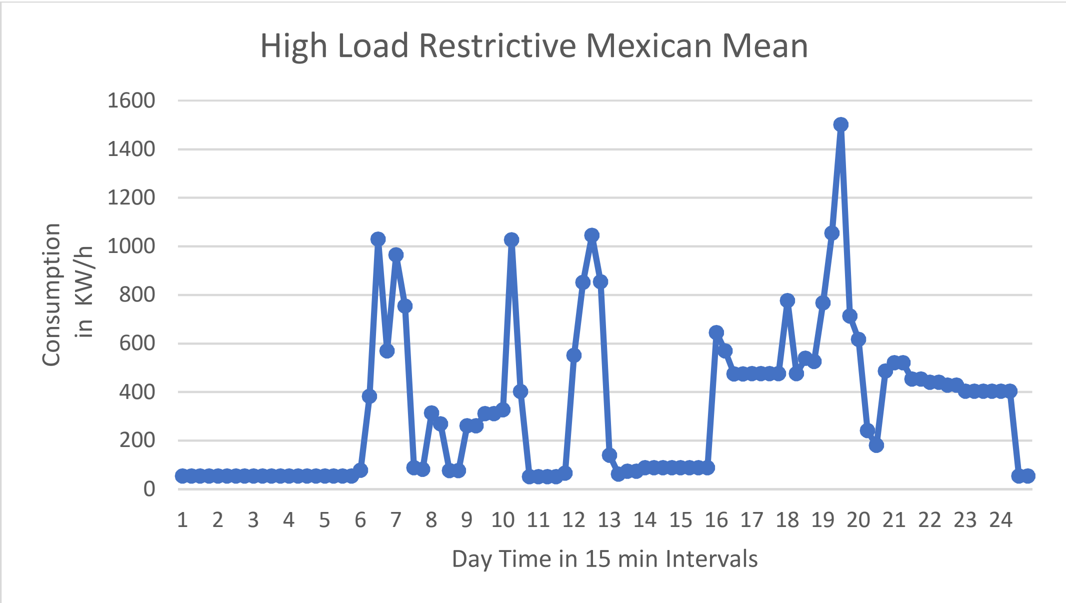

Figure 51High Load Restrictive Mexican Mean

HLP Using Gas For Cooking and Heating Restrictive

Appliance	Consumption Used For Calculation (Wh)	Work Hours per Day	Quantity	Total Energy Consumption Wh/day
Frontyard Lighting	23	4,5	1	103,5
Backyard Lighting	23	4,5	1	103,5
Kitchen Lighting	13	3	1	39
LivingRoom Lighting	13	3	3	117
DinningRoom Lighting	13	2,75	1	35,75
BathRoom Lighting	13	1,5	1	19,5
Window Air Conditioner 12,000 BTU NA	1200	6,75	1	8100
Fan (Ceiling)	75	3,5	2	525
Fan (Portable)	50	9,5	1	475
Radio	40	2	1	80
50" LED TV	100	9,5	1	950
DVB Digital receiver	25	24	1	600
Reader-CD / DVD Player	30	3	1	90
DVD Player	60	3	1	180
Game Console	180	3	1	540
Mobile phone charger	6	3,25	4	78
Tablet Computer	10	5,25	1	52,5
American-style Fridge Freezer	180	24	1	4320
Air extractor (bell)	500	0,75	1	375
Blender	450	0,75	1	337,5
Bottle warmers	330	0,25	1	82,5
Bread toaster	900	0,25	1	225
Coffee Machine	1000	0,5	1	500
Dishwasher	1800	1	1	1800
Electric can opener	60	0,5	1	30
Kettle - Electric	1200	0,5	1	600
14-15" Laptop Computer	70	5	1	350
Desktop Computer (Standard)	200	3	1	600
Inkjet Printer	30	0,25	1	7,5
Projector	270	1	1	270
Scanner	18	0,25	1	4,5
Clothes Dryer - Electric	3000	3	1	9000
Curling Iron	35	0,25	1	8,75
Electric iron	1100	0,5	1	550
Electric Shaver	20	0,25	1	5
Hair Dryer	1500	0,25	1	375
9" disc sander	1200	0,25	1	300
Chain Saw - 12"	1100	0,25	1	275
Drill - 1/2"	750	0,25	1	187,5

Hedge Trimmer	450	0,25	1	112,5
Lawnmower	1400	0,25	1	350
Strimmer	500	0,5	1	250
Weed Eater	500	0,5	1	250
Electric blanket	180	1	1	180
Humidifier	26	0,5	1	13
Sewing machine	125	0,25	1	31,25
Vacuum cleaner	1400	0,5	1	700
Clothes Washing machine	800	0,5	1	400
Water Pump	746	0,5	1	373
ADSL / Wifi router	10	9	1	90
				35041,75

III. Appendix III Irradiation values per day

In this appendix it is possible to find the general meteorological data perceived in the region and one representative day of each month of the year. All the information was generated by using the PvSyst generation tool (version 6.79).

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Hourly meteorological data

Meteo data : **San pedro de honor;NREL NSRDB Typ. Met. Year PSMv3_1998 to 2016;Sintético**

File San Pedro de Honor_NREL_SYN.MET of 13/06/19 12h53

Situation Latitude 22.36° N Longitude -105.17° W

Time defined as Legal Time Time zone UT-7 Altitude 932 m

Source file characteristics Synthetic Data generation

Monthly Meteo Values Source San Pedro de Honor_NREL_TMY.SIT -- NREL NSRDB Typ. Met.

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Year	
Hor. global	142.1	160.2	209.7	225.4	234.7	174.5	178.0	174.3	144.0	162.4	150.3	135.9	2091.5	kWh/m².mth
Hor. diffuse	39.6	34.1	48.1	55.3	62.9	70.9	87.4	76.3	76.9	52.3	32.3	31.6	667.7	kWh/m².mth
Extraterrestrial	221.9	232.6	294.4	314.9	340.6	333.3	341.9	330.8	296.2	269.9	223.9	210.7	3411.0	kWh/m².mth
Clearness Index	0.640	0.689	0.712	0.716	0.689	0.524	0.521	0.527	0.486	0.602	0.671	0.645	0.613	
Amb. temper.	19.6	21.1	21.9	23.0	25.1	25.3	24.9	24.3	23.7	23.2	21.7	20.4	22.8	°C
Wind velocity	4.2	4.1	4.8	7.1	5.7	6.7	6.5	5.7	5.7	5.4	6.1	4.2	5.5	m/s

Figure 52 Hourly Meteorological Data in San Pedro de Honor

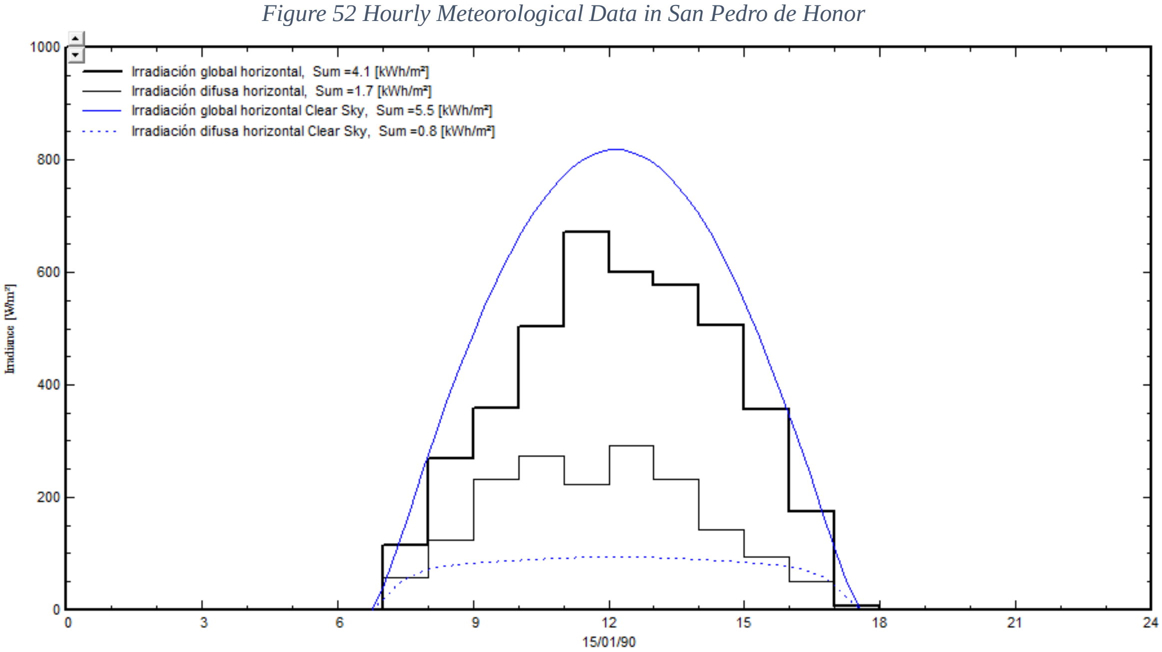

Figure 53 Representative Irradiation values in the locality (January)

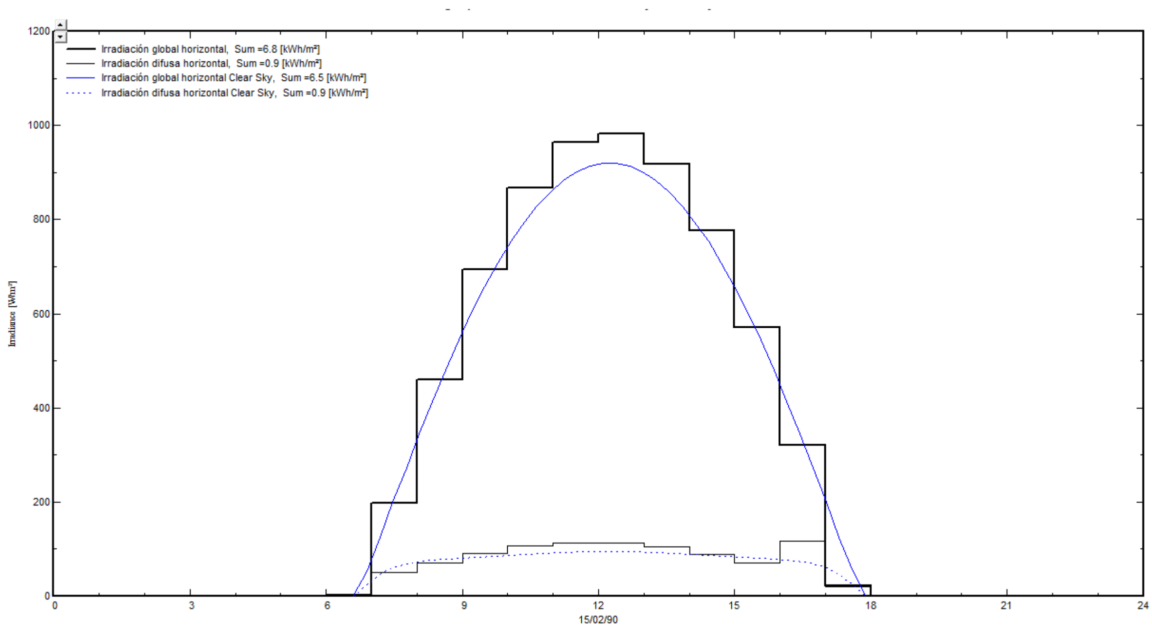

Figure 54Representative Irradiation values in the locality (February)

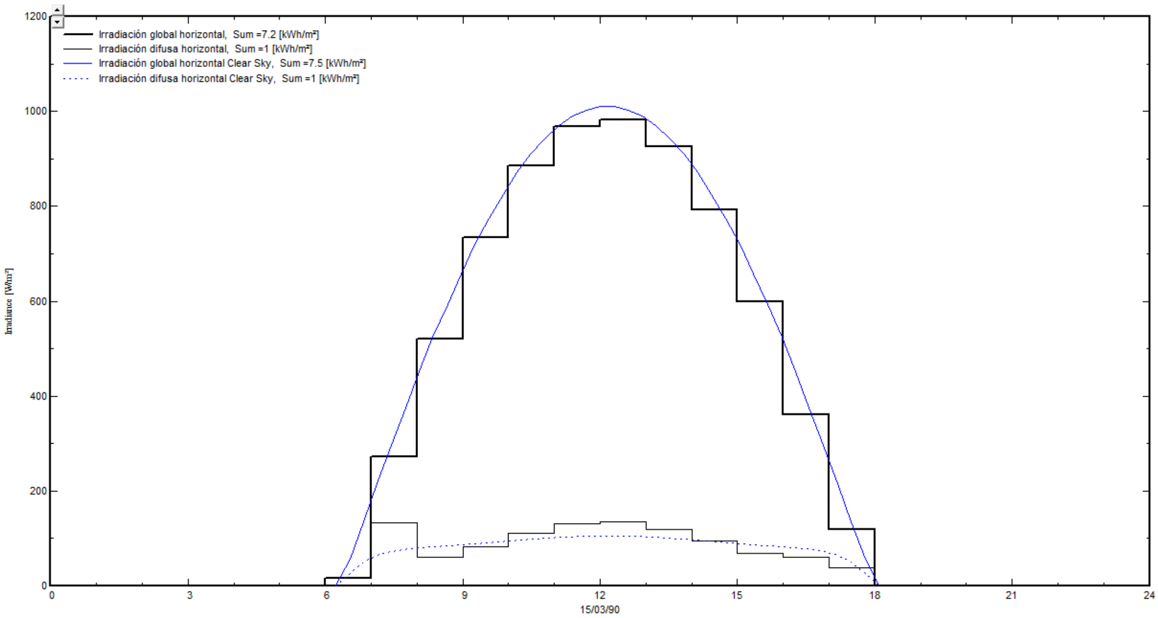

Figure 55Representative Irradiation values in the locality (March)

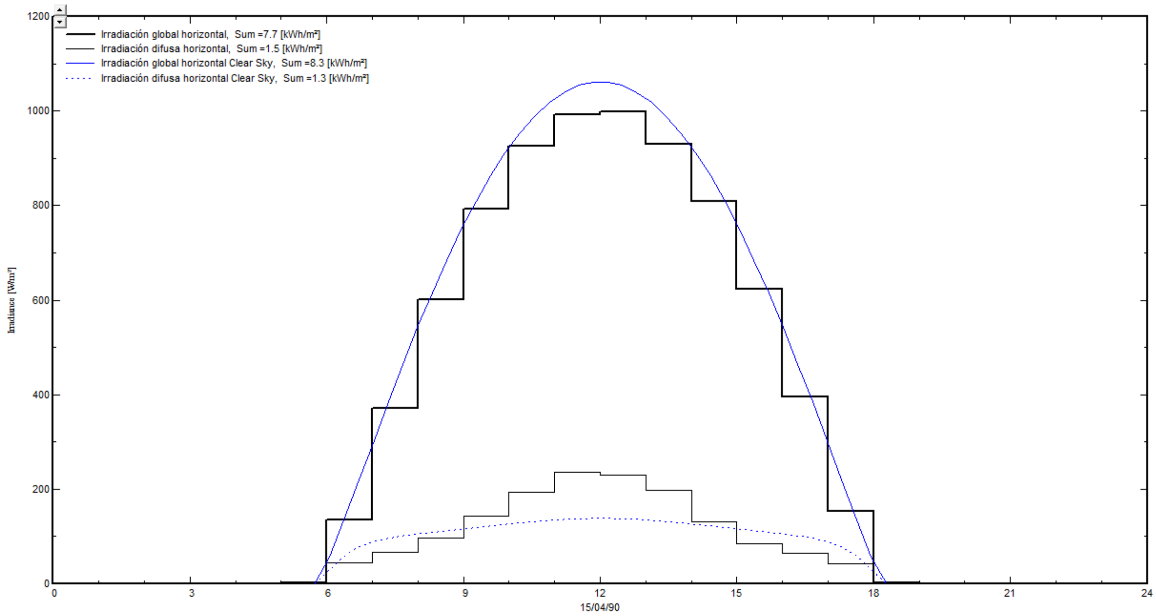

Figure 5634Representative Irradiation values in the locality (April)

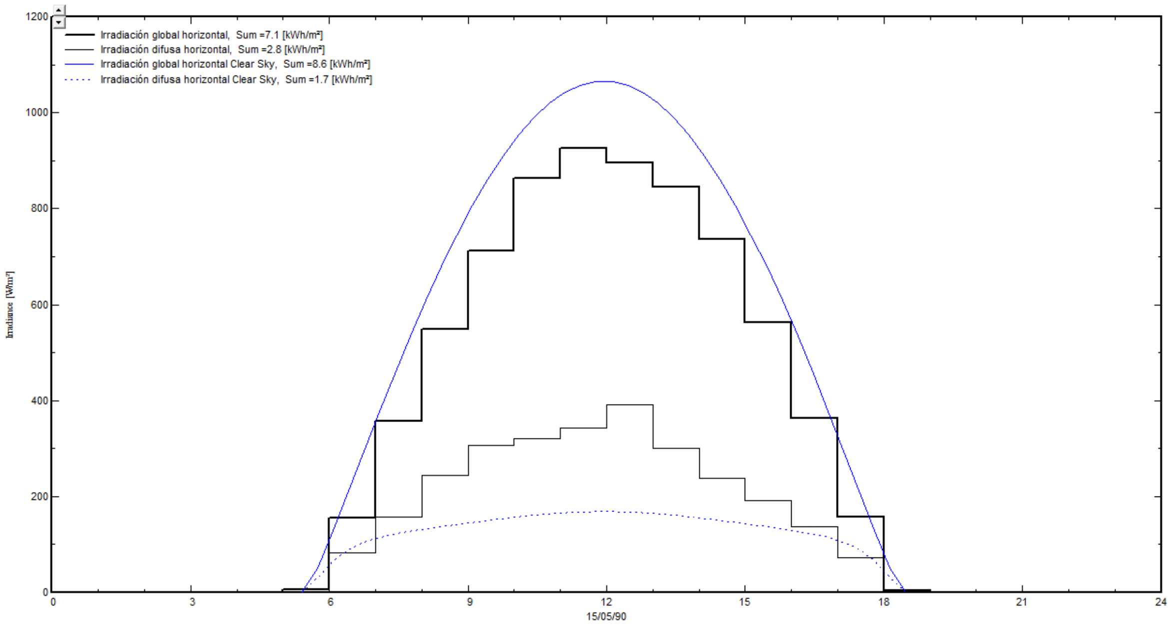

Figure 5734Representative Irradiation values in the locality (May)

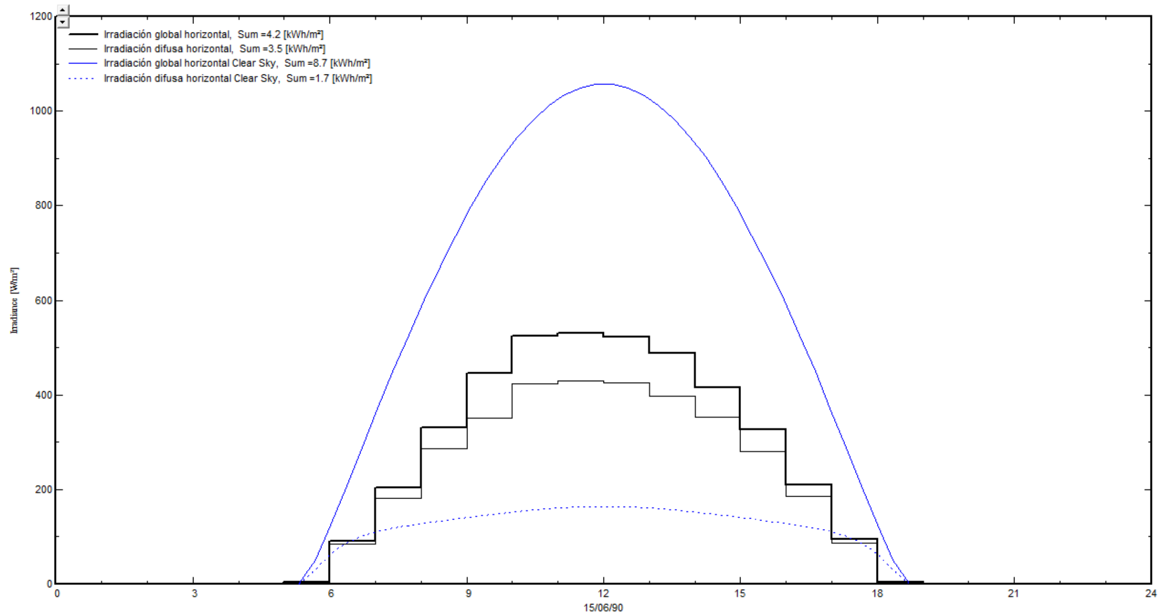

Figure 5834Representative Irradiation values in the locality (June)

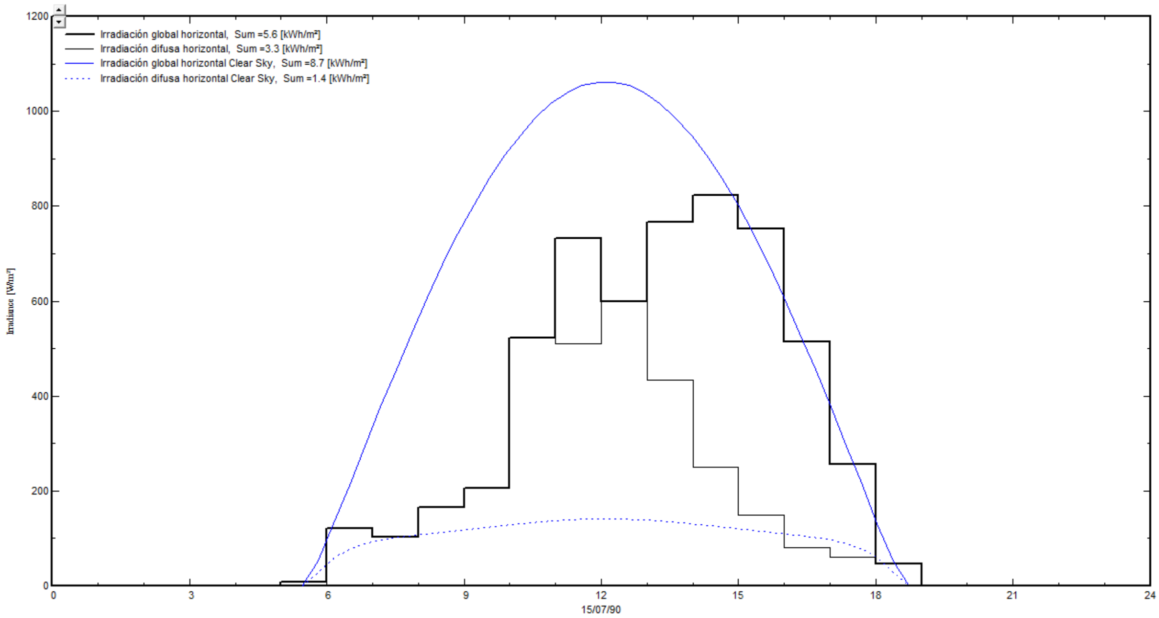

Figure 5934Representative Irradiation values in the locality (July)

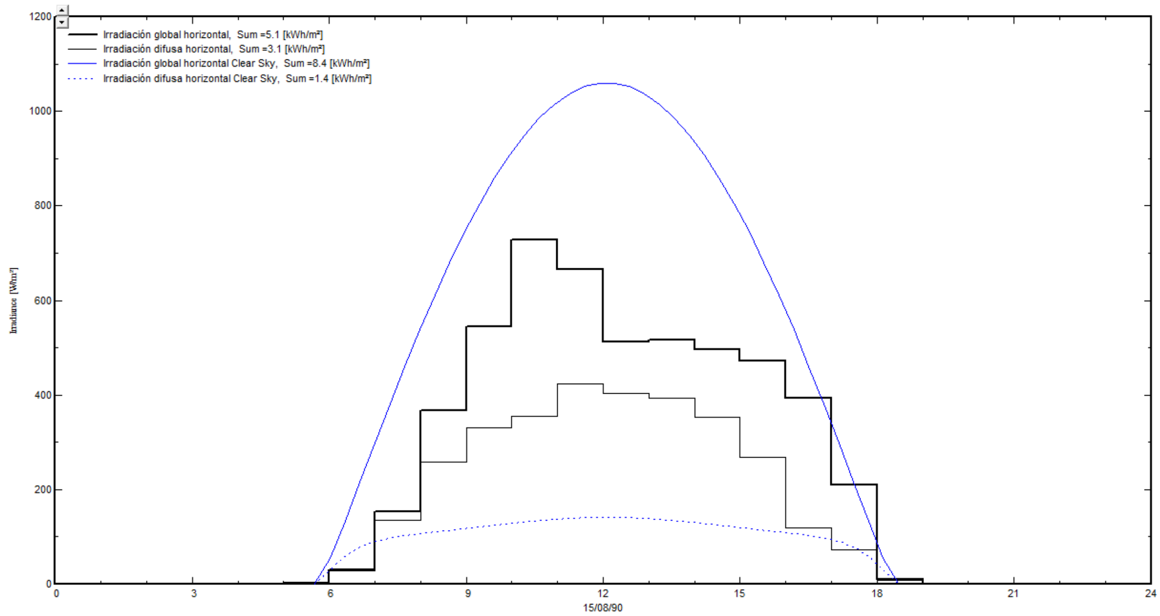

Figure 6034Representative Irradiation values in the locality (August)

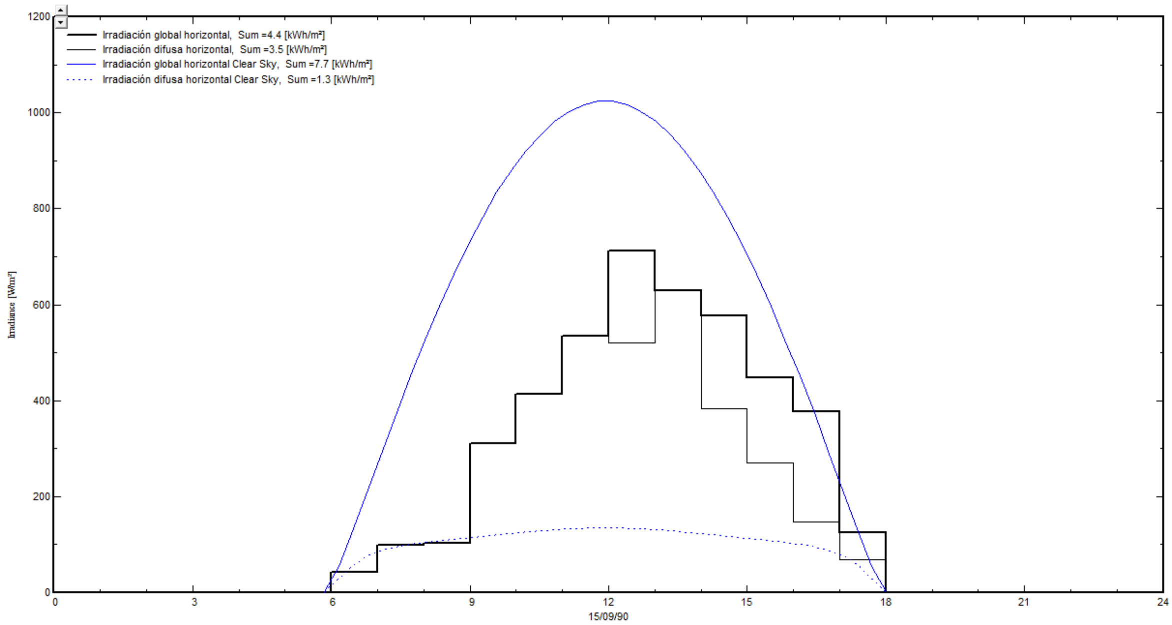

Figure 6134Representative Irradiation values in the locality (September)

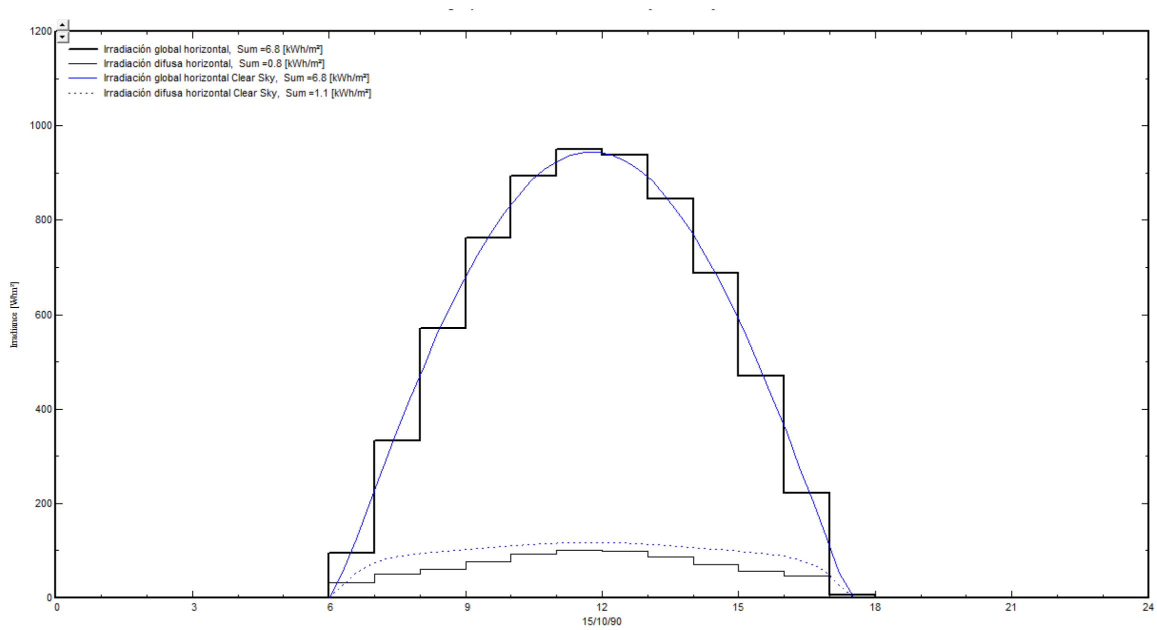

Figure 6234Representative Irradiation values in the locality (October)

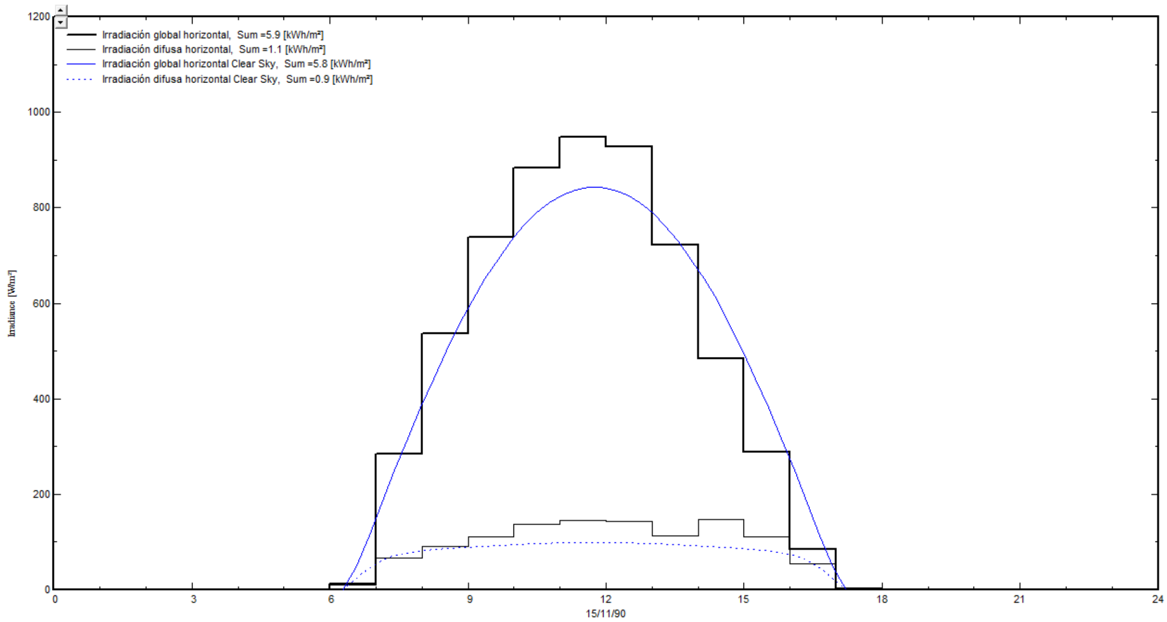

Figure 6334Representative Irradiation values in the locality (November)

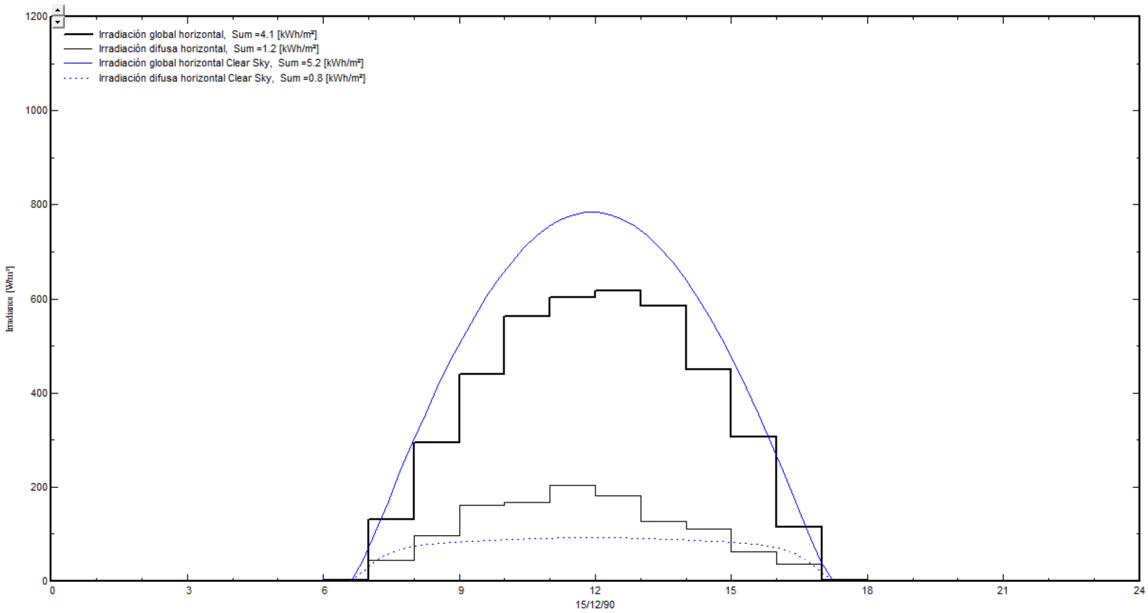

Figure 6434Representative Irradiation values in the locality (December)

IV. Appendix IV: Main grid distribution network in Mexico and it cost tariff by Region

In this section the most relevant information regarding the Mexican electric Cost tariff is displayed:

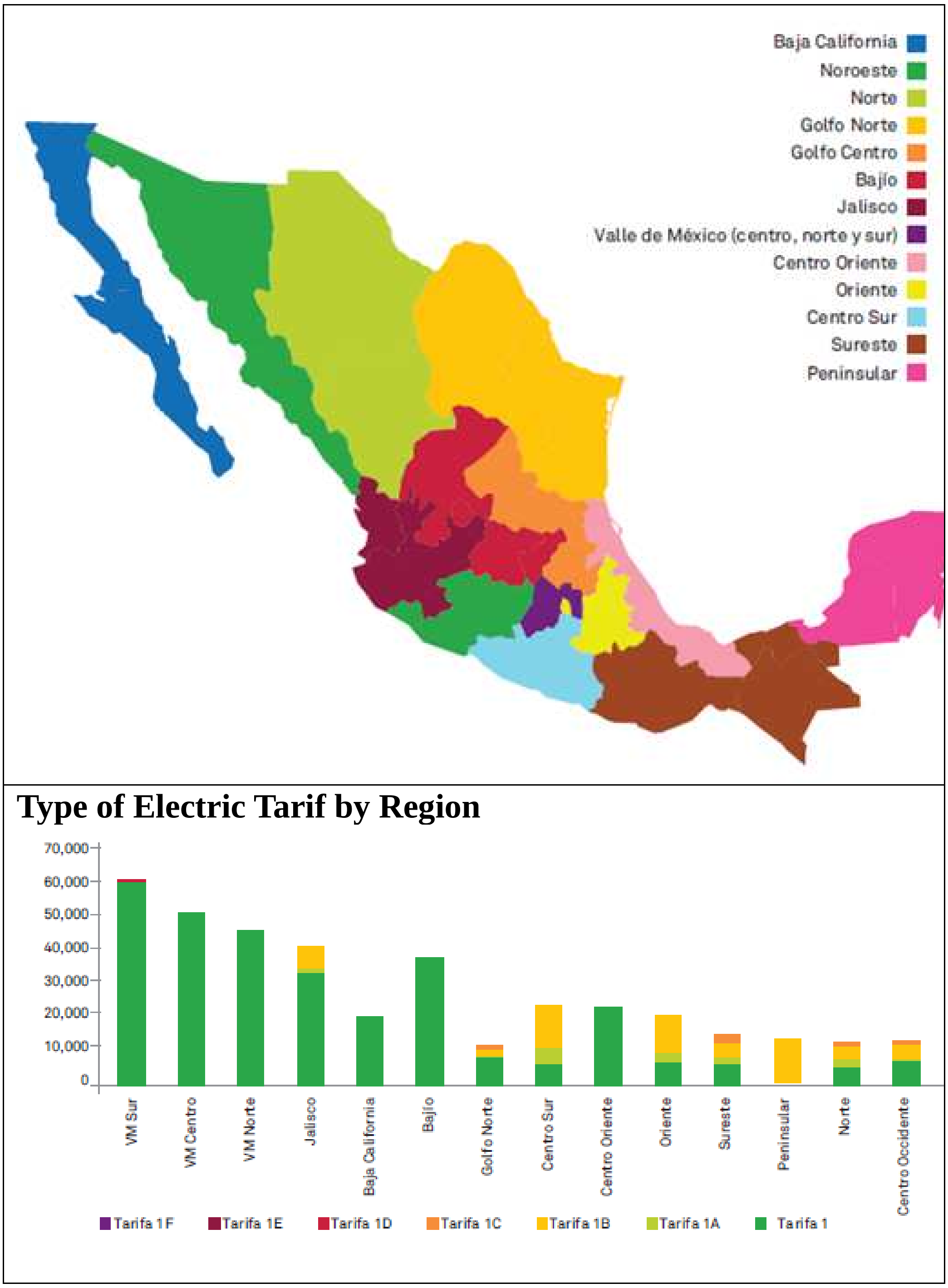

Figure 65 Main grid distribution network in Mexico and it cost tariff by Region (Source: ABM, 2017)

Type of Cost Tariff	1	1A	1B	1C	1D	1E	1F
Minimum temperature during summer	Rest of the localities	25ºC	28ºC	30ºC	31ºC	32ºC	33ºC

Table 21 Structure of electricity rates in the residential sector
(Source: ABM, 2017)

Type of Tariff	1	1A	1B	1C	1D	1E	1F
High consumption limit (kWh)	250	300	400	850	1,000	2,000	2,500

Table 22 Limits of high monthly consumption by electricity rates, 2016
(Source: ABM, 2017)