escola superior de tecnologia e gestão
instituto politécnico de leiria

Dissertation

Master in Electrical Engineering

# *Aproveitamento de Fontes Renováveis em Redes Isoladas*

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Leiria, *October of 2017*

Dissertation

Master in Electrical Engineering

# *Exploration of renewable sources for isolated systems*

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Leiria, *October of 2017*

# Dedication

I dedicate my dissertation work to my parents, Alejandro and Carmelina, for their love, endless support and encouragement. My brothers and sisters, Eliza, Cristy, Pepo and Vini, who have been a constant source of support and encouragement during the challenges of education and life. *I am truly thankful for having them in my life*.

I also dedicate this work to my family and many friends, who have supported me throughout the process. *I will always appreciate all they have done*.

# Acknowledgements

I would like to acknowledge all the people who contributed in the development of this research work. First and foremost, I thank my academic advisors, Dr. Pedro Marques and Dr. Ismael Minchala, for the continuous guidance, support, and motivation.

Additionally, I would like to thank the economic and institutional support provided by the co-financed scholarship program "Senescyt-Polytechnic Institute of Leiria", as well as the support provided by the University of Cuenca, Ecuador.

# Resumo

Fornecer acesso universal à eletricidade é uma prioridade global. As fontes de energia renovável (FER) desempenham um papel importante no fornecimento de energia para áreas rurais e remotas, onde a eletricidade através da rede não é viável ou o custo da extensão da rede é grande. Comunidades isoladas na região amazônica do Equador caracterizam-se por estarem muito distantes umas das outras, constituídas por casas dispersas, têm uma densidade populacional muito baixa e cercadas por vegetação densa. Alcançar essas comunidades é feito através de estradas pequenas, acesso por rios, em alguns casos, através de pequenos aviões. Portanto, implementar linhas de transmissão e distribuição para fornecer energia é dispendiosa e prejudicial para o meio ambiente. Assim, o uso de FER representa uma oportunidade brilhante para fins de geração de energia. Os Sistemas Domésticos Fotovoltaicos (SDFV) são tipicamente utilizados para fornecer eletricidade para casas em comunidades rurais não conectadas à rede. No entanto, os Sistemas Centralizados Fotovoltaicos (SCFV) com sua própria rede de distribuição de baixa tensão (RDBT) também estão sendo considerados como uma alternativa para eletrificação rural.

Esta tese apresenta uma revisão exaustiva sobre o uso de FER para geração elétrica, fornecendo as principais características desta tecnologia, classificação e diagramas esquemáticos de sistemas híbridos (SH), a fim de satisfazer a demanda de energia para um ou um grupo de casas nas áreas rurais. Esta pesquisa também analisa duas opções de fornecimento de energia para fornecer eletricidade à comunidade rural Yuwints na Amazônia equatoriana. O sistema mais adequado é selecionado após uma comparação do valor presente líquido (VPL) de vários sistemas de energia renovável, por exemplo, PV-Battery systems, Wind-battery systems, PV-Wind-battery systems, etc. A análise técnico-econômica é realizada através do software de otimização de microrede Homer Energy. O resultado do presente estudo propõe o SCFV como a melhor opção de energia elétrica para a comunidade, permitindo uma cobertura completa da carga e garantindo uma operação segura do sistema.

*Palavras chave: Sistema Centralizado Fotovoltaico, Sistema Híbrido, Sistemas Doméstico Fotovoltaico, Fontes de Energia Renováveis*

# Abstract

Providing universal access to electricity is a priority worldwide. Renewable Energy Sources (RES) play an important role in the supply of energy to rural and remote areas, where grid electricity is not available, or the cost of the grid extension is excessively. Isolated communities in the Amazon region of Ecuador are frequently far away from each other, formed by scattered housing, exhibit very low population density, and are surrounded by dense vegetation. Supplying such communities is typically done through small paths, fluvial access, and in few cases through small planes. Therefore, implementing transmission and distribution lines for supplying energy is costly and harmful to the environment. Hence, the use of RES represents a crucial opportunity for power generation purposes. Photovoltaic Home Systems (PVHS) are typically used to provide electricity to the dwellings in off-grid rural communities. However, Centralized Photovoltaic Systems (CPVS) with their own low voltage distribution network (LVDN) is also being considered as an alternative for rural electrification.

This thesis presents a comprehensive review on the use of RES for electricity, by providing the main features of this technology, classification, and schematic diagrams of hybrid systems (HS) in order to satisfy the energy demand for a single or an entire group of households in rural areas. This research also evaluates the electrical supply through PVHS and through a CPVS to provide energy to the rural community of Yuwints in the Ecuadorian Amazon. The most suitable system is selected after a comparison of the Net Present Cost (NPC) of various renewables system *e.g.* PV-Battery systems, Wind-battery systems, PV-Wind-battery systems, etc. The techno economic analysis is carried out through the microgrid optimization software Homer Energy. The result of the present study proposes the CPVS as the best option for the electrical supply of the community, allowing a full coverage of the load and guaranteeing a safe operation of the system.

Keywords: *Centralized Photovoltaic System, Hybrid System, Photovoltaic Home System, Renewable Energy Sources*

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# List of acronyms

| *Abbreviation* | |
|---|---|
| **COE** | Cost of Electricity |
| **CPVS** | Centralized Photovoltaic System |
| **CSI** | Current Source Inverter |
| **DEG** | Diesel Engine Generators |
| **DMUp** | Projected Maximum Unit Demand |
| **EC** | Electricity Coverage |
| **ESS** | Energy Storage System |
| **FDV** | Voltage Load Factor |
| **GS** | Generation System |
| **HAWT** | Horizontal Axis Wind Turbine |
| **HS** | Hybrid Systems |
| **LS** | Load System |
| **LVDN** | Low Voltage Distribution Network |
| **MHPS** | Micro-Hydropower Systems |
| **MPP** | Maximum Power Point |
| **MPPT** | Maximum Power Point Tracking |
| **NPC** | Net Present Cost |
| **PCS** | Power Conditioning System |
| **PESN** | Public Electricity Supply Network |
| **PVHS** | Photovoltaic Home Systems |
| **PWM** | Pulse Width Modulation |
| **RES** | Renewable Energy Sources |
| **SHPS** | Small Hydropoer Systems |
| **SHS** | Solar Home Systems |
| **THD** | Total Harmonic Distortion |
| **VAWT** | Vertical Axis Wind Turbine |
| **VSI** | Voltage Source Inverter |

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Chapter 1

# 1. Introduction

### 1.1. Motivation

Nowadays, approximately 16% of the worldwide population does not have access to electricity, or their energy requirements are covered by fossil fuels[1]. Factors such as low population density, long distances from generation systems to consumers, and difficult access, inhibits the power supply to a large part of the population, especially rural and marginal urban areas.

Expansion of the electrical grid is typically planned by a government energy office. This procedure is viable when the consumption center is large enough to represent economic attractiveness for a concessionaire. Diesel engine generators (DEG) working as islands instead of backup systems, are another alternative of providing energy to remote areas due to their low initial investment, and easy installation and operation. However, such solution has a high operational cost due to generator maintenance and fuel distribution logistics, in addition to the significant environmental impacts produced [1].

Provide energy to rural areas reducing both the implementation costs and environmental impacts, is also achieved using local renewable energy sources (RES) to generate electricity. Solar, wind, bioenergy and hydropower systems, can either individually, or combined provide energy for many applications that are not connected to the electric grid. The most widely used system combines photovoltaic (PV) and wind conversion systems. Nevertheless, finding a suitable system for a given area is a challenging task, which depends on local characteristics.

Hybrid systems (HS) use multiple energy sources for generating electricity and an energy storage system, which accumulates energy when there is excess of generation within the system. HS combining RES and DEG have become popular in recent years. DEG is important to ensure service quality when the outputs from the RES and batteries are low, or when the demand is large. Microgrids based on HS reduce both the economic cost and environmental impacts through reduction of diesel consumption and $CO_2$ emission, in addition to represent a better solution for isolated areas and rural electrification [2].

[1] Data obtained from the International Energy Agency. [online]. Available at: http://www.worldenergyoutlook.org/resources/energydevelopment/energyaccessdatabase/

### 1.1.1. Access to electrical energy

Access to energy is one of the central aspects of economic and social development. It is essential for clean water provision, efficient illumination, heating, cooking, sanitation and healthcare, among others basic services.

Approximately 1,2 billion people around the world do not have access to electricity supply, and more than 2,7 billion people rely on the traditional biomass for cooking[1]. More than 95% of people without energy are in rural and poor regions of Sub-Saharan Africa and developing Asia. In Latin America and the Caribbean about 22 million people do not have access to electricity and an estimated of 65 million people lack adequate fuel for cooking[1]. Table 1-1 shows the electricity access and the traditional use of solid biomass for cooking in the world.

*Table 1-1: Electricity access and traditional use of solid biomass for cooking*

| Electricity access and population relying on traditional use of biomass for cooking in 2014 | | | | | | |
|---|---|---|---|---|---|---|
| **Region** | **Population without electricity<br>millions** | **Electrification rate<br>%** | **Urban electrification rate<br>%** | **Rural electrification rate<br>%** | **Population relying on traditional use of biomass<br>millions** | **Percentage of population relying on traditional use of biomass<br>%** |
| Developing countries | 1185 | 79% | 92% | 67% | 2742 | 49% |
| Africa | 634 | 45% | 71% | 28% | 793 | 69% |
| *North Africa* | *1* | *99%* | *100%* | *99%* | *1* | *0%* |
| *Sub-Saharan Africa* | *632* | *35%* | *63%* | *19%* | *792* | *81%* |
| Developing Asia | 512 | 86% | 96% | 79% | 1.875 | 50% |
| *China* | *0* | *100%* | *100%* | *100%* | *453* | *33%* |
| *India* | *244* | *81%* | *96%* | *74%* | *819* | *63%* |
| Latin America | 22 | 95% | 98% | 85% | 65 | 14% |
| Middle East | 18 | 92% | 98% | 78% | *8* | *4%* |
| Transition economies & OECD | 1 | ≈100% | 100% | ≈100% | N/A | N/A |
| **WORLD** | **1186** | **84%** | **95%** | **71%** | **2742** | **38%** |

Governments around the world have established various rural electrification projects to increase the supply of electricity through the employment of small RES [3].

Electricity coverage (EC) in Ecuador has grown positively in the last years. According to the National Institute of Statistics and Census (INEC), the national EC reached 93,19% in 2010. In 2014 Ecuador was positioned as one of the countries with the highest EC in Latin America and the Caribbean reaching 97,04% of EC. Figure 1.1 shows the evolution of the national EC in Ecuador between 2005 and 2014.

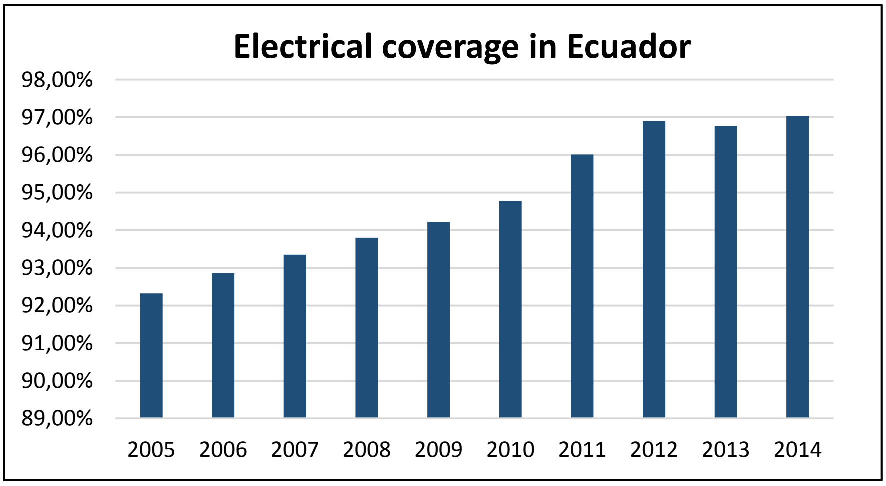



*Figure 1.1: Evolution of electrical coverage in Ecuador*

### 1.1.2. Urban and rural electrification in Ecuador

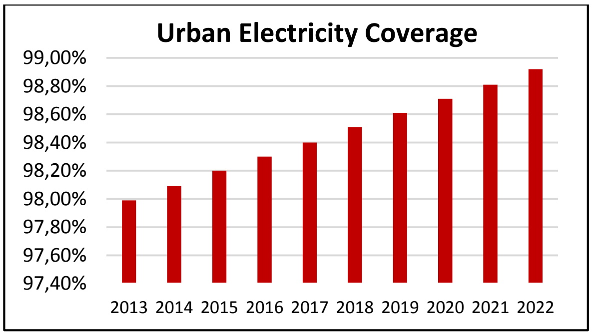
The normative framework to increase the EC is established in the republic constitution and the various associated programs PNBV[2], LOSPEE[3], PME[4], among others, which promote electricity supply in rural and marginal urban areas.

The expansion of EC is carried out by the Fund for Rural and Urban Marginal Energy (FERUM). It mainly focuses on supplying electricity to rural and marginal urban areas and regions which do not have access to basic services. The Ministry of Electricity and Renewable Energy (MEER), is responsible for the management of rural electrifications projects using RES. Therefore, it works and cooperates with the Ecuadorian electricity sector, non-governmental entities and electric distribution companies, in order to increase the EC in their concession area. Figure 1.2 shows the EC projections for 2013-2022, according to PME.

[2] The National Plan for Good Living (PNBV) is the planning tool of the Ecuadorian government that articulates public policies with public management and investment. The PNBV promotes the improvement, and expansion of the electrical coverage system through the change of the productive, and energy matrix, guaranteeing the sustainable use of the natural resources.

[3] The Organic Law of Public Service of the Electric Sector (LOSPEE) published in 2015, regulates the participation of the public and private sectors in activities related to the public electricity service, emphasizing the change of the productive matrix, optimization of natural resources, energy efficiency and environmental responsibility.

[4] Electrification Master Plan (PME) seeks to transmit relevant information on the evolution, development, sustainability and expansion of the Ecuadorian electricity sector.



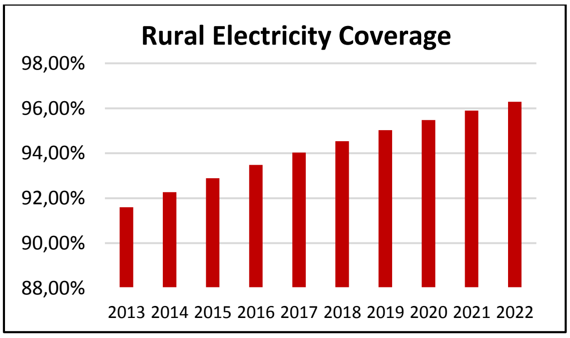




*Figure 1.2: Goals for urban and rural electricity coverage (2013-2022)*

### 1.1.3. Rural electrification in the Ecuadorian Amazon

The use of RES as a viable option to electrify isolated rural areas in the Amazon region, has been motived by several factors [4], such as:

- high dispersion, difficult access, and transportation
- low electricity consumption
- high costs through conventional service
- operation, maintenance, and troubleshooting

The Amazon region is composed by six provinces: Orellana, Pastaza, Napo, Sucumbíos, Morona Santiago, and Zamora Chinchipe. Morona Santiago stands out for being mostly rural and having reduced access to basic services.

The largest number of renewable systems implemented in the Amazon are located in isolated communities, and they are mainly based on individual PV systems. The basic electricity requirements in those regions are mainly for:

- *family households*: radio, TV, DVD;
- *small schools*: illumination classroom, small computer center;
- *communal houses*: illumination, use of electrical sound equipment for special occasions and sports;
- *health centers*: illumination, Refrigeration;
- *water pumping*: water extraction, irrigation and purification;
- *transport and tourism*: illumination of tourist cabins.

The main rural energy programs for rural electrification supported by the MEER are:

- Euro-solar program
- Consolidation of renewable energies in the northern Amazon of Ecuador
- Renewable energy unit for the Ecuadorian Amazon center
- Rural electrification project with renewable energies in isolated areas of Ecuador - IDB / GEF Project

## 1.2. Problem definition

Providing universal access to electricity is a priority worldwide. Access to electricity plays an important role for human development, since it allows the operation of numerous basic systems such as illumination, cooling, grinding, pumping, and water purification, etc., in order to improve the quality of life of people and reduce manual effort during productive activities.

The proportion of households without electricity in rural areas of Ecuador is 10,97%. The localities belonging to the Amazon region are the ones with the lowest electrical coverage, in addition to having a high level of poverty.

Due to the physical characteristics of this region, the implementation of a micro-network for the electricity supply is not feasible, since it is expensive and harmful to the environment. Therefore, the use of RES for power generation purposes, represent a key alternative to provide electricity to these communities.

An optimal combination of different energy system for isolated communities involves a rigorous assessment on:

- the current energy demand and how it might increase;
- renewable resource availability,
- how can they be provided efficiently and cost-effectively;
- location difficulties such as geography characteristics and weather.

### 1.3. Objectives

The general objective of this research is:

> Design a viable renewable energy system to satisfy the energy requirements of the rural community of Yuwints in the Ecuadorian Amazon, considering two options of energy supply:
>
> - Through a stand-alone home system for each dwelling in the community.
> - Through a centralized system, using a low voltage distribution network (LVDN).
>
> For this purpose, this research will use the microgrid simulation software Homer Energy to determine an optimal design from an economic approach by minimizing the NPC of the candidate systems.

The particular objectives are:

- Description of RES technologies (PV, Wind, Hydro and Biomass) for electricity generation purposes.
- Description of the renewable system components and different connections topologies used in stand-alone applications.
- Data collection of electric consumption and available resources in the Yuwints community.
- Determine an optimum placement for the centralized system and sizing the LVDN at the lowest cost.
- Selection of suitable equipment for each system topology, justifying the selected technology, costs and availability in the market.
- Simulate the renewable system for the community:
  a) through stand-alone home systems
  b) through a centralized system
- Determine the most suitable HS to supply electricity to the community, from a technical and economical approach.

### 1.4. Literature review

To support the theoretical framework in this research work, a literature review of scientific articles, web pages and thesis works was performed.

Reports of The Ministry of Mines and Energy in Brazil [1], [5], [6] provide information about energy solutions for rural electrification in the Amazon. These researches describe the main concepts of electricity generation from renewable sources *e.g. Solar, Wind, Hydro, Biomass* and promote the use of local resources as a feasible alternative to provide electricity to remote areas in the Amazon region, with individual PV systems being the most used option.

Several researches have been carried out using Homer Energy software, in order to obtain a viable configuration of RES for stand-alone systems [2],[7],[8],[9],[10]. The result of these studies showed optimal configurations of HS for different locations mainly in Asia *e.g.* Sri Lanka, India, Bangladesh with high participation of RES and significant reduction of CO2 emissions.

There are few studies that compare stand-alone systems and centralized systems for rural electrification. For instance, reference [11] describes a CPVS approach as the best option for a particular off-grid application, but it requires extended planning and high initial investments, whereas the solar home systems (SHS) approach can be gradually built bottom-up. Reference [12] shows the economic viability of the implementation of a CPVS in villages with a large number of dwellings, densely populated and located on flat terrains. It is also concluded that the most convenient option for small villages situated in rough terrains with scattered dwellings is SHS.

### 1.5. Hypothesis

Analysis of RES availability as well as the electric consumption behavior of a specific area, contributes to a correct sizing for both grid connected systems and isolated systems. Stand-alone home systems are typically used for providing electricity to off-grid applications. However, centralized system with their own LVDN are also being considered for rural electrification. This research work also seeks to answer the following questions:

- Is it possible to satisfy the electric consumption of a rural household through one or several types of renewable sources?
- What kind of technologies are the most appropriate for the design of a HS integrating RES?

- What are the most favorable conditions regarding weather, location and costs, to integrate HS with RES in a microgrid configuration within the Ecuadorian Amazon region?

Chapter 2

# 2. Theoretical framework

## 2.1. Isolated and centralized systems

An isolated system should be capable of producing the energy needed to satisfy its own consumption, avoiding connection to the public electricity supply network (PESN). Two types of isolated systems can be distinguished:

a) Individual isolated system: this type of system consists of a single consumer, *e.g.* a dwelling, public facilities and productive applications, etc. It may be limited to provide basic services with reduced energy consumption.

b) Centralized isolated system: this system can supply electrical energy to different users who are physically grouped. The electric energy distribution is done by a micro-network, which may be composed of several generation systems that use one, or several primary production sources. If the community grows, or the energy demand increases, and if it is economically affordable, this micro-network can be interconnect to the PESN.

A suitable renewable generation system depends on various factors [4] such as:

- availability of RES *e.g.* solar, wind, hydro, biomass;
- reliability of power supply;
- characteristics of local infrastructure;
- physical distribution of the consumers;
- relationship between the cost consumption per unit, and the cost of generation, installation, operation and maintenance.

An isolated HS that integrates RES is formed by the following systems:

❖ Generation system (GS): it is the main element of the system. GS is responsible for producing electrical energy from one, or more renewable energy sources;

❖ Energy storage system (ESS): it is responsible for storing the excess of energy produced by the generation system. The energy storage system should also return the accumulated energy to the microgrid, when the generation is low or zero;

❖ Load system (LS): it consists of devices that operate through alternant current (*ac*), or direct current (*dc*);

❖ Power conditioning system (PCS): it is responsible for the management and joint operation of the GS, ESS and LS. It verifies the allowable operating levels such as current, voltage and frequency to ensure the balance between production and energy consumption. The main functions, characteristics and constituent elements of PCS are described in section 2.2.

## 2.2. Power conditioning system

An isolated system can be coupled in either *ac*, *dc,* or both. Therefore, the use of electric components such as charge controllers, dc-dc converters, inverters and rectifiers are needed for each configuration. These components transform and couple the system at several voltage levels on the *dc* side, or the *ac* side. In *dc* coupled systems, *dc* generation systems are connected through *dc-dc* converters, whereas *ac* generation systems are connected by rectifiers. In *dc* coupled system, all loads and generators are coupled exclusively at the battery voltage level. Adding a power inverter in the *dc* system, is also possible to supply electricity to *ac* loads[5]. Figure 2.1-a shows a hybrid system with *dc* coupled components.

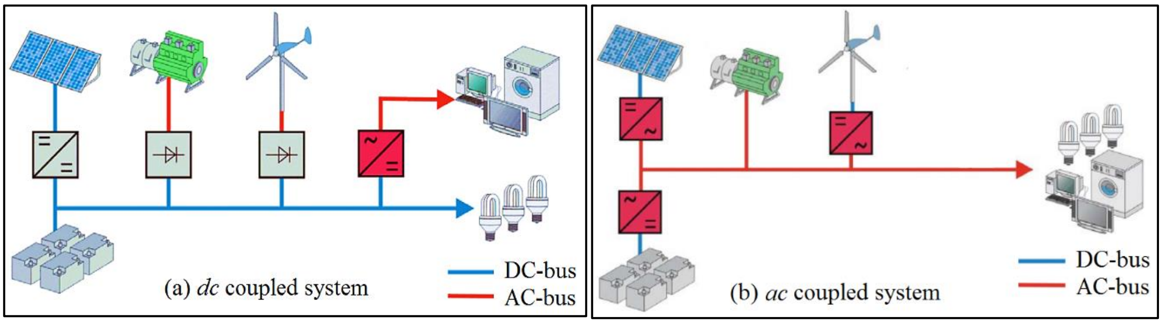


*Figure 2.1: Hybrid system with dc and ac coupled components*

In *ac* coupled systems, the *ac* generation systems are connected directly to the microgrid; the EES and *dc* generation systems are coupled to the microgrid through a power inverter[5] (see Figure 2.1-b). In *dc-ac* coupled systems, several equipment must be used to adjust the electricity levels and supply energy to both types of loads.

The main objective of the PCS is optimize the control of the GS and consumption of energy, in order to minimize the use of resources and maintain reliable levels of energy [1]. Figure 2.2 shows the PCS system and its interaction with the GS, LS, and ESS.

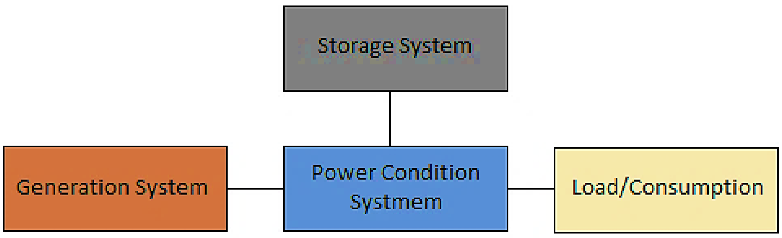


*Figure 2.2: Block diagram of a stand-alone system*

[5] Data obtained from SMA solar Technology AG. [online]. Available at: http://www.sma.de/en/

### 2.2.1. Charge controller

Stand-alone systems for rural areas are often implemented using a combination of PV panels and an ESS, typically batteries. To ensure a proper operation of the ESS and increase its useful life, the state of charge of the batteries must be monitored. These functions are performed by the regulator, also known as charge controller. It is an electronic device whose main function is to supervise and manage the charging and discharging process of batteries. The main functions of a charge controller are:

- *<u>Overcharge protection</u>*: prevents damage in batteries when they are fully charged and the generation system still supplies energy. This protection interrupts, or restrict the current flow from the GS to the batteries and regulates the batteries voltage;
- <u>Over discharge protection</u>: during periods of excessive use of energy from the ESS, the state of charge of the batteries could approach to the minimum discharge level. The charge controller disconnects the ESS, or interrupt the power supply to *dc* loads in order to avoid damage of batteries. If the system is composed of *ac* loads, the management of the storage system is done by the inverter device.

Systems intended to supply electricity to loads with little variation of energy consumption, can be designed to operate without a charger controller, whenever the voltage supplied by the generator is compatible with the voltage of the battery. These types of systems are called *self-regulating systems* [13]. Charge controllers must be used with the type of battery for which they were designed. Some regulators models allow the adjustment of their parameters to adapt their use to different types of batteries and loads, and may be have several additional functions to provide information of the state of charge of the ESS such as current, voltage and energy generated, etc. [1]. Figure 2.3 shows different types of charge controllers available in the local market [14]–[16].


*Figure 2.3: Charge controllers available in the Ecuadorian market*

### 2.2.2. Power inverter

A power inverter, also known as *dc-ac* converter is an electronic device that generates an *ac* output from a *dc* source. In off-grid PV systems, the power inverter may be connected to the batteries, whereas in grid connected PV systems, the inverter is connected to the

PESN. According to the operating principle, the inverters are divided into two main groups: grid-switched and auto-switched. The auto-switched inverters can be operated as a current source inverter (CSI), or a voltage source inverter (VSI). VSI is the most used for stand-alone systems applications. It mainly consist of a power stage, an electronic controller and the necessary auxiliary circuits for isolation, output filtering, voltage and current sensing, signal conditioning and protection, etc. [17].

The *dc-ac* conversion is performed by switching mechanism, which can be placed in conduction, or block state at any point in the wave-cycle by means of a control signal. The output waveform of a VSI can be a square wave, a modified square/sine wave, multi-level, or a pure sine wave. These wave forms are described as follow:

- *Square wave inverters*: they are the most economical inverters, as the output wave has a square shape and is obtained through a simple inversion of voltage and current (see Figure 2.4-a). The resulting waveform has 40% of content of harmonic signals. Square wave inverters have an efficiency between 50% - 60%. They are often used with small inductive, or resistive loads;
- *Modified square/sine wave inverter*: this waveform is obtained through additional switches, which give it a trimmed format (see Figure 2.4-b). Modified square wave inverters eliminate all third order harmonic signals and their multiples, decreasing the total harmonic distortion (THD) around 20%. They have an efficiency around 90%. They are technically more suitable than square wave inverters, and are used in rural electrifications to power common electronic equipment such as TV, radios, computers, etc;
- *Pure sine wave inverters*: these inverters are the best solution to connect electric motors without presenting problems with the THD, or voltage stability. The output voltage regulation is performed by PWM control. This control technique allows the semiconductor devices switching at high frequency, obtaining a highly sinusoidal signal with high frequency harmonics easily filterable (see Figure 2.4-c). This filtering stage can be done with conventional passive filters [17].

Figure 2.4 shows the waveform of power inverters.

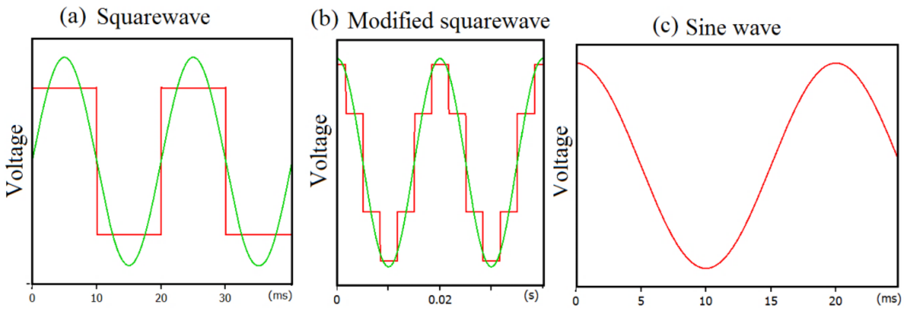



*Figure 2.4: Inverter waveforms*

In stand-alone applications with higher levels of electricity generation and energy consumption, a more complex inverter is required. The stand-alone power inverter is equipped with various management systems, which guarantee the stable operation of the system. They also incorporate an internal monitoring system and displays to indicate the different parameters of the system operation. Some inverters commercially available, allow several power generators to be connected on the *ac* side (see Figure 2.5).

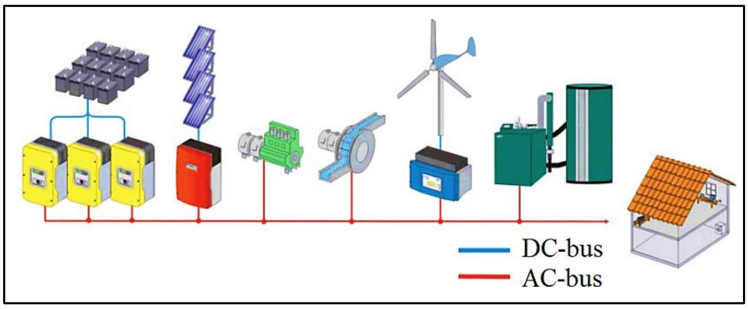



*Figure 2.5: Integration of a stand-alone inverter in a hybrid system*

Stand-alone power inverters can be operated in parallel with other coupled inverters. Each inverter operates by using a cascade controller as its voltage source. In this way, the consumption and active power output of each one, is independently controlled as a function of the stand-alone grid frequency. If the frequency increases due to a sudden reduction in load, all inverters will reduce their power input, thus the system will remain balanced[5]. Figure 2.6 shows different types of power inverters available in the market [14]–[16].

*Figure 2.6: Power inverters available in the Ecuadorian market*

### 2.2.3. DC-DC Converter

A *dc-dc* converter is an electronic circuit used to change a *dc* source from one voltage level to another. According to the relationship between the input and output voltages, a *dc-dc* converter can be designed to reduce the voltage level (*buck converter)*, to increase the voltage level *(boost converter),* or both *(buck-boost converter)* [17]. A *dc-dc* converter is commonly used as a charge controller of batteries in a PV system and as internal elements of more complex equipment. It can be integrated with an MPPT control system to obtain a better performance of the system [13]. Its efficiency depends on the power semiconductors used, the rated power, and the voltage multiplication factor. Reducer converters typically have higher efficiencies than elevating voltage converters.

### 2.2.4. Rectifiers

The *ac-dc* conversion is often called rectification, and the converter used is called a rectifier. In an ideal rectifier, the output voltage is a pure *dc* signal without any ripples, and the input current is in phase with the voltage. According to the power electronic devices used, rectifiers can be divided into uncontrolled rectifiers with diodes, phase-controlled rectifiers with thyristors, and PWM-controlled rectifiers with IGBTs or MOSFETs [17].

#### *2.2.4.1. Uncontrolled rectifiers*

These rectifiers can only provide a fixed output voltage. The simplest rectifiers consist of a diode (see Figure 2.7-a). This circuit allows only the positive half cycle of the input voltage to pass the diode to reach the load. The resulting *dc* output voltage contain a significant amount of harmonic currents. For reducing the ripples in the output voltage, several diodes are connected to form bridge rectifiers. In this circuit both half cycles of the input voltage are passed to the load. Figure 2.7-b shows the scheme of a single–phase bridge rectifier.

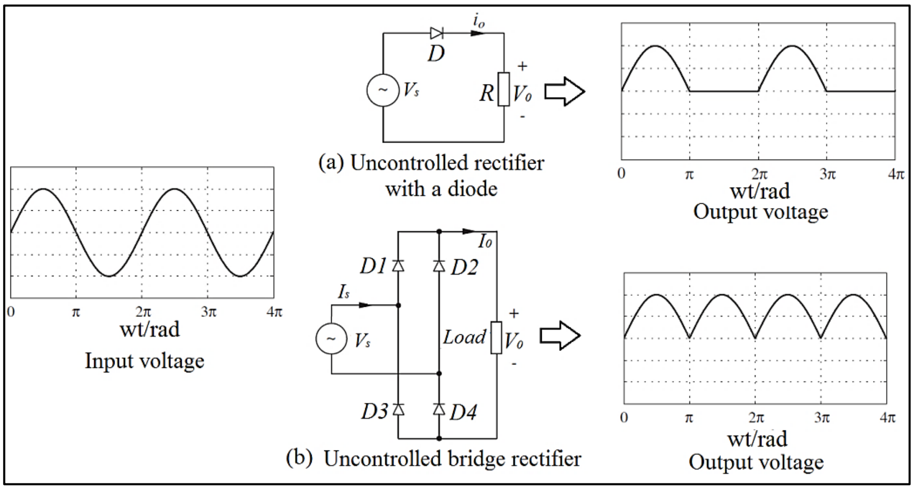



*Figure 2.7: Uncontrolled rectifier: (a) with a diode. (b) single-phase bridge rectifier*

For three-phase applications, a configuration with three pair of diodes can be adopted. The pair of diodes with the highest instantaneous line voltage conduct for 120° at each time. The output voltage is the envelope of the line voltages with six ripples. The rectifying equipment incorporates a filtering stage, in which the *ac* component of the output signal is reduced. In practice, filters are connected to reduce the voltage ripples, and inductors are adopted to smooth the load current [17].

##### *2.2.4.2. Phase controlled rectifier*

Thyristors are commonly used to provide a variable *dc* output voltage. They can be turned on, by applying a firing pulse, when forward biased. The output voltage of a phase-controlled rectifier can be changed by varying the firing angle (α) of the thyristors [17]. Phase controlled rectifier are widely used in variable speed drivers, and they can be implemented in three-phase configuration.

## 2.3. Solar energy exploration

It is estimated that 84 min of solar radiation falling on earth is equal to the world energy demand for one year [18]. Solar energy has an enormous potential that can be utilized by various types of technologies[6]. Some examples of these technologies are:

- *PV systems*: PV installations offers an attractive solution for both, grid-connected and off-grid applications. They can be used to provide energy to small dwellings, or villages in rural areas without access to electricity; moreover, they can be used to guarantee a continuous supply of water for drinking purposes, or irrigation activities;
- *Solar thermal energy*: technical exploitation of solar heat has been developed over time. Solar thermal energy is suitable for heating systems applications, even in areas of low solar radiation. Solar cooling is another thermal application of great interest, mainly in countries with high demand for air conditioning.

### 2.3.1. Solar radiation

Solar radiation is a physical phenomenon due to the energy emission by the sun in electromagnetic radiation form. These electromagnetic waves may have different wavelengths. The set of waves emitted by the sun is called solar spectrum, which is approximately formed by the following percentages of electromagnetic radiations: ultraviolet: 7%, visible light: 43%, infrared: 49%, and the remaining: 1%.

The total solar radiation reaching the earth's surface is reduced, because a large part of it is scattered, reflected back out into space, and absorbed by the earth atmosphere. Since

[6] Data obtained from publications by the German Energy Agency. [online]. Available: https://www.dena.de/en/publications/

the solar radiation travels through the earth atmosphere, waves of very short length *e.g.* X-*rays and gamma rays* are absorbed at extremely high altitude. The waves of relatively longer length *e.g. ultraviolet rays* are absorbed at 15-40 km above the earth's surface. Solar radiation in the infrared range is absorbed by water vapor and carbon dioxide. Therefore, little solar energy reaches the ground [18]. As a result of the atmospheric interaction, the incident solar rays are separated into different components, which are:

- *Direct or beam radiation*: it comes from direct radiation from the sun's rays;
- *Diffuse radiation*: it comes from all directions, resulting from the incidence of indirect solar rays, whose direction was altered due to the refraction and reflection phenomena in the atmosphere;
- *Ground reflected irradiation*: it is the result of the direct, or diffuse radiation by the surrounding medium, it is only noted in inclined planes.

The sum of the direct, diffuse, and reflected ground irradiations is called global, or total radiation. Figure 2.8 shows the components of solar radiation in the atmosphere.

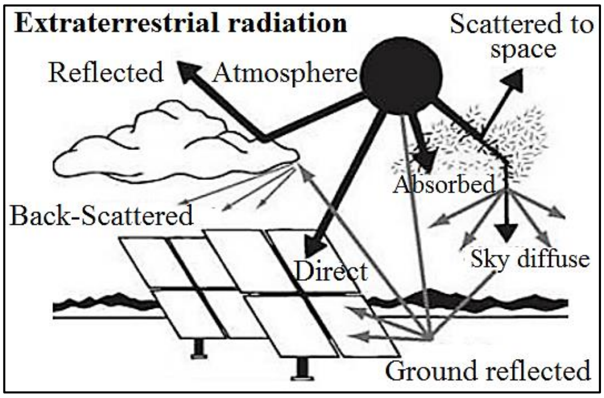



*Figure 2.8: Solar radiation components*

### 2.3.2. Solar radiation measuring equipment

Solar radiation parameters such as: global solar radiation, direct radiation, diffuse radiation, and sunshine duration are needed for the design, sizing, performance, and evaluation of solar energy applications. The detection of the electromagnetic radiation is primarily performed by conversion of the beam's energy in electric signals, which consequently can be measured by conventional techniques. There are three types of solar radiation measuring instruments [19], which are:

- *Pyranometer*: It is an instrument used to measure the total solar radiation. It can also measure only the diffuse solar radiation if the sensing element is shaded from the direct radiation. For measuring the diffuse component of solar radiation, a small shading disk can be mounted in an automated solar tracker to ensure that the pyranometer is continuously shaded;

- *Pyrheliometer*: It is an instrument used to measure the direct beam component of solar radiation at normal incidence. Consequently, the instrument should be permanently pointed towards the sun. The beam radiation is received in a limited circumsolar region, but all diffuse radiation from the rest of the sky is excluded;
- *Sunshine recorder*: Sunshine duration is measured by the sunshine recorder. Sunshine duration is defined as the time during which the sunshine is intense enough to cast a shadow. It also has been defined by the World Meteorological Organization as the time, during which the beam solar irradiance exceeds the level of 120 W/$m^2$ [18], [19].

Figure 2.9 shows the instruments to measure the solar radiation parameters.

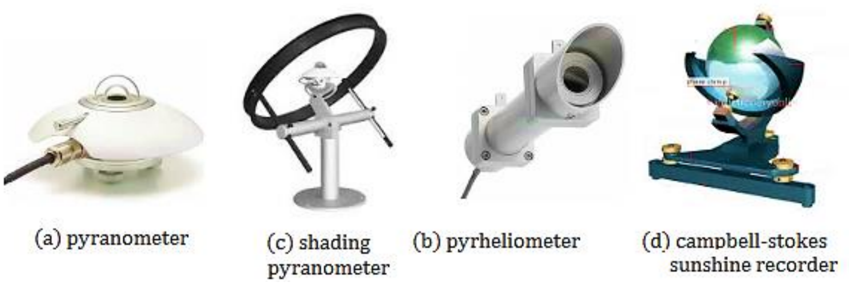



*Figure 2.9: Solar radiation measuring equipment*

### 2.3.3. PV conversion process in a solar cell

The PV effect is defined as the direct conversion of light into electricity. It is a physical-chemical phenomenon, where voltage or electric current is generated by certain materials when are exposed to light. Its intensity is correlated to the intensity of the light source, the light wavelengths supplied, the physical composition, and the material structure. The PV effect fundamentals are based on the theory of the n-p junction diode and the free electrons obtained by the PV effect. Silicon is the semiconductor material most used in the manufacture of PV cells. Silicon atoms are characterized by having four valence electrons that bind to the neighboring atoms by means of covalent bonds forming a crystal lattice [20].

When the semiconductor material is pure, it has the valence band completely filled and the conduction band empty. For the material acquires the ability to conduct electrical current, the silicon structure must be modified. The technique used is known as "*doping*", which introduce an atom of another element called "*dopant"* into the silicon crystal to alter its electrical properties. The dopant may have three or five valence electrons, as opposed to silicon's four. When the dopant has five valence electrons like *phosphorus*, the bond will cause the appearance of a free electron, which may travel to the conduction band, forming the so-called n-type semiconductor. On the other hand, the dopant with three valence electrons like *boron*, will create an electron deficiency in the valence band called "*holes"*, and forming the p-type semiconductor (see Figure 2.10-a) [20].

If phosphorus atoms are introduced on one side, and boron atoms on the other side of a pure silicon structure, the n-p junction is formed. At this junction, free electrons move from the n-side to the p-side, where they are captured by the holes; this causes a positive charge on the n-side of the n-p junction, and a negative charge formed on the other side. Therefore, this overpopulation of opposite charges creates an electric field across the interface (see figure 2.10-b) [20].

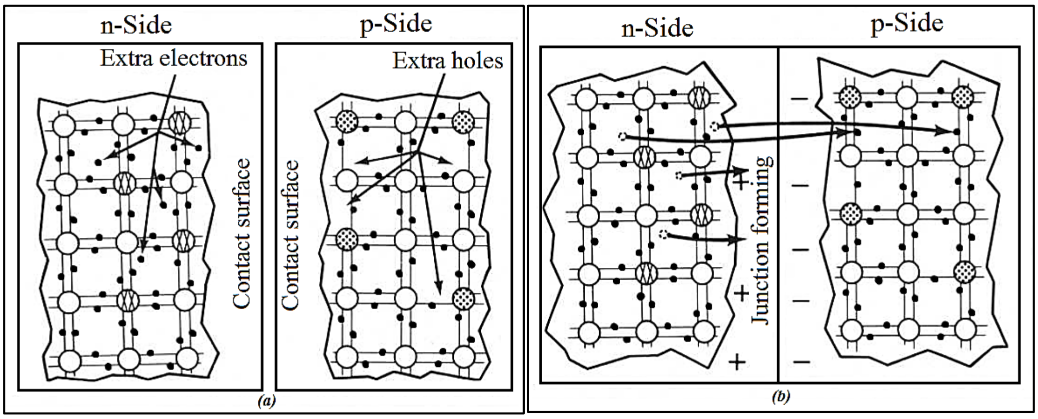



*Figure 2.10: Silicon material structure (a) n-type and p-type semiconductor (b) electric field at the n-p junction*

When a photon is absorbed by a silicon atom, an electron-hole pair is created, and both the electron and the hole being moved through the material. The electric field pushes new electrons to one side of the junction and new holes to the other. This sorting-out process is what drives the charge carriers in an electric circuit.  The level of energy known as the band gap energy, is the amount of energy required to move an outer-shell electron, from the valence band to the conduction band. This energy is different for each material and for different atomic structures of the same material (see Figure 2.11).

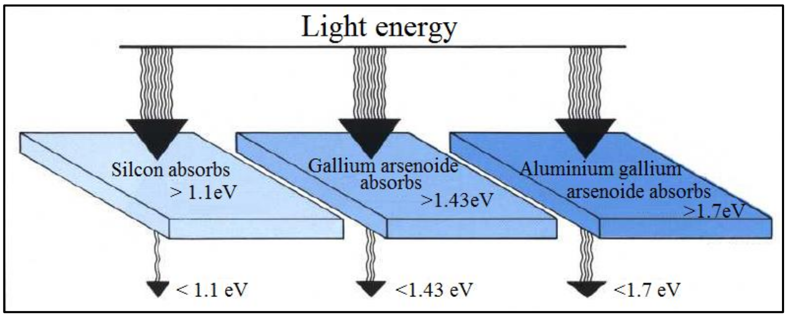



*Figure 2.11: Energy band-gap characteristics for different PV materials.*

Attaching an external electric circuit, allows the electrons to flow from the n-layer through the electric circuit and back to the p-layer, where the electrons combines with holes to repeat the process. Photons with only certain level of energy are able to release electrons from their atomics bonds to contribute to the PV effect and generate electric current.

### 2.3.4. Solar cells and PV modules

The solar cell is the smallest practical element that harnesses the photovoltaic effect to generate electricity. Other elements apart from silicon are used in PV cells manufacture, such as cooper, gallium, or cadmium [21]. PV panels may be differentiated between thick film and thin film technologies[6]. The thick film technologies for PV panels are:

- *Monocrystalline (Si) Cells*: they are the most used commercially. Monocrystalline silicon cells have the highest efficiency (up to 22%). Their manufacture involves the extraction of high-purity silicon rods from a cast, and cutting them into thin wafers, which then are processed into PV cells. The disadvantages are the high cost of the production and high energy consumption, due to the construction and manufacture process. They can be recognized by an uniform external color, which indicates silicon of high purity (see figure 2.12-a);
- *Polycrystalline (Si) cells*: unlike monocrystalline silicon, the silicon is cast in blocks. When it hardens, it forms crystal structures with different sizes at whose borders some defects may appear, which reduce the solar cell efficiency (up to 16%). A good way to differentiate monocrystalline and polycrystalline cells is that polycrystalline solar cells look perfectly rectangular with no rounded edges (see figure 2.12-b);
- *String ribbon solar cells*: in this technology, a sheet of silicon "*the ribbon"* is pulled vertically from a bath of molten silicon to form a multi-crystalline silicon crystal. These PV panels are more economical, because they require only half of the silicon used to manufacture monocrystalline PV panels. However, the electrical performance is lower than conventional wafer technology.

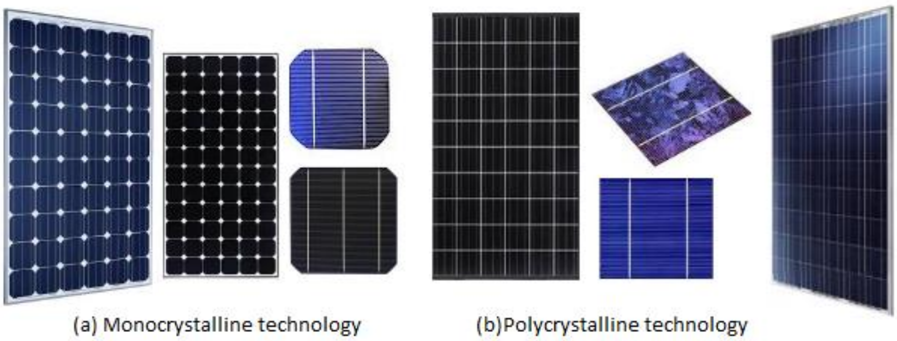



*Figure 2.12: Monocrystalline and polycrystalline photovoltaic modules.*

In the thin film technology, PV cells are manufactured by piling thin layers of photovoltaic materials deposited on a substrate such as glass, polymer, or metal. The cost of the production using this technology is lower compared to the crystalline silicon technology. The different types of thin-film solar cells can be categorized according to the PV material deposited onto the substrate, such as: Amorphous Silicon (a-Si), Cadmium tellurium (CdTe), Copper indium gallium selenium (CIGS). Figure 2.13 shows thin film PV panels.

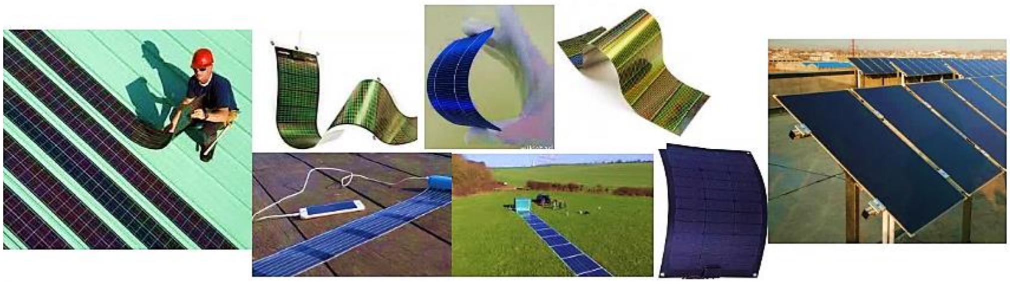


*Figure 2.13: Thin-film PV solar cells technologies*

### 2.3.4.1. Connections of solar cells and PV modules

Photovoltaic devices such as: cells, modules, and strings can be associated in series, and/or parallel in order to obtain the required voltage and currents levels. PV modules consist of solar cell circuits sealed in a laminate for environmental protection, and they are the fundamental components of PV systems. A string is referred to as a group of modules connected in series. A photovoltaic array is the complete power-generation unit. It can be composed of various PV modules, which can be connected in series, parallel, or both. Figure 2.14 shows the connection of solar cells and PV modules.

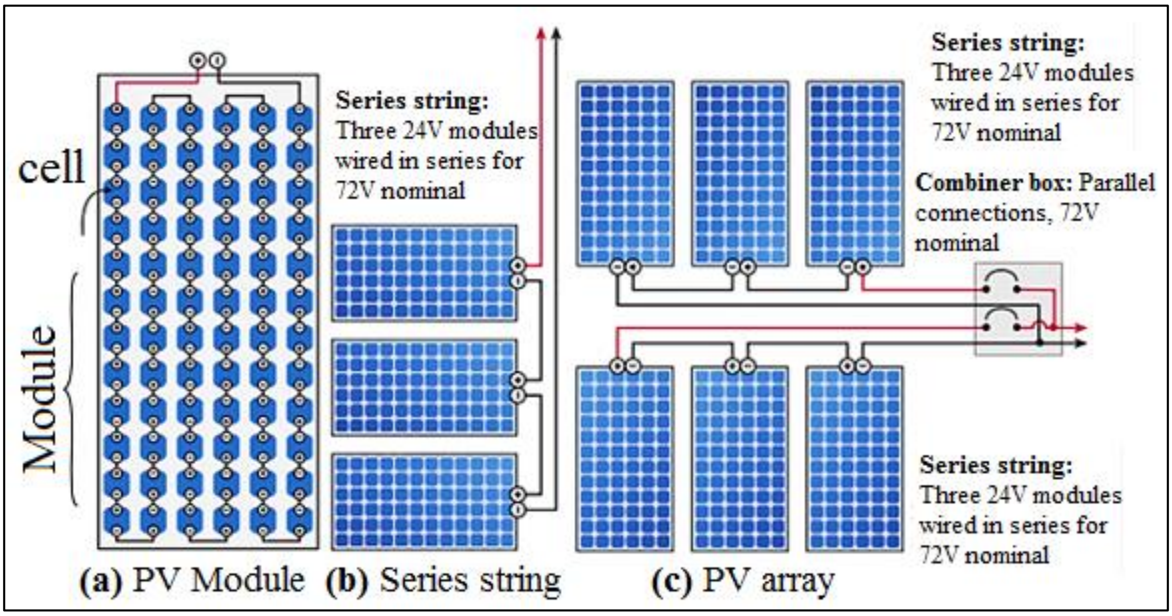



*Figure 2.14: Solar cells and modules connection (a) PV module (b) String (c) PV array*

### 2.3.4.2. Electrical characteristics of cells and PV modules

Electric power, voltage, and current are the most important electric characteristics of solar cells and PV modules. From the characteristics of the I-V curve of a PV panel, the following electrical parameters can be determined (see Figure 2.15) [13]:

- *Open circuit voltage ($V_{OC}$)*: it is the voltage at the terminals of the PV cell when no electrical current is flowing. $V_{OC}$ varies according to the PV cell technology;
- *Short-circuit current ($I_{SC}$)*: it is the maximum current obtained from the module when the voltage at the terminals is zero. $I_{SC}$ varies according to the cells technology;
- *Form factor (FF)*: it is the ratio between the maximum power of the cell and the product of $I_{SC} \times V_{OC}$. The smaller the resistive losses, the I-V curve will be closer to the rectangular shape;
- *Efficiency (η)*: it defines the conversion effectiveness of solar energy into electric energy. It represents the ratio between the electric power produced by the module, and the power of the incident solar energy.

Figure 2.15 shows the I-V and P-V curve of a PV module.

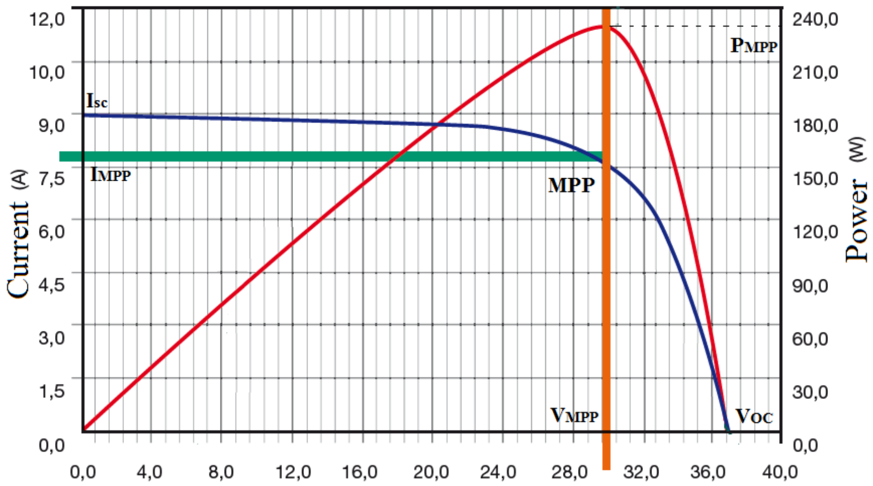



*Figure 2.15: Current–voltage and power–voltage solar cell characteristics*

The power curve can be determined from the I-V curve as a function of the voltage, it is called the P-V curve. Figure 2.16 shows the P-V curve and highlights the maximum power point (MPP). The voltage at the MPP is less than $V_{OC}$, and the current is lower than $I_{SC}$. At the maximum power point, the current and voltage have almost the same relation to the irradiance and the temperature as the short circuit current and the open circuit voltage.

Among the external factors that influence the solar module characteristics, irradiance and temperature are the most important.

- Low irradiance levels reduce the generation current, whereas voltage varies slightly;
- High temperatures reduce the voltage, whereas the current increases slightly.

### 2.3.5. Topologies connection of PV systems

PV systems can be used to provide energy both, grid connected and non-grid connected applications. They can operate alone, or combined with other generation technologies to supply electricity to a single household, production facilities, commercial sites, or even entire communities by means a distribution network. A PV system can be scaled to any size, from a single Watt (W) or several hundred kWp. The electric configurations of an off-grid PV system are [13]:

- *Electrical supply in dc*: this configuration only allows the connection of devices that operates in dc, therefore, it is limited to a lower consumption (up 100 Wp). This type of system requires a single *dc* circuit, and it is usually used to power illumination systems and small electrical loads. The scheme is shown in figure 2.16-a;
- *Mixed electrical supply dc-ac*: an inverter device is added to the system previously described, which allows the power supply of *ac* appliances. This configuration presents greater flexibility and operational reliability, since the system could have a *dc* circuit for the illumination system and an *ac* circuit for all other loads. If a fault occurs in the inverter device, the illumination system will not be affected. The maintenance of this type of system is more complex than the previous one, besides to present a higher installation cost;
- *Electrical supply in ac*: this system is formed by the same components as the mixed configuration. However, all loads must be operated in alternating current. This type of system requires a single *ac* circuit (see figure 2.16-b). Unlike the *dc* configuration, it uses smaller diameter wiring and electrical equipment of greater availability in the market.

Figure 2-16 shows the *ac* and the *dc* configuration of a stand-alone PV system.

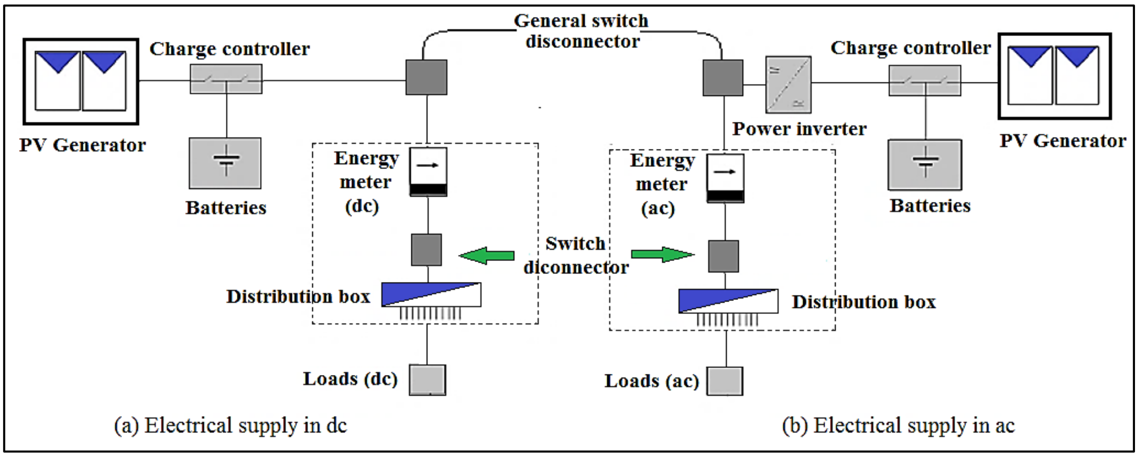



*Figure 2.16: (dc) and (ac) configuration for PV system applications*

In particular applications like water pumping, the PV system may not require batteries for electrical storage, since the daily water needed is pumped into a reservoir during daylight hours. Otherwise, HS are used to generate electricity continuously in order to pump groundwater to the surface, or into tanks, as necessary.

Regarding to the environmental issues, the PV technology does not generate any type of solid, liquid, or gaseous effluents during the electricity generation. It is a technology that does not emit noises. The environmental impacts of PV systems are restricted to the visual aspects and occupation of wide areas. However, an important factor to consider is emission of pollutants and energy consumption during the manufacture process of the modules [1].

## 2.4. Wind energy exploration

Wind is the result of air in motion in the earth's atmosphere, and like other renewable energy resources, it is a secondary form of solar energy. Approximately 2% of sun's energy reaching the earth is converted into wind energy. Wind energy has been regarded as an environmentally friendly energy source, and has attracted most of the attention in recent years.

### 2.4.1. Characteristics of the wind

The uneven heating of the earth's surface caused by energy from the sun, creates regions where the air pressure is temporarily higher, or lower than average. This differences in air pressure causes atmospheric gases, or wind to flow from the high-pressure regions to low-pressure regions. The regions around the equator, at 0° latitude, are heated more than the rest of the planet. Hot air is lighter than cold air, thus, it will raise into the sky until it reaches approximately 10 km altitude, and will spread to the north and the south [22]. Due to the air temperature reduction in its movement towards the poles, it returns to the equator at approximately 30°N, and 30°S forming a mechanism of three cells in each hemisphere. Solar radiation, surface cooling, humidity as well as the rotation of the earth, all play important roles to determine the wind behavior [1]. Figure 2.17 shows the global wind circulation model.

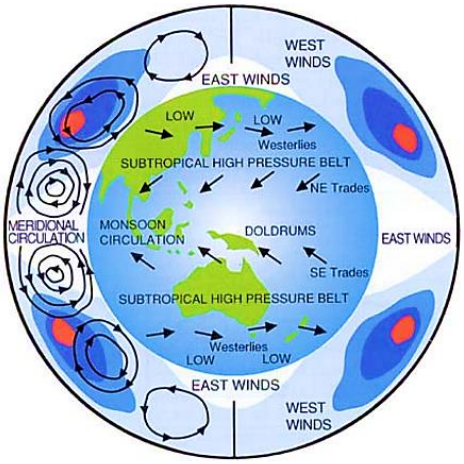



*Figure 2.17: Global wind circulation model*

Winds are very influenced by the ground surface at altitudes up to 150m. Close to the surface of the earth, the following effects influence the flow pattern of the wind.

- *Sea breeze*: during the day, the air above the land heats up more quickly than the air over water. The air raises, flow out to the sea, and creates a low pressure at ground level, which attracts the cool air from the sea. At night, the winds are reversed, because the air cools more quickly over the land than over the water. The land breeze at night generally has lower wind speed, because the temperature difference between land and sea is smaller at night (see figure 2.18);
- *Mountain breeze*: during the day, the slopes of the mountain are heated, the density of the air decreases, and the air ascends towards the top of the mountain following the surface of the slope. At night, the mountain slopes get cooled, and the wind direction is reversed producing a down-slope wind (see figure 2.18). If the valley floor is sloped, the air may move down or up the valley, as a canyon wind.

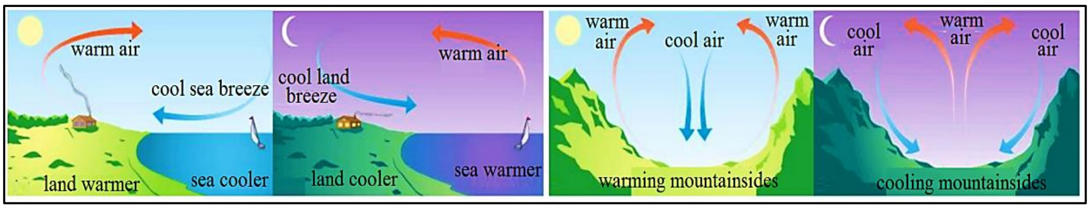



*Figure 2.18: Flow pattern of the wind: mountain breeze and sea breeze*

#### 2.4.1.1. Local effects on wind flow

For the installation of wind turbines, local winds are perhaps the more important aspect to consider, since, due to the local effects, a specific site may have a very low wind, even if it is situated in a predominantly wind area. The main local effects on the wind flow are:

- *Friction and surface roughness*: wind does not flow smoothly over the earth's surface due to friction between it and the air. This results in a phenomenon called ground drag, which varies according to the roughness on the surface. The wind speed is assumed zero at the ground level surface. Near the ground, the wind speed increases faster, however, it decreases notably to greater heights. The variation is not significant at an approximate height of 150m, and it is null approximately 2km from the ground [1]. The variation of the wind velocity to height is denominated *“vertical profile of the wind”* (*see* Figure 2.19) [23];

- *Wind shade adjustment*: strong winds are usually present behind obstacles such as buildings and trees. For example, for a specific height (H) of a building, turbulence bubbles, or wind shadows can extend up to (2H) above the ground, up to (20H) downwind, and (2H) upwind the obstacle (see Figure 2.19). A common recommendation is to ensure that the lower blade tip of the wind turbine rotor is installed at least 9m above obstacles within 152m [23];
- *Turbulence*: turbulence occurs when air flowing across the earth´s surface encounters objects, such as trees or buildings. They interrupt the smooth and laminar wind flow, causing it to tumble and swirl. The rapid changes in wind speed occur behind large obstacles, and winds may even flow in opposite direction to the wind. Turbulence intensity is a major issue for small wind turbines. It can reduce the annual energy output estimate from 15% to 25%.

Figure 2.19 shows the local effects on wind flow.

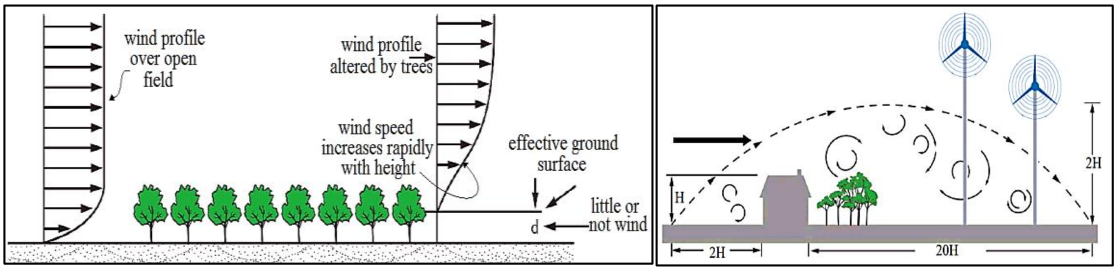



*Figure 2.19: Vertical profile of the wind and disturbed wind zone*

#### 2.4.1.2. Wind measurements

Before using suitable wind measurement equipment, it is desirable to use any information, which may already be available in the earth’s surface, at least for preliminary investigations. Some regions of the earth's surface are under severe climate effects, and persistent strong winds, which produce eolian landforms such as sand dunes, Playa Lake, sediment plumes, and wind scour. Eolian landforms do not give accurate estimates of average wind speed at a given site, but can identify the best site in a given region for further study [24].

Living plants indicate the effects of strong winds, as well as eolian features on the earth. The effect can be observed on coniferous evergreens, because their appearance to the wind remains relatively constant during the year. One of the classifications that describe the wind effects on vegetation is the Griggs-Putnam index. Another visual form to obtain a preliminary analysis of the wind potential is using the Beaufort scale, which relates wind classes to indicators observed on land and at sea.

The variability of the wind makes accurate measurement difficult, therefore, expensive equipment is often required. The main measurement equipment to determine the wind speed and its direction are [24]:

- *Wind speed sensors*: Wind speed measurement instruments can be classified into two types [1]:
  - Rotational: the most used devices are: *cup and propeller anemometers;*
  - Non-rotational: it has a greater variety of types such as: pressure-tube anemometer, hot-wire anemometer, ultrasonic, and laser anemometer, etc.

  Rotational anemometers measure the horizontal wind speed. They are the most used for wind speed measurements. In these types of anemometers, the angular velocity of their axes varies linearly with the wind speed, they have a wide range of accuracy and lower costs than non-rotational anemometers. Unlike propellers anemometers, cup anemometers are more accurate when they are exposed to turbulence, variation of wind direction, and non-horizontal winds produced by obstacles. Figure 2.20 shows rotational and non-rotational anemometers.

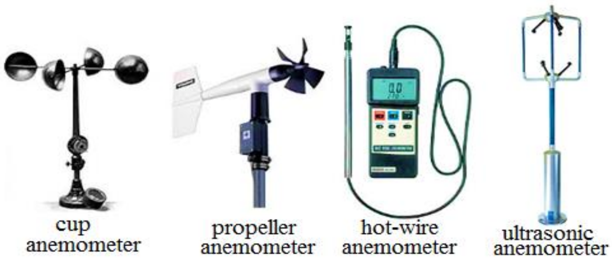



*Figure 2.20: Rotational and Non-rotational anemometers*

- *Wind direction sensors:* wind vanes are mechanical devices, which freely rotate to show the wind direction. The output is generally analogue, but digital versions are also available. They have an accurate response, even at low wind;
- *Temperature, pressure and humidity sensors*: despite temperature and atmospheric pressure are less influential than wind speed and direction, they are important to determine the wind potential. Temperature sensors should be mounted at least 10m from the ground to ensure suitable distant from heat radiating from the earth. Humidity and temperature sensors are often integrated in the same device.

### 2.4.2. Electricity generation from wind power

The kinetic energy of moving air can be used both, to produce mechanical energy and electrical energy. Wind turbines are responsible for transforming the kinetic energy of the wind into rotational mechanical energy. This mechanical energy can be used for specific applications such as grinding grains and pumping water, etc. If the wind turbine is coupled to a generator, the mechanical energy is transformed into electrical energy. The wind power produced is proportional to the dimensions of the rotor and to the cube of the wind speed[7]. Theoretically, when the wind speed doubles, the wind power increases eight times. The main factors of the output power are the swept area of the blades and the wind speed.

#### *2.4.2.1. Small Off-grid wind systems*

Small wind systems are increasingly becoming in a feasible solution for stand-alone electricity generation. They can supply electricity as stand-alone systems, or can easily be integrated into existing island networks, or hybrid systems. There is no internationally agree upon definition of small wind turbine. However, according to the International Electrotechnical Commission Standard 64100-2:2006, small wind turbines have a maximum rotor area of $200m^2$, which equates to a nominal power of a maximum 50kW for an electrical voltage below 1000V (*ac*) or 1500V (*dc*)[6]. Other national organizations in major small wind markets such as: China, the United States and the UK, define a small wind turbine as having a rated power of less than 100kW.

#### *2.4.2.2. Components of a small wind system*

A small wind system is composed by the wind turbine, the tower, and auxiliary devices of the system. The components of a small wind system are described below.

***Wind turbine***. The wind turbine is the most visible part of a wind system. Small wind turbines operate lower to the ground and at lower wind speeds that utility-scale turbines. The most common type is the horizontal axis wind turbine (HAWT). Some characteristics of this turbine are:

- The rotating shaft is mounted parallel to the wind flow/ground;
- The efficiency is reduced when they operate in turbulence regime;
- The maintenance is more complicated, due to the mounting height of the generator.

[7] Information obtained from publications by the International Renewable Energy Agency (IRENA) and the Energy Technology Systems Analysis Programme (ETSAP). [online]. Available at: www.irena.org/

The vertical axis wind turbine (VAWT) has a radically different design, whose main characteristics are:

- The blades rotate around a vertical shaft;
- They operate at lower wind speeds, and can be placed at lower height than the HAWTs;
- VAWTs can generate power from winds blowing in any direction, even vertically;
- Heavy components like generator, can be mounted at ground level, this result in easier maintenance and lighter-weight towers;
- Since they operate at lower wind speeds, they generate less power than HAWTs.

Wind turbines consist of several internal components, which are[8]:

- *Rotor*: it consist of blades with specially shaped aerodynamic surface. The Blades convert the kinetic energy of the wind, into mechanical energy. They should be light-weight, strong, and durable. They are usually constructed of a composite material "*fiberglass*", but they can also be made of another materials such as: wood, aluminum and steel.
  The rotor of HAWATs may be designed with 1, 2, 3, 4, 5, or more blades, whereas in VAWTs the minimum number of blades is two. A great number of blades reduce the mechanical stresses on the system, but increases the cost of the rotor. Figure 2.21 shows horizontal and vertical axis wind turbines.

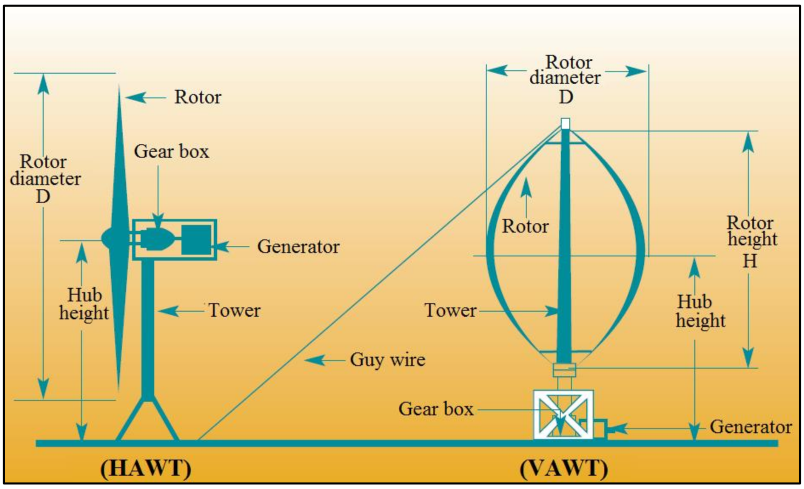



*Figure 2.21: HAWT's and VAWT's: Horizontal and Vertical Axis Wind Turbines*

- *Generator*: small wind turbines, commonly use permanent magnet generators. However, induction generators are also used in small wind turbines. Turbines

[8] Data obtained from "Guía sobre Tecnología Minieólica" by Fundación de la Energía de la Comunidad de Madrid (FENERCOM) and from "Stand-Alone Wind Energy Systems" by Natural Resources Canada. [online]. Available at: www.fenercom.com | http://www.nrcan.gc.ca/energy/publications/sciences-technology/renewable/wind/6225

using induction generators must always be connected to the grid, or to a reactive power source. The electric generator should present the smaller starting torque for easy starting at low wind speeds, thus maximizing the wind resource.

- *Gearbox*: wind turbines, mainly those above 10kW use a gearbox to increase rotational speed from a low speed-rotor to a higher speed electrical generator. However, the generator of most micro and mini turbines rotates at the same speed as the rotor;
- *Nacelle:* it is an enclosure to protect the generator, gearbox, and other internal components. It is removable to allow for maintenance;
- *Yaw system*: it is responsible for aligning the HAWT to the wind. Most micro and mini systems use a simple tail vane that directs the rotor into the wind;
- *Control and protection systems*: it can be constituted for simple switches, fuses, batteries, and computerized systems for controlling and protection of the system.

***Tower***. The tower is an integral part of a wind system. It is responsible to maintaining the turbine at a suitable height, to take advantage of higher wind speeds. The tower also raises the turbine above the air turbulence that can exist close to the ground, due to obstacles such a hills, buildings, and trees, etc. Wind towers must be able to withstand adverse environmental conditions such as lightning strikes, extremely winds, hail, and icing. Therefore, the cost of a tower in a wind system can easily make up 50% of the total cost of the system. There are three types of towers for small wind turbines: freestanding, fixed guyed and tilt-up towers [25]. Figure 2.22 shows the types of towers for small wind turbines.

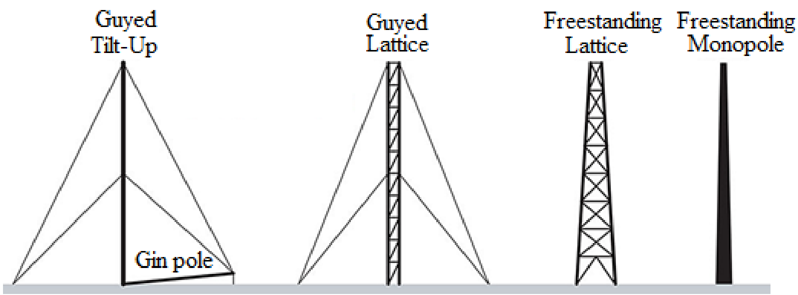



*Figure 2.22: Types of wind towers: Guyed Tilt-up, Guyed lattice, Freestanding*

***Auxiliary components of the system.*** According to the type of energy supply required, the system may need additional equipment to provide electricity at a required voltage and current level. These types of equipment were previously described in section 2.2.

#### *2.4.2.3. Topologies connection of wind power systems*

Small wind systems are commonly installed far from the grid, and where the connection to the grid would be expensive. The simplest off-grid wind system uses a *dc* bus to provide power to devices in remote locations, such as telecommunication equipment and water pumps. These systems may use an ESS, typically batteries to provide backup power in the absence of wind. An inverter device may be added to the system to allow the electricity supply to *ac* appliances. Some stand-alone wind systems do not require energy storage, as in the case of irrigation systems, where all pumped water is directly consumed. Like PV systems, the electricity can be supplied in *dc, ac*, or both. Figure 2.23 shows a typical electric scheme of a stand-alone wind system.

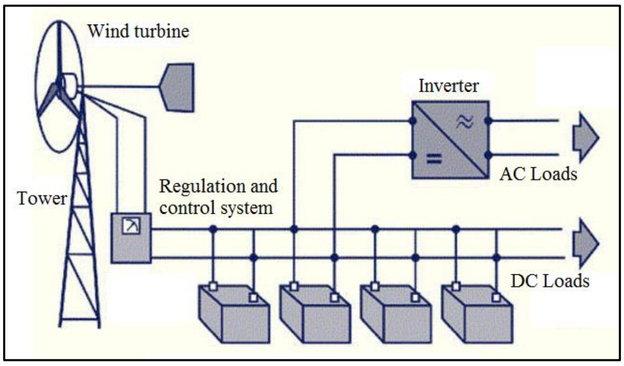



*Figure 2.23: Small off-grid wind system with storage system*

Small wind systems can also be combined with other types of renewable generation sources such as PV systems and diesel generators, which can be a feasible option in places where the wind may fluctuate, or users do not want to be totally dependent on the wind. These systems can provide a reliable supply of energy regardless of wind conditions, but can also be more costly and complex.

### 2.5. Hydro energy exploration

Water energy is obtained from the use of kinetic and potential energies from water streams, natural waterfalls, and tides. It is one of the oldest energy source and has been used for several thousand years in varous usefull tasks such as watermills, textile machines, and sawmills, etc. The growing demand for energy, rapid socioeconomic development, and climate change are factors, by which many governments worldwide have promoted the use of large hydroelectric plants for energy production. The construction of this electric plants involve high investment costs and important environmental impacts *e.g*. flooding, land movement, clearing of vegetation for roads, etc. On the other hand, small hydropower systems (SHPS) up-to 100kW do not produce significant environmental impacts, they can be easily and quickly installed, which makes them a feasible alternative to provide energy in remote areas. The water is considered as a renewable resource, since it is part of a constantly regenerating natural cycle, known as hydrologic cyle.

### 2.5.1. The hydrologic cycle

The hydrologic cycle is a continuous exchange of moisture between the oceans, the atmosphere, and the land. Figure 2.24 shows the hydrologic cycle.

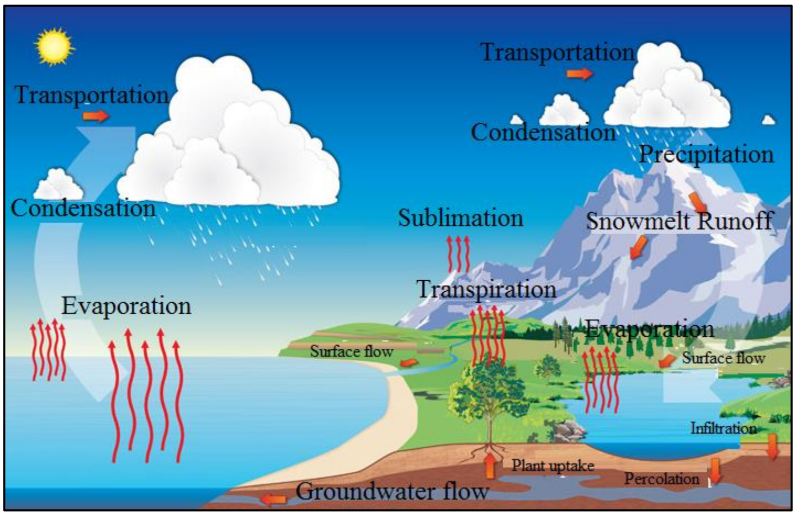



*Figure 2.24: The hydrologic cycle*

The evaporation from the oceans is the primary vehicle for driving water particles from the earth's surface. After the water enters to the lower atmosphere, upward air currents carry it high into the atmosphere. There,  water vapor is in a cooler air, and it may to condense from a gas to a liquid to form cloud droplets. Cloud droplets may grow, and produce precipitation including rain, snow, freezing rain, and hail, etc, which is the primary mechanism for transporting water from the atmosphere to the earth's surface [26].  When precipitation falls over the land surface, some of it evaporates returning to the atmosphere, some seeps into the ground as groundwater, and some runs off into rivers, streams, and lakes, where evaporation is constantly occurring and the cycle remains.

### 2.5.2. Small hydropower systems

Large hydropower plants are classified according to their energy production capacity. However, for small hydroelectric systems this classification may vary in each country. There is no universal consensus specifying the maximum and minimum power ranges for small-scale hydroelectric systems.  According by European Small Hydropower Association and the European Comission, the upper limit of the SHPS is usually taken as 10 MW. Neverthelesses, this limit can be much higher in large countries such as India and China, rising to 25 and 50MW respectively. The SHPS can be also classified into mini, micro, and pico-hydropower plants. Table 2-1 shows a typically classification of hydropower systems.

*Table 2-1: Hydropower systems classification according to the generation capacity*

| Hydropower classification | |
|---|---|
| **Designation** | **Power output** |
| Large | >100MW |
| Medium | 10-100MW |
| Small | 1-10MW |
| Mini | 100kW-1MW |
| Micro | 5-100kW |
| Pico | <5kW |

The present research focuses on the micro and pico-hydropower systems, because they are the most used in developing countries to provide electricity to rural communities and stand-alone applications.

### 2.5.3. Micro and Pico-hydropower systems

Micro-hydropower systems (MHPS) is a mature technology, which is economically feasible and produce minimal environmental impacts. MHPS is one of the most suitable renewable energy solution for productive procedures and rural electrification. It can be easily constructed, operated, and maintained locally. MHPS have several advantages related to PV systems and Wind systems technologies, which are [27]:

- high efficiency (70%-90%)
- high capacity factors (>50%) compared with 10% of solar PV, and 30% for wind power plant
- slow rate of change (*the output power varies only gradually day to day not from minute to minute*)

To determine the energy potential of water flowing in a river or stream, the flow rate of water, and the vertical fall of water known as *"head"* must be determined [28]:

- *Flow rate (Q):* it represent the volume of water passing per unit time ($m^3/s$) in a given point. For small schemes, the flow rate may also be expressed in liters/second, where 1000 liters/second is equal to $1m^3/s$;
- *Gross head (H):* it is the maximum available vertical fall of the water in *meters*, from the upstream level to the downstream level. The gross head is reduced when the water is conveyed into, and away from the machine, this reduced head is known as the *"net head"*. These head losses depend on the type, diameter, and length of the penstock piping, and the number of the bends or elbows. The gross head can be used to estimate the availability of energy and general feasibility, but the net head is used to calculate the actual power available.

#### *2.5.3.1. Water flow measurement*

There are numerous ways to measure the flow rate of rivers and streams. The three most common methods of flow rate measurement are [29]: (a) velocity-area method, b) overflow weir Gaugin method, and c) bucket method.

a) To measure the flow rate of a river, channel, or stream, the surface water velocity (m/s) and the cross-sectional area ($m^2$) must be determined. The product of these two measurements gives the flow rate per unit time Q = V *A ($m^3$/s).
   - Since the depth of the river varies, the best method is to divide the river into sections of equal width, and measure the depth of each section. Then, the total cross-sectional area can be calculated as the sum of the cross-sectional area for each section;
   - The water velocity can be measured using a current meter, which consist of a propeller which point upstream, and is turned by the water flowing. In order to make a reasonably estimate, the average velocity can be found by taking two readings in each section, one at 0.8, and one at 0.2 of the depth.

   Figure 2.25 shows the total cross-sectional area of a stream, and a typical current meter for water speed measurement.

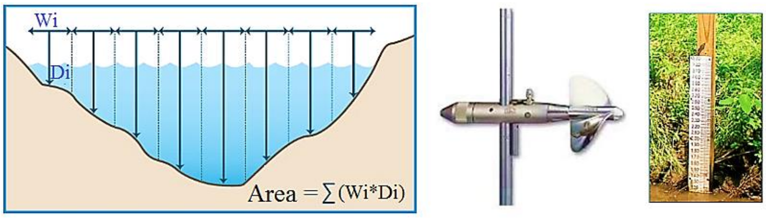



*Figure 2.25: Measurement of cross-sectional area and water velocity in a stream*

b) Gauging weirs are used to accurately measure the flow rate of small streams and channels. Weirs can be permanent or movable structures, which are placed across the stream to raise the water level and control the flow. These structures have an opening cut into the crest. The water from the stream flows through the opening, and must fall freely on to the stream bed below. The flow of the water can be determined by measuring the depth of water flowing over the weir, and using a standard calculation for each type of weir.

   Flumes can also be used to measure the flows of small streams. These are structures placed across the stream, which reduce the width of the stream. The flow rate is calculated from the head of water flowing through the flume. Figure 2.26 shows weirs and flumes for water flow measurement.

*Figure 2.26: Weirs, flumes and current meters for flow rate measurements*

c) It is the simplest flow measuring method, and is used in small streams or channels. This method consist of diverting the flow of the stream into a bucket, and record the time it takes to fill. The volume of the container is known, and the flow rate is simply obtained by dividing this volume by the filling time.

#### *2.5.3.2. Implementation schemes for MHPS*

MHPS can be integrated in natural systems such as streams, rivers, irrigation water networks, and even in drinking water, or wastewater network. The most commonly implementation schemes for MHPS are: run-of-river systems, or systems integrated into existing water infrastructure. In run-of-river schemes, the hydropower system generate electricity when there is sufficient water from the river. When the water flow falls below the minimum technical flow for the turbine, the generation ceases. The run-of-river schemes with medium and high vertical fall of water, use weirs to divert water to the intake, from where it is conveyed to the turbines via a pressure pipe, or penstock. An alternative to the pressure pipe is to convey the water by a low-slope channel, that running alongside the river to the pressure intake or forebay, and then via a short penstock to the turbines. If the use of a channel is not convenient, a low-pressure pipe can be an economical option. Sometimes a small storage reservoir can be built in the forebay, in order to the hydro-plant operates when there is not sufficient water. At the outlet of the turbines, the water is discharged to the river. Figure 2.27 shows the run-of-river scheme of MHPS.

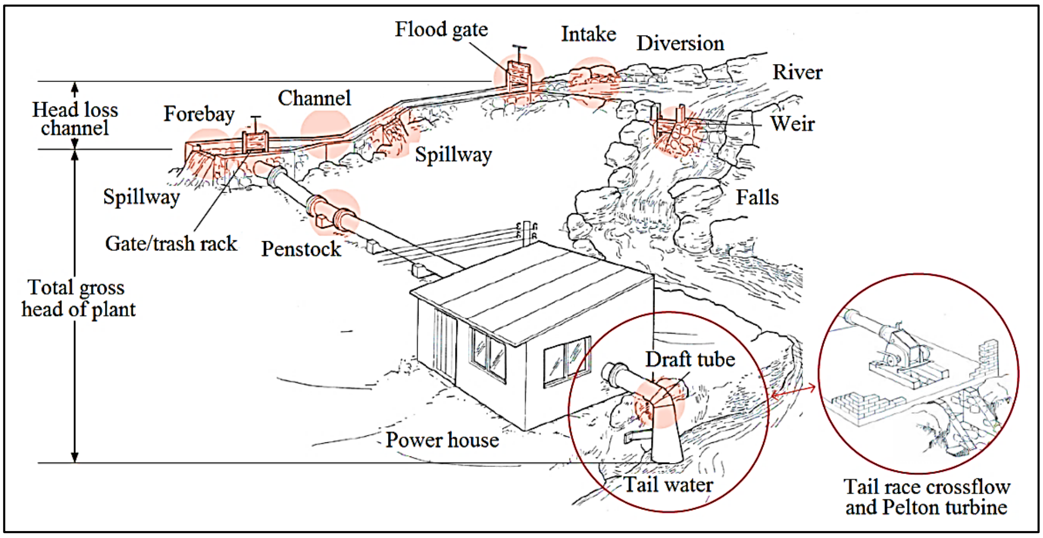


*Figure 2.27: Run-of-river scheme for MHPS*

Pico-hydropower systems require only small flows of water, therefore there are numerous suitable sites for implementation. Since the components parts of these systems are small and compact, they can be easily transported into rural and remote regions. Pico-hydropower systems are based in similar schemes than MHPS, but in smaller size.

#### 2.5.3.3. Components of a MHPS

The main components of a MHPS are described according to the figure 2.27 [30]:

- **Weir:** it is a barrier built in the river, or stream to regulate the water and ensure a constant water flow through the intake.
- **Intake:** it is placed nearby the weir, and its function is to ensure that an optimal amount of water enters the channel and goes to the turbine.
- **Channel:** the purpose of the channel is to transport water from the intake to the forebay. The channel must remain at a constant elevation, avoiding losses of the total gross head of the plant. One of the main challenges when constructing the channel is to make the water flow at an adjusted speed. The channel can be completely natural, or it may be built by sand and clay, or it can be strengthened with a concrete or cement lining.
- **Spillways:** they are necessary to empty the channel and the forebay. They also serve as protection against damage from excessive water flow.
- **Forebay:** the main objective is to slow down the water to allow the sediment sink to the bottom. Therefore, turbulence must be avoided in the forebay.
- **Penstock:** it transports the pressure water from the forebay to the turbine. Due to friction in the penstock some head is always lost on the way to the turbine. The friction depends on the diameter of the penstock, therefore, a wider pipe has less friction than a narrower pipe, but a wider pipe is more expensive.

- **Power house:** it is the place where the turbine/generator set, and the auxiliary equipment are installed. For very small hydro-systems, a power house is not required. The hydro-turbine is coupled to a generator, thus the kinetic energy of falling water is transformed into electrical energy. The choice of the turbine depends of the head and the flow rate. The two main types of hydro turbines are: impulse turbine and reaction turbine. Table 2-2 shows the hydro-turbines classification [31].

*Table 2-2: Hydro-turbine classification*

| Turbine runner | Pressure head | | |
|---|---|---|---|
| | High | Medium | Low |
| Impulse | Pelton turgo<br>Multi-jet pelton | Crossflow turgo<br>Multi-jet pelton | Crossflow |
| Reaction | | Francis pump as turbine (PAT) | Propeller kaplan |

The main characteristics of these turbines are presented below:

*Impulse turbine*: the blades of an impulse turbine rotate in the air by the force of water, which is directed to the blades from one, or more jets of water, known as nozzles. This type of turbine operates in a fully open, or semi open casing, therefore, there is no pressure drop across the turbine. Since, the nozzle can be adjusted to deliver more or less water, they can be used in seasons with different flows of water;

*Reaction turbines*: the blades of a reaction turbine are completely immersed in water, and are enclosed within a pressurized casing. It starts to rotate by the pressure change, known as "pressure drop". A reaction turbine can be used to pump water and vice versa, since the flow of water of this turbine can be reversed due to the angle of the internal blades.

An electric generator is coupled to the rotating shaft, and it is responsible to converts the mechanical energy into electric energy. Induction, and synchronous *ac* generators, as well as *dc* generators are often used in MHPS. The main advantage of an *ac* scheme, is that the power can be transmitted over quite long distances. This make *ac* generators suitable for rural electrification projects, because the electrical loads are usually quite spread out. Induction generators are preferred in remote areas, because they are robust and very reliable [31]. DC generators are used in low energy consumption systems to power small electrical appliances and illumination systems. Additional electronic equipment such as charge controller, inverter, metering devices, fuses, and electronic load governor are placed in the power house for controlling and protecting the system. In addition, an ESS can be also integrated in the power house.

- **Drive tube:** it is used to discharge the water into the river again.

Figure 2.28 shows turbine/generator sets and various components of a MHPS [15], [32].


*Figure 2.28: Turbine/generator sets and different components of MHPS*

#### *2.5.3.4. Topologies connection of MHPS*

Like PV systems and Wind systems, mini and micro hydropower systems can supply energy in *dc*, *ac*, or both. They can be connected to a grid, or operate as stand-alone systems.

*DC* coupled schemes are commonly used to provide energy to small illumination systems, and for charging batteries, therefore, these systems should be installed near the hydro-power plant. In *ac* coupled schemes, the energy produced by the generator is fed directly to the load by means electronic controllers, which guarantee the operation of the system at a suitable frequency and voltage level. These systems are used to provide energy to higher loads such as motors, single household, and villages. MHPS are also combined with other type of generation systems for supplying reliable energy to isolated communities, or productive activities. The turbine/generator set, usually incorporate a frequency and voltage control system. Figure 2.29 shows different electrical schemes for hydro-power systems.

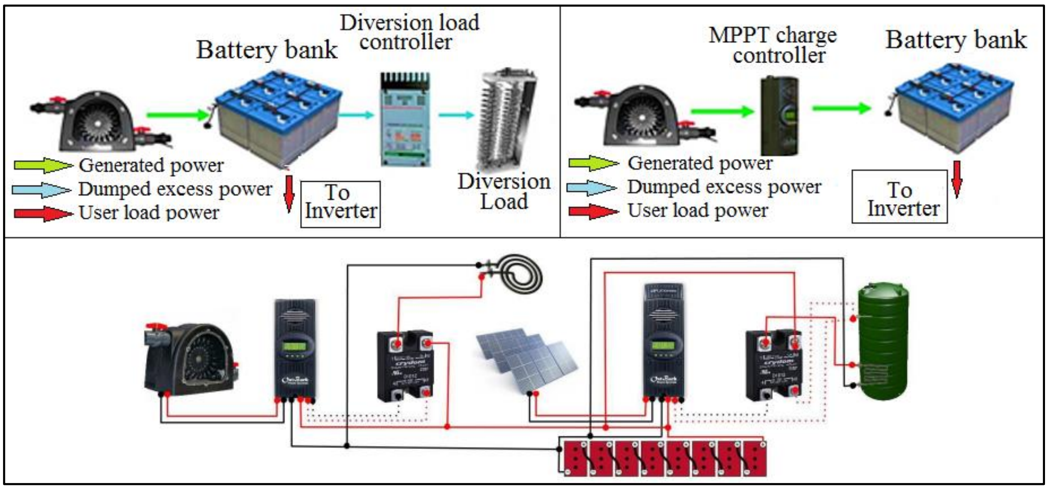



*Figure 2.29: Electric schemes for MHPS applications*

## 2.6. Biomass energy

Biomass is a renewable energy source that has been used as fuels since humans first learned to control fire, and it is still the main type of fuel for many people that lack access to electricity and suitable fuels for cooking. Bioenergy represents approximately 10% of global energy supply; two thirds of the biomass are consumed in developing countries for cooking and heating [33]. Biomass is a form of solar energy storage, since plants capture solar energy, transform it into chemical energy, and store it in its chemical structure *e.g.* trunk, roots, leaves, etc. Biomass represents the biodegradable fraction of products, wastes, and residues derived from biological origin such as agriculture, forestry, fisheries, and aquaculture. It includes the biodegradable fraction of industrial and municipal waste.

Bioenergy could be considered as CO2 neutral, since the production of biomass captures similar amounts of CO2 that is released during combustion. The most commonly used biomass for electricity, and/or heat production can contribute towards a reduction of 55% to 98% CO2 emissions over fossil fuels[9]. However, different production steps such as cultivation, harvesting, pre-treatment, and transportation may cause greenhouse gas emission. Biomass can be converted into solid, liquid, and gaseous forms of energy. The combustion of them is used to produce heat, cold, electricity, mechanical power, or a combination of these. This conversion process is carried out through thermal-chemical process such as combustion, gasification, and pyrolysis, or bio-chemical processes like anaerobic digestion.

### 2.6.1. Biomass combustion technologies

This is perhaps the simplest method of extracting energy from biomass. Biomass is burned, and the energy produced can be used for different applications. In remote

[9] Data obtained from "Six Sources of Energy – One Energy System" by the Vattenfall's Energy Portfolio and the European Energy System [online]. Available at: https://corporate.vattenfall.com

regions, it is only used as fuel for cooking and heating. For electricity generation purposes, the combustion of biomass is used in a wide range of scales, from few MW to 100MW, or more. The two main components of a combustion-based biomass plant are: the biomass-fired boiler to produce steam, and the steam to generate electricity.

The boilers can be fueled entirely by biomass or can be co-fired with a combination of biomass and a coal or other solid fuels. Figure 2.30 shows different biomass co-firing configurations[10].

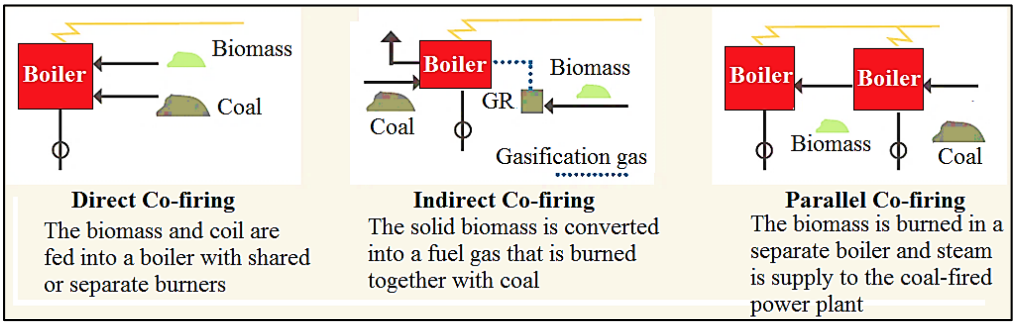



*Figure 2.30: Different biomass co-firing configuration*

### 2.6.2. Biomass gasification technologies

Gasification is achieved by the partial combustion of solid biomass in a low oxygen environment, at more than 700°C. Synthetic gas "*syngas*", is a result of the gasification process. The resulting gas is a mixture of carbon monoxide, water, CO2, char, tar, and hydrogen, and it can be used for generating electricity, heating, and as fuel. Biomass gasification could be a feasible solution for remote rural areas with an abundance of shrubs, straw, rice husk, or other forms of biomass [34].

The gasification process comprises two steps, although a third step is something include:

1- Pyrolysis: it is the decomposition of the biomass feedstocks by heat.
2- Gasification process: in this process the volatile hydrocarbons and the char are gasified at higher temperatures.
3- Filtering: the resulting gas can be clean-up to remove contaminants.

The small-scale gasifiers often use the fixed-bed technology, which produces a fairly clean gas, and is the most economical option for small systems (up to 100kW). In this type of gasifiers, the biomass and reactive agents are introduced at the top of the reactor, the tars pass through the oxidation and charcoal reduction zones. They tend to require a homogeneous feedstock to achieve the best results. Figure 2.31 shows a downdraft fixed-bed power gasifier.

[10] Data obtained from "Biomass for Power Generation" by the International Renewable Energy Agency (IRENA) [online]. Available at: www.irena.org/

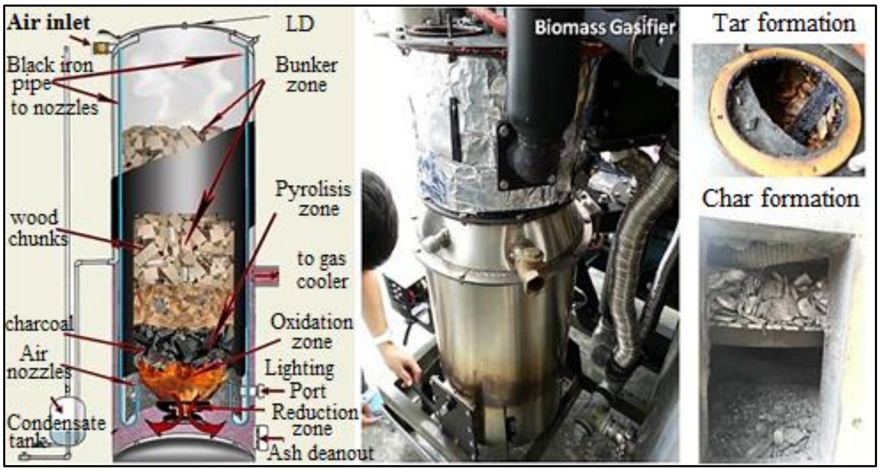



Figure 2.31: Downdraft fixed-bed power gasifier

### 2.6.3. Anaerobic digestion for biogas production

Anaerobic digestion is the process of organic matter decomposition that occurs in the absence of oxygen. The result of this process are biogas, and a liquid residue rich in minerals that can be used as a bio fertilizer. After a filtering stage, the biogas can be used in internal combustion engines for electricity generation, or it can also be upgrades to bio methane for distribution. The anaerobic fermentation consists in four stages:

- *Hydrolysis*: at this stage the bacteria break down long chains of complex carbohydrates, proteins, and lipids into shorter parts.
- *Acidogenesis*: the fermentative bacteria break down the intermediate products from hydrolysis, forming lower fatty acids along the carbon dioxide, and the hydrogen.
- *Acetogenesis*: at this stage the rest of the acidogenesis products are further digested by acetogenic bacteria to produce acetic acid, carbon dioxide, and hydrogen. The acetogenic bacteria are facultative anaerobic, and can create an anaerobic condition, which is essential for methane producing microorganisms.
- *Methanogenesis*: during this stage, all acetic acid, hydrogen, and carbon dioxide are converted into methane by strictly anaerobic methanogenic archaea.

The four phases of anaerobic degradation take place simultaneously. During the anaerobic fermentation, the environmental parameters such as oxygen, temperature, pH value, nutrient supply, and inhibitors, etc., play an important role on the methane concentration level of the output gas [35]. The energy content of the output gas depends mainly on its methane content. The gas produced consists about 50-75% methane, 25-45% carbon dioxide, 2-8% water vapor, and traces of $N_2$, $NH_3$ and $H_2H_2S$.

Small biogas systems are mainly used for cooking and heating, whereas large biogas systems are used to generate electricity and provide energy to farms, or even inject energy into the grid. The small scale systems used to produce biogas are:

- Biogas system for household: this system is composed of a household biogas digester. The Household digester is characterized by a low implementation cost and simple operation. It is commonly used in isolated areas, and use substrates from small agriculture activity, as well as human wastes for biogas production.
- Covered lagoon system: this type of biogas system operates at small and large-scale. It is commonly used in farms with large organic wastes.
- Industrial biogas plant: in this system, the plant includes large reactors and auxiliary systems like piping, stirring, circulation, gas cleaning, and handling as well as monitoring, and control systems to obtain a high quality biogas.

#### *2.6.3.1. Household digesters*

The design of a household digester varies depending on the geographical location, availability of substrates, and climate conditions. There are several types of biodigesters developed, however, the fixed dome model developed by China and the floating drum model developed by India have been the most adopted, and are currently still used. Several types of household digester are described below [36]:

- *Fixed dome digester*: a fixed-dome digester is usually built underground. It consists of a fixed, non-movable gas holder, which sits on top of the digester. The digester is loaded through the inlet pipe until it reaches the bottom level of the expansion chamber. The biogas produced is accumulated at the upper part of the digester. The difference in level between the slurry and the expansion chamber creates a gas pressure. The collected gas presses part of the substrate into the expansion chamber, causing the slurry flows back into the digester (see Figure 2.32-a).
- *Floating drum digester*: floating-drum technology consists of an underground cylindrical or dome-shaped digester, and a movable inverted drum (see Figure 2.32-b). The weight of this inverted drum applies the pressure needed for the gas flow through the pipeline. The gas is collected in the gas drum, which rises or moves down, according to the amount of gas stored.
- *Plug flow digester*: this is a portable digester that have a constant volume, but produce biogas at a variable pressure. It consists of a narrow and long tank with an average length to width ratio of approximately 5:1. The inlet, and outlet are located at opposite ends, kept above ground, while the remaining parts are buried.

This digester can be placed in an incline position. The inclined position produce a two-phase system, which longitudinally separates acidogenesis and methanogenesis. A gable, or roof can be placed on top of the digester during the night in order to avoid temperature fluctuations.

Figure 2.32 shows the fixed dome and floating drum household digesters.

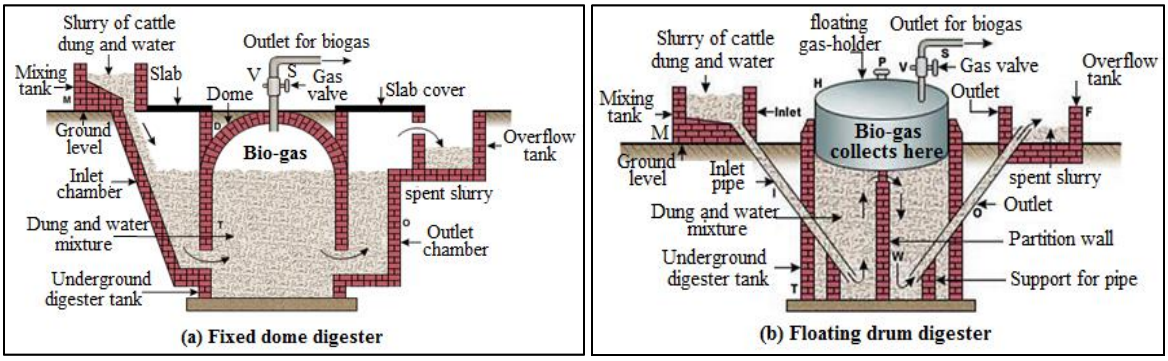



*Figure 2.32: Household digesters: (a) Fixed dome digester (b) Floating drum digester*

#### *2.6.3.2. Applications of biogas from household digesters*

The most common applications for biogas from small digester are [36]:

- *Cooking and heating*: the biogas obtained is mainly used for cooking. Biogas burning is not possible in commercial butane and propane burners due to its physiochemical properties. Therefore, burners are modified in the gas injector, its cross-section, and maxing chambers.
- *Fertilizer*: the slurry obtained from digesters is rich in nitrogen, phosphorus, and potassium, and can be used as a fertilizer. The nutrient concentration of the slurry can easily be taken up by plants, increasing the agricultural production.
- *Illumination and power generation*: Biogas lamps are most efficient that kerosene powered lamps, but the efficiency is quite low compare to electric-powered lamps. To generate electricity, internal combustion engines are typical used, but, since biogas requires a liquid fuel to start ignition, diesel can be combined with biogas for driving an electric generator.

Figure 2.33 shows different household digester for rural application.

*Figure 2.33: Household digesters for rural applications*

#### 2.6.3.3. *Covered lagoon biogas system*

This type of technology is mostly used for the treatment of liquid wastes with higher organic solved loads. The most suitable substrates for this kind of technology are liquid manure, palm oil effluents, and effluents from starch, or from production plants. The most successful arrangement includes two lagoons connected in series to separate biological treatment for biogas production and storage for land application. The characteristics of this system are:

- The primary lagoon is anaerobic and operated at a constant volume to maximize biological treatment, methane production, and odor control.
- The secondary lagoon receives effluent from the primary lagoon and contaminated runoff to be stored and used for irrigation, recycle flushing, or other purposes.

The process of operation is as follows: The effluent is deposited by a piping system in the primary lagoon, which has the bottom insulated by impermeable geomembranes, and is covered by a gas-hermetic membrane. The primary lagoon has suction pipes that allow collect the sediment. At the end of the lagoon, extraction pipes suck the digested effluent away, and distribute it to a secondary lagoon, which is characterized by being smaller and open. Figure 2.34 shows the scheme of a covered lagoon biogas system.

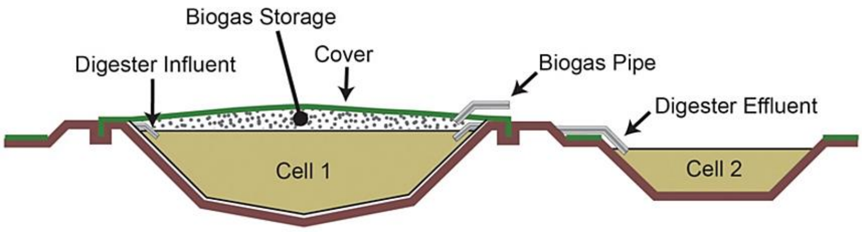



*Figure 2.34: Scheme of covered waste lagoon*

#### 2.6.3.4. *Agricultural biogas plant*

Agricultural biogas plants use a mix of crops and liquid manure to produce biogas, fertilizer and electricity. As a first step, the co-substrate might be pre-treated in order to improve the performance of the digestate process. In some cases the pre-treatment system is not required. Pre-treatment process refers to the sorting of the substrate to reduce the amount of contamination, as well as sterilize the substrate according to the hygiene regulations valid for animals wastes[11]. Figure 2.35 shows a sketch of biogas plant for agricultural application.

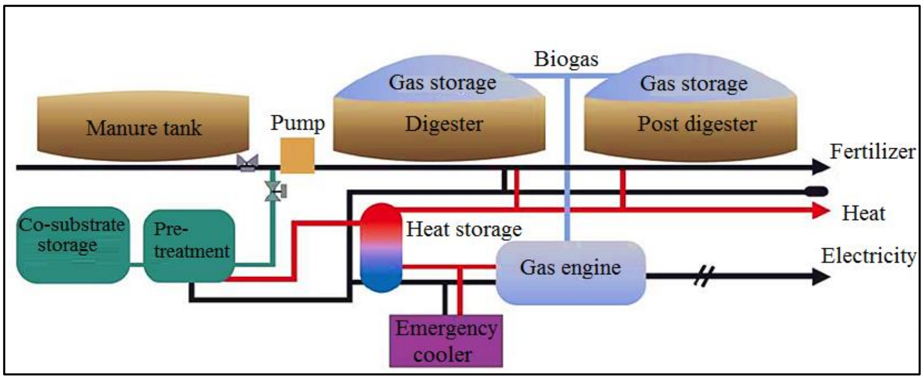



*Figure 2.35: Sketch on a biogas plant for agricultural application*

To conserve the fermentation process, a part of the heat generated is used as heating to provide a suitable temperature for the bacteria. This types of biogas plants can be designed both, as single, or two-stage processes. In a plant of a single stage, the four processes of anaerobic digestion occur in one digester, whereas a plant of two stages allow the separation of hydrolysis and acidogenesis in one digester and the acidogenesis and methanogenesis in the main reactor[10].

## 2.7. Energy storage systems for stand-alone applications

The nature of RES is intrinsically variable in time, due to the daily cycles, seasons, and environmental conditions. Therefore, an ESS is usually required for storing the excess of energy produced and providing continuous power to the loads when there is low or null energy generation. Storage technologies can be classified as follow:

- *Electrochemical storage*: Lead, lithium, nickel, sodium-based and flow batteries
- *Chemical energy storage*: Hydrogen, synthetic natural gas
- *Electrical energy storage*: Capacitors, superconducting magnetic energy storage
- *Mechanical energy storage*: Flywheels, pumped hydro, compressed air
- *Thermal energy storage*: Heat (*hot water/phase-change material*), molten salt (*concentrated power solar thermal*)

This work focuses on electrochemical energy storage, because they are the most effective storage technology applied for rural electrification, and has been implemented in numerous off-grid installations. There are several batteries available in the market,

[11] Information obtained from "Biogas technology and Biomass" by the Renewable Academy (RENAC) AG [online]. Available at: www.renac.de

therefore, numerous guidelines should be considered when selecting batteries for off-grid applications, which are [37]:

- Automotive batteries of any type are not suitable for use in off-grid systems, since an automotive battery is designed for providing high current for a short duration. These batteries in off-grid systems would have a short lifetime, therefore, they have to be regularly replaced;
- All batteries used in off-grid systems operate on a daily basis in various states of charge, therefore a deep cycle batteries are required to provide high reliability. The batteries selection should consider the best technology to fulfill the specific technical and environmental requirements of the system.

### 2.7.1. Measuring performance of batteries

In order to measure the battery performance, and determine the best choice for a specific application, several indicators and parameters are described below.

- *Energy storage capacity (kWh/Ah)*: it represent the amount of energy than can be stored, or consumed in a battery. It is generally calculated in Amperes hour (Ah);
- *Energy density (kWh/kg, kWh/m$^3$, kWh/l)*: it measures the energy storage capacity according to its volume. Energy density is an important factor in applications with reduced spaces;
- *Efficiency (%)*: it is the relation between the useful output and the input.
- *Operating temperature (°C)*: the operation of batteries is based on an electrochemical process, therefore, they lose power in cold environment and also are sensitive to heat. Batteries have their optimum performance in a certain temperature range;
- *Depth of discharge DOD (%)*: it measures how deeply a battery is discharged. DOD varies depending on the type of battery. Most of batteries designed to operate in renewables systems can operate at a partial state of charge without compromising their lifetime;
- *Lifetime of a battery (years)*: the life time of a battery is calculated for a given operating temperature, discharge current, and number of cycles with specified DOD. According to the battery technology, the lifetime may vary significantly.

### 2.7.2. Description of the types of batteries

#### *2.7.2.1. Lead-based batteries*

These types of batteries are the most widely used. Lead acid battery systems are used in both, mobile, and stationary applications. Their typical applications are emergency power supply systems, PV stand-alone systems, and starter batteries in vehicles, etc. They have the following features [37]:

- low cost/kwh;
- proven technology in stationary applications;
- robust design;
- high resource efficiency and recyclability.

There are two families of lead-based batteries

- <u>Vented/flooded batteries</u>: they require periodic maintenance for refilling water;
- <u>Valve-regulated lead acid (VRLA) batteries</u>: they are sealed and maintenance free.

Figure 2.36 shows the classification of lead-based battery, and some general indicators.

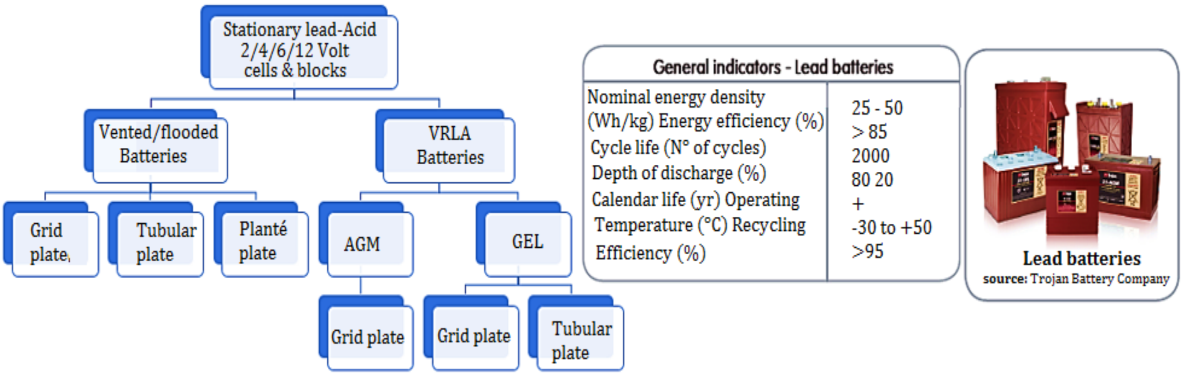



*Figure 2.36: Classification of lead-based battery*

#### *2.7.2.2. Nickel-cadmium batteries*

These batteries have been used for several decades as alternative to lead-based batteries. The main characteristics of nickel-cadmium batteries are [37]:

- long calendar life (typically over 20 years);
- high cycle life in cycling applications;
- high reliability and robustness;
- gradual loss of capacity when aging;
- ability to operate at extremes temperatures.

These characteristics makes them well suited for rural electrification systems under extremes environmentally conditions. Nickel cadmium batteries are built with different electrode designs. Figure 2.37 shows the classification of Nickel-cadmium batteries.

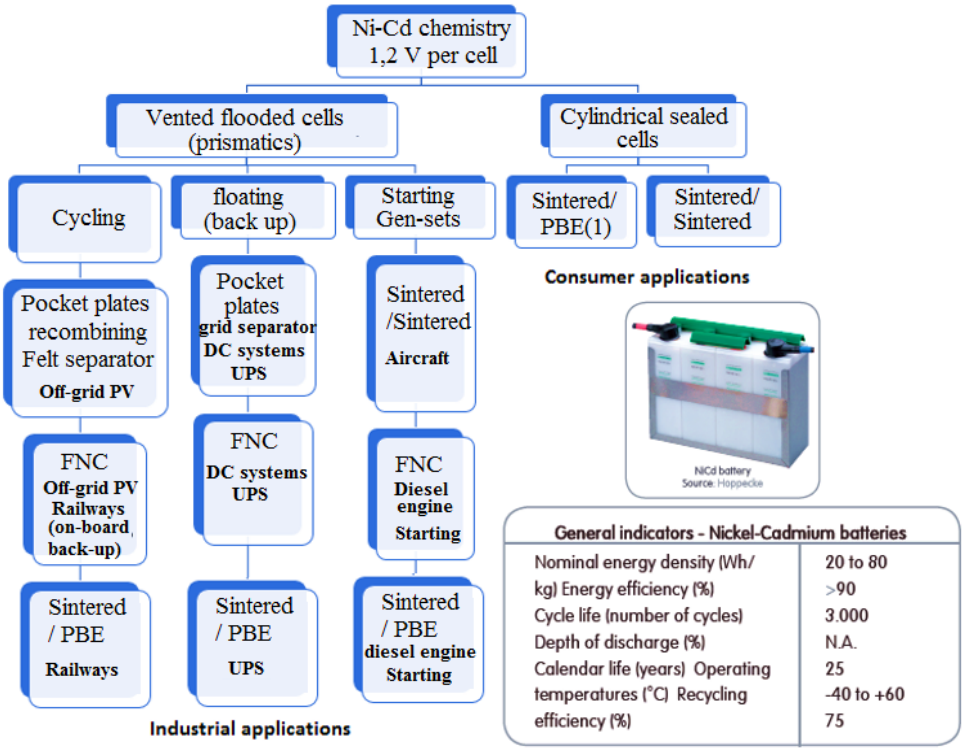



*Figure 2.37: Classification of nickel-cadmium batteries*

### *2.7.2.3. Lithium-ion batteries*

They are a well-established technology for consumer portable electronics and electric vehicles. The main features of these batteries are [37]:

- high energy density and efficiency;
- maintenance-free design;
- lighter weight;
- excellent charge acceptance;
- long calendar and cycle lifetime.

Lithium-ion batteries are most suitable for rural applications when the volume and weight play an important role as driving factor than initial costs. These types of batteries require a sophisticated electronic control to avoid overcharge, monitor cell temperature, and perform cell balancing. Figure 2.38 shows the types of lithium-ion batteries and general indicators.

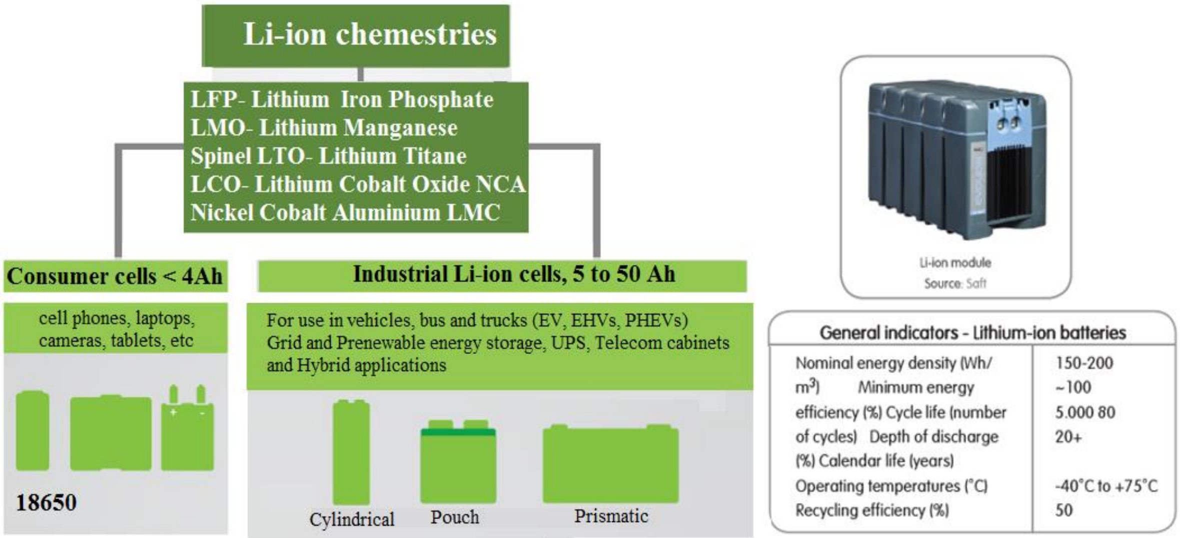


Figure 2.38: Classification of lithium-ion batteries

### 2.7.2.4. Sodium-nickel chloride batteries

The commercial applications of these types of batteries are limited to large scale grid stabilization "*power quality and peak shaving*". In industrial applications, the main features are [37]:

- high specific energy;
- constant performance and cycle life in harsh operating environment (-40 to 60°C);
- low maintenance requirements.

Since their cycle life remains constant although external temperature, these batteries are best suited for rural application characterized by harsh ambient system. Figure 2-39 shows the types of sodium nickel chloride batteries and general indicators.

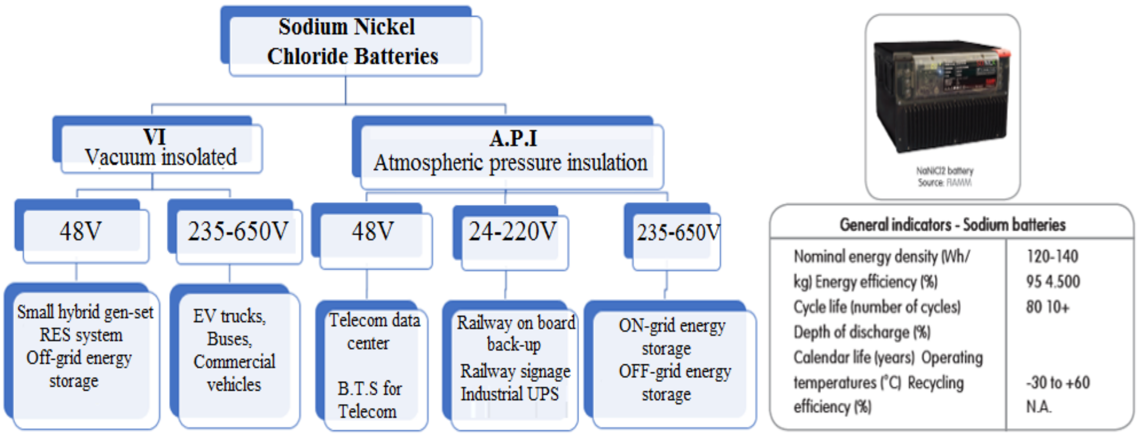


Figure 2.39: Classification of sodium-nickel chloride batteries

Chapter 3

# 3. Methodology

## 3.1. Case study

The techno-economic analysis by using stand-alone home systems and a centralized system as an alternative to electricity supply, was carried out in the Yuwints community. Yuwints belongs to the Taisha canton in the Amazon region of Ecuador. Taisha has a population of 22028 inhabitants, and it is constituted of 5 parishes: Taisha, Macuma, Tuutinentsa, Huasaga, and Pumpuentsa with a total of 147 communities belonging to the Shuar and Achuar ethnic groups. This region is crossed by a great number of streams and six main rivers that are most of the year navigable. However, the most representative rivers are Kankaim and Macuma rivers, since they can be navigated with boats up to 40 passengers.

Yuwints community is located in the Macuma parish at the geographic coordinates (2° 09' 53,9'' S° | 77° 34' 38,4'' W), at an altitude of approximately 492 meters above sea level. This area enjoys of a tropical climate, with a significant amount of rainfall throughout the year. The average temperature is 23,4 °C, reaching its maximum in December, with a temperature of 24,1 °C and its lowest temperature of 22,3 °C during the month of July[12]. Figure 3.1 shows the location of Macuma parish and the physical distribution of the dwellings in the Yuwints community.

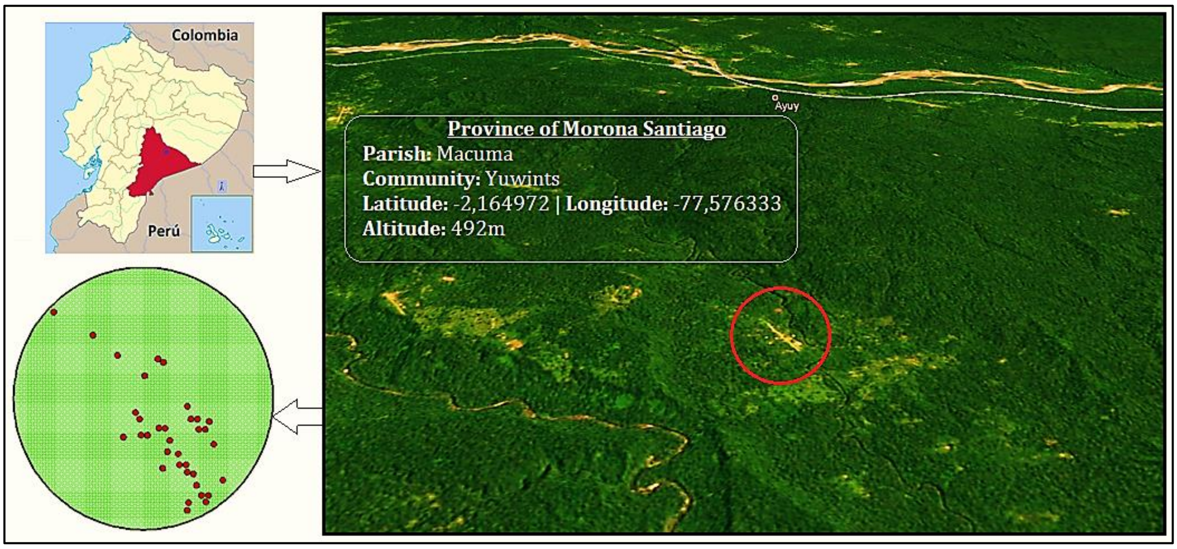



*Figure 3.1: Location of the Macuma parish and physical distribution of households in Yuwints*

[12] Data obtained from CLIMATE-DATA.ORG [online]. Available at: https://es.climate-data.org/location/179626/

### 3.2. Data collection

The features of the location, as well as its renewable potential were obtained by visiting the community. The visit was carried out with the help of a local guide, and with two fellow researchers on similar topics. The options to access the community are currently by air (using a small plane), or by land (walking). It was decided to choose the second option.

The starting point was the parish center of Macuma, from which there is about 13,2km to the Yuwints community. The hike was done through a difficult terrain (*mud and vegetation*), and under typical local climatic conditions (*rain*), whereby the total walking time was approximately six hours. During our stay in the community, the information on the physical characteristics of the community, functionality of existing PV systems, electrical appliances available in the dwellings, use of electrical equipment by the inhabitants, and availability of renewable energy resources for electricity generation was obtained. In order to improve the quality of life of people, the use of biomass resources as an alternative for cooking and heating has been also analyzed. Figure 3.2 shows images of the journey to Yuwints, as well as the activities carried out within the community and nearby communities.


Figure 3.2: Journey to the Yuwints community

#### 3.2.1. Solar energy resource

The Yuwints community is located close to the equator, therefore it receives an abundant supply of solar radiation throughout the year. The monthly average radiation data was obtained from the Solar Atlas of Ecuador. According to this information, this area receives an annual average solar radiation of 4,43 kWh/m$^2$/day. In addition, solar radiation data was also obtained from the NASA Surface Meteorology and Solar Energy Web Site in order to compare the average, maximum and minimum radiation values, and the months where they were registered. Table 3-1 shows the monthly average of solar radiation for this area.

*Table 3-1: Monthly average of solar radiation for the Yuwints community*

| Month | Surface meteorology and solar energy (NASA) | | Solar Atlas of the Equator |
|---|---|---|---|
| | **Daily solar radiation-horizontal surface** | | **Average global radiation** |
| | $kWh/m^2/d$ | Clearness index | $kWh/m^2/d$ |
| January | 3,66 | 0,356 | 4,22 |
| February | 3,44 | 0,327 | 4,27 |
| March | 3,47 | 0,330 | 4,42 |
| April | 3,66 | 0,363 | 4,41 |
| May | 3,64 | 0,385 | 4,26 |
| June | 3,45 | 0,381 | 3,92 |
| July | 3,53 | 0,383 | 4 |
| August | 3,88 | 0,397 | 4,35 |
| September | 4,04 | 0,392 | 4,91 |
| October | 4,24 | 0,405 | 4,92 |
| November | 4,25 | 0,413 | 4,99 |
| December | 3,85 | 0,379 | 4,54 |
| Average | 3,76 | 0,376 | 4,43 |

The solar radiation levels obtained from the Solar Atlas of Ecuador are more promising, therefore these values will be used for the simulations. Annex A.1 shows the solar radiation map of Ecuador.

### 3.2.2. Wind energy resource

According to data provided from Wind Atlas of Ecuador, the availability of this renewable resource is not enough to be considered as a feasible electric generation system. However, the monthly average of wind speed will be considered for simulation purposes of possible systems candidates. Since the data provided in the Wind Atlas of Ecuador were taken at 80 m height, it was decided to refer these values at 10 m height, and compare with the monthly wind speed data obtained from the NASA website. The formulation used to refer the wind speed values at a different height, is described as follow[13].

$$v_{(2)} = v_{(1)} \frac{ln\left(\frac{H_{(2)}}{z_0}\right)}{ln\left(\frac{H_{(1)}}{z_0}\right)} \tag{1}$$

Where:

- $v_{(1)}$ represents the wind speed at height $H_{(1)}$
- $v_{(2)}$ represents the wind speed at height $H_{(2)}$
- $z_0$ represents the roughness length (0,2)

[13] Data obtained from the Wind Atlas of Equator [online]. Available at: http://biblioteca.olade.org/opac-tmpl/Documentos/cg00041.pdf

Table 3-2 shows the monthly average wind speed for the Yuwints community.

*Table 3-2: Monthly average of wind speed for the Yuwints community*

| Month | Surface meteorology and solar energy (NASA) | Wind Atlas of the Equator | |
|---|---|---|---|
| | **Wind speed (m/s at 10m)** | **wind speed (m/s at 80m)** | **Wind speed (m/s at 10m)** |
| January | 1,8 | 3 | 1,96 |
| February | 1,8 | 3 | 1,96 |
| March | 1,8 | 3,5 | 2,29 |
| April | 1,9 | 3,5 | 2,29 |
| May | 2,1 | 3,5 | 2,29 |
| June | 2,5 | 3,8 | 2,48 |
| July | 2,6 | 4,5 | 2,94 |
| August | 2,5 | 3,9 | 2,55 |
| September | 2,3 | 4,5 | 2,94 |
| October | 1,9 | 4,2 | 2,74 |
| November | 1,9 | 4,1 | 2,68 |
| December | 1,8 | 4 | 2,61 |
| Average | 2,08 | 3,79 | 2,48 |

The solar radiation levels obtained from the Wind Atlas of Ecuador are more promising, therefore these values will be used for the simulations. Annex A.1 shows the feasible short-time potential map of wind resource of Ecuador.

### 3.2.3. Hydro energy resource

The nearest water source is a river located 200m from the community. There is the availability of a fall of approximately 15-20 m, in a distance of 1,3 km. The Cuzutka river may represent a feasible solution for small scale electricity generation, since the river flow does not decrease significantly throughout the year. Figure 3.3 shows an image of the Cuzutka river.

*Figure 3.3: Cuzutka river*

### 3.2.4. Biomass energy resource

Biomass could represent another feasible solution for energy generation in this community. Nevertheless, there is neither any study about the raw material available in the community, nor a methodology for the correct use of this resource.

Products obtained from agricultural activities are only used for domestic consumption. Therefore, there is no large-scale agricultural activity in this region. The agriculture activity is shared between orchard crops for own consumption and local sales. The main products are: cassava, banana, corn, and Chinese potato, etc. The agricultural production in home orchards, guarantees the feeding, health, and survival of the families, since a wide variety of products and medical plants are grown in places that do not require much space. On the other hand, the cattle activity is very little practiced, representing the 1,53% of the total of 1877 heads of cattle existing in the Macuma parish[14].

It should be noted that few years ago, a system of domestic biodigesters for food cooking was implemented in some dwellings in the community, but due to lack of maintenance it got damage, forcing the people to cook by using firewood. Most of the inhabitants perform the cooking food in closed and in some cases poorly ventilated areas, which could cause serious respiratory illness due to the emanation of toxic gases during the cooking process (see Figure 3.4). Therefore, improving the electricity service to this community will also improve the quality of life of the inhabitants.

*Figure 3.4: Conventional way of cooking of inhabitants in the Yuwints community*

### 3.2.5. Load profile of the community

The community is composed of 34 dwellings, one school, and a health center. The users behavior did not allow a proper record of the consumption data. For instance, users keep

[14] Data Obtained from "The Plan for Development and Territorial Organization of the Decentralized Autonomous Government of Macuma Rural parish", 2015.

the inverter off for long time intervals, while turning on the inverter for a specific use for any appliances for a limit amount of time. The data, and information needed to determine the load curve of the users were based on a survey, which aims to determine the electrical appliances available within the dwellings as well as their time and period of use (see Annex A.2). Table 3.3 shows the power of typical electrical devices available in the homes of the Yuwints community.

*Table 3-3: Electric equipment's in dwellings of the Yuwints community*

| Typical electrical devices in the community | | | |
|---|---|---|---|
| Item | **Description** | **Power (W)** | **Type of load** |
| 1 | Lamp | 11 | DC |
| 2 | Radio | 6-10 | AC |
| 3 | Television | 65-85 | AC |
| 4 | DVD | 15-20 | AC |
| 5 | Computer | 65-150 | AC |
| 6 | Cell phone chargers | 5 | AC |
| 7 | Satellite phone | 10 | AC |

Figure 3.5 shows the representative daily load curve for the whole community, considering the school and the health center load profiles.

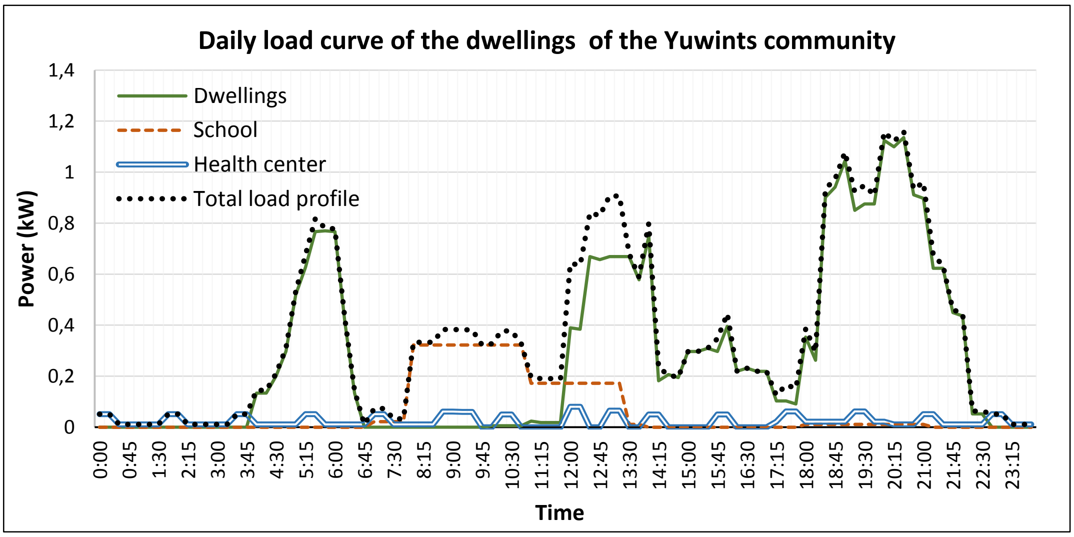



*Figure 3.5: Daily load curve of the Yuwints community*

The load consumption of the community presents three specific periods of consumption: morning, afternoon and night (see Figure 3.5). The maximum power is 1,157 kW reached at 20:00, and the daily energy consumed is 8,725 kWh. The maximum energy consumption of a dwelling is 0,4935 kWh/day, the minimum is 0,02475 kW/h/day, and the average consumption of the dwellings in the community is 0,196 kWh/day.

### 3.2.6. Component costs and available technologies

The selection of suitable equipment and components, mainly depend on technical requirements of the system and local environmental characteristics. Various aspects to consider are the following:

- energy demand;
- power range of generation systems;
- minimum and maximum values of renewable resources availability;
- space available in the dwellings and the community;
- minimum and maximum temperature levels;
- humidity;
- altitude above sea level;
- IP protection;
- Costs.

In recent years, a large number of renewable systems for electric generation purposes have been developed *e.g.* PV systems, Wind systems, Hydropower systems, etc. Manufacturers provide several models with different electrical and mechanical features, which allow the systems to adapt to different applications. Annex A.3 presents the costs of various components provided by two distribution companies at national level[15].

## 3.3. System design

To satisfy the energy requirements of the Yuwints community, it has been considered the analysis of two scenarios:

1- Electrical supply through stand-alone home PV-Wind-battery systems for each dwelling, the health center, and the school;
2- Electrical supply through a centralized PV-Wind-battery system for the entire community.

This analysis focuses on determine an optimal design from an economic approach by minimizing the net present cost of the candidate systems. Therefore, the microgrid simulation software Homer Energy will be used. Homer Energy is a computer model that simplifies the task of evaluating design options for both, off-grid and grid-connected power systems. The software evaluates the economic and technical feasibility of a large number of systems, and for variation in technology costs and energy resource availability. Homer designs an optimal power system to fulfill the requirements of the desired loads through

[15] The component costs for the renewable system were taken from RENOVAENERGIA S.A and PROVIENTO S.A. [online]. Available at: http://www.renova-energia.com/ | http://www.proviento.com.ec/inicio.html

hundreds, or thousands of hourly simulations to ensure the best possible matching between electricity supply and demand.

### 3.3.1. Electrical supply through stand-alone home systems

This electrical supply option is the most used in isolated communities of the Ecuadorian Amazon. The usual procedure for supplying electricity involves determining a single load profile that satisfies the energy requirements of each dwelling, and to size the hybrid system based on this load profile. The representative load profile was determined based on the maximum consumption values at all time of the surveyed dwellings. Figure 3.6 shows the representative load profile for the design of the hybrid system for all dwellings in the community.

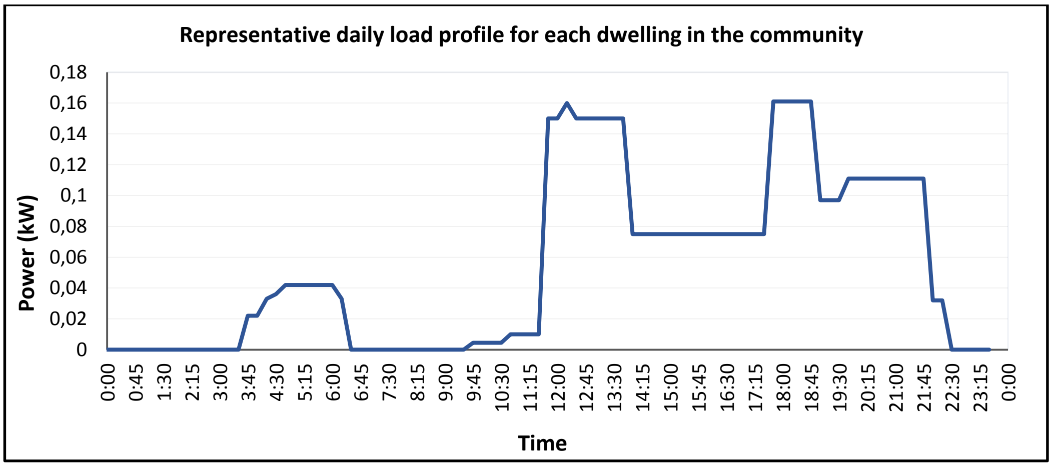



*Figure 3.6: Representative daily load profile for each dwelling in Yuwints*

The maximum power load is 0,161 kW, and it is reached between 18:00 to 19:00, the daily energy consumption of the representative load profile is 1,275 kWh (see Figure 3.6). It is important to note that the energy consumption of the representative load profile is 2,62 times greater than the dwelling with highest consumption in the community, and it is 6,1 times greater than the dwelling with the average energy consumption. Therefore, it is apparent that by using this procedure to design the hybrid system, the dwellings with low energy consumption will be oversized.

Approximately sixty percent of the dwellings in the community have a lower than average energy consumption. Therefore, it is convenient to classify the dwellings according to their energy consumption, and to determine a hybrid system for each category, which are:

- A system for the dwellings with higher than average energy consumption in the community. *Using the load profile of the dwelling with the highest energy consumption;*

- A system for the dwellings with lower than average energy consumption in the community. *Using the load profile of the dwelling with the average energy consumption*.

Figure 3.7 shows the load profiles of dwellings classified according to energy consumption.

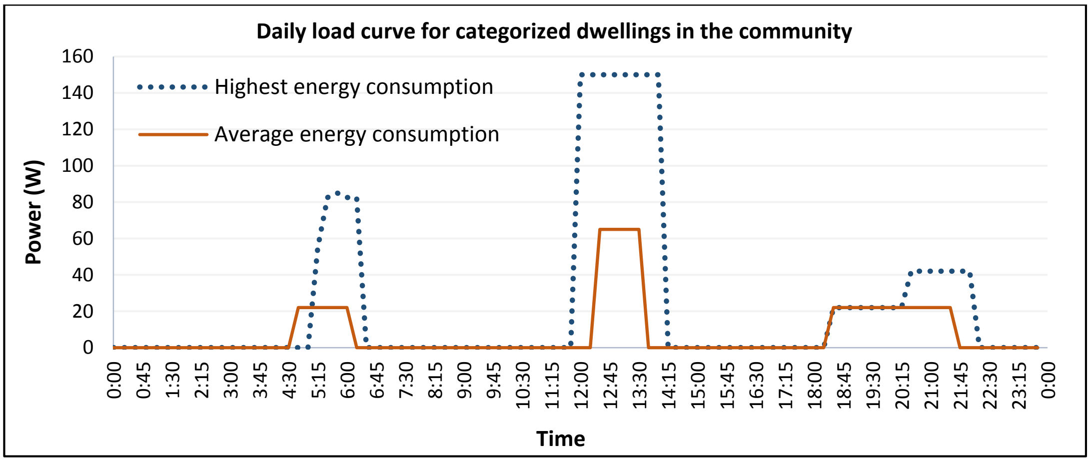



*Figure 3.7: Dwellings load profiles classified according to energy consumption*

In order to carry out a proper sizing, and estimated an accurate cost of the stand-alone home system, a dwelling composed of the following components is taken as reference: 2m wooden pole to support the PV panel, 8m of cable for electrical connection of the PV panel and the electrical panel, an electrical panel, PV components, and electrical protections (see Figure 3.8).

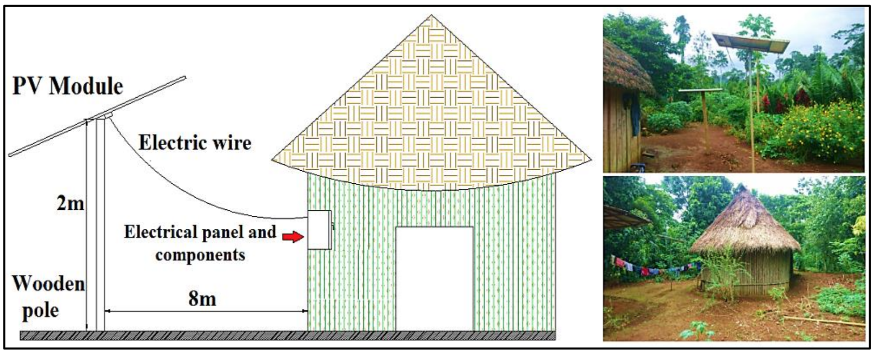



*Figure 3.8: Reference dwelling for the individual sizing of the hybrid system*

### 3.3.2. Electrical supply through a centralized system

Electrical supply through a centralized system requires a low voltage distribution network. To estimate the total cost of this option of electricity supply, the additional cost of the LVDN must be determined. Therefore, the physical characteristics and distribution of the dwellings in the community play a key role to determine the suitable location of the PV centralized system, and the possible trajectories of the micro-network. Annex A.4 shows the landing track, the distances, and physical distribution of the dwellings in the community. It should be noted, that the farthest dwellings from the landing track could be powered through stand-alone home systems. This option could be beneficial in economic terms. However, in this research work all dwellings will be supply through a micro network.

#### *3.3.2.1. Location of the centralized PV system*

In order to reduce the distance from the generation system to consumers, and optimize the conductor diameter for the LVDN, the PV generation system should be located in a central point of the community, where there is a greater grouping of dwellings. Since, the community is surrounded by dense vegetation, the PV system will be constrained to be located around the landing track (see Figure 3.9).

*Figure 3.9: Landscape of the community Yuwints*

To find the optimum placement of the PV system, it is proposed an optimization problem. The procedure to find the formulation of the optimization model is described as follows: As a first step, a system of Cartesian coordinates was established for the community, which has its origin (0,0) in the center of the landing track. The landing track is modeled using an equation for a conic curve. Figure 3.10 shows the system of Cartesian coordinates and the dwellings location. The dwellings identification is represented as showed in annex A.4.

**Cartesian coordinates**

| Vivienda | X | Y |
|---|---|---|
| 1 | -168 | -280 |
| 2 | -145 | -250 |
| 3 | -67 | -287 |
| 4 | -57 | -258 |
| 5 | -72 | -249 |
| 6 | -70 | -194 |
| 7 | -65 | -124 |
| 8 | -82 | -115 |
| 9 | -83 | -85 |
| 10 | -99 | -66 |
| 11 | -179 | -43 |
| 12 | -80 | -17 |
| 13 | -122 | 17 |
| 14 | -85 | 61 |
| 15 | -185 | 140 |
| 16 | -200 | 148 |
| 17 | -282 | 180 |
| 18 | -90 | 130 |
| 19 | -106 | 139 |
| 20 | -170 | 222 |
| 21 | -173 | 258 |
| 22 | 56 | -231 |
| 23 | 104 | -176 |
| 24 | 96 | -59 |
| 25 | 64 | 43 |
| 26 | 79 | 35 |
| 27 | 129 | 50 |
| 28 | 56 | 104 |
| 29 | 71 | 96 |
| 30 | 67 | 166 |
| 31 | -50 | 396 |
| 32 | 45 | 439 |
| 33 | 57 | 427 |
| 34 | -123 | 457 |
| 35 | -185 | 689 |
| 36 | -304 | 878 |

**The equation describing the conic is:**

$$G(x, y) = 218.035x^2 + y^2 - 89057.8$$

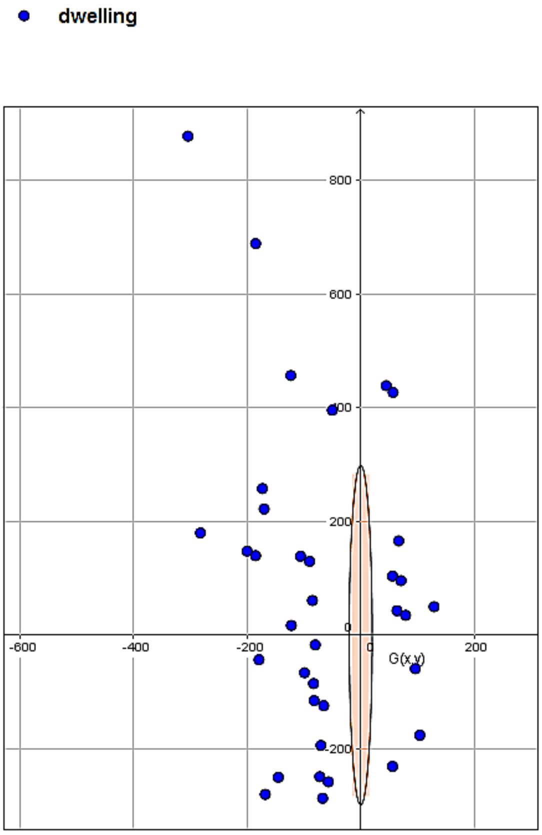



*Figure 3.10: Cartesian coordinates system for the Yuwints community*

The objective function to be minimized is:

$$\min F_k(x, y) = \sum_{i=1}^{N} [(V_x i - x)^2 + (V_y i - y)^2] P_{ki}$$

$$k = 0,1,2 \qquad (2)$$

s.t

$$G(x, y) = 218{,}035x^2 + y^2 - 89057$$

Where:

- $N$ represents the number of dwellings;
- $V_x$ *and* $V_y$ represent the cartesian coordinates for the dwellings;
- $F_k(x, y)$ represents the objective function. It is the sum of the distances of each one of the dwellings to the point (x, y), which is constrained to the conic equation $G(x, y)$;
- $P_k$ represent a weighting vector for the dwellings, where:
    - $P_{0i} = 1$

- $P_{1i}$ is determined according to the distance from the first point determined, $F_0$, to each of the dwellings

$$P_{1i} = \frac{1}{\sqrt{(V_x i - F_{0x})^2 + (V_y i - F_{0y})^2}} \quad i = 1 \dots N$$

- $P_{2i}$ is constituted according to the importance of the electricity supply. The weight value for the dwellings is 1, for the school is 3 and for the health center is 5

This problem can be solved analytically, or by using the mathematical software MATLAB. By the analytical method, the solution is obtained using the method of Lagrange multipliers, which is defined as follows:

$$\nabla F(x,y) = \lambda \nabla G(x,y)$$

Where: (3)

$$\nabla F = \left(\frac{\partial}{dx}, \frac{\partial}{dy}\right) F(x,y)$$

Applying the Lagrange multipliers method to the objective function, $F_k(x,y)$; the following system of equations were obtained:

$$F_0(x,y) \ = 36x^2 + 36y^2 + 4836x - 5282y - 3388603$$

$$\begin{cases} x + 67{,}1667 \ = 2725{,}43\lambda x & (I) \\ y \ - 73{,}3611 = 12{,}5\lambda x & (II) \\ 218{,}035x^2 + y^2 = 89057{,}8 & (III) \end{cases}$$

Solving the system of equations, the first point, $F_0$, for the PV system is determined.

$$F_{0x} = -19{,}61 \ ; F_{0y} = 72{,}55.$$

To obtain the optimum placement point, $F_2$, of the PV system, the weighting vectors must be applied to the objective function. Repeating the calculation process, the optimum placement point obtained is:

$$F_{2x} = -20{,}03 \ ; F_{2y} = 38{,}79.$$

By using the MATLAB calculation tool, it is possible to solve the problem quickly. For this purpose, the *fmincon* function is used. This function finds a minimum of a constrained nonlinear multivariable function. Using the equations previously described as parameters of the *fmincon* function, the optimum point obtained is the same as that calculated in the analytical form. Annex A.5 shows the algorithm developed to find the optimum location of the PV system.

Figure 3.11 shows the physical characteristics of the community as well as the optimum placement point of the centralized PV generation system.

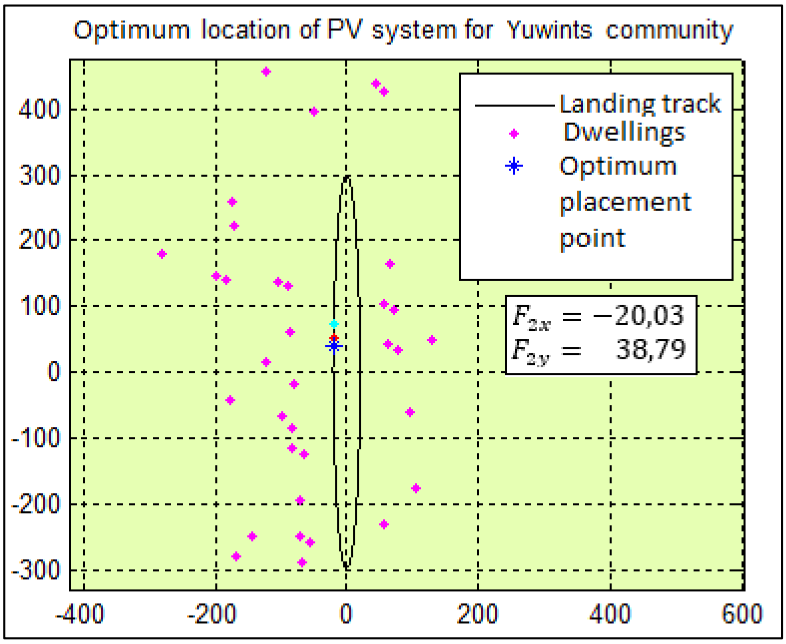



*Figure 3.11: Optimum point for location of PV system in the Yuwints community*

#### *3.3.2.2. Dimensioning of the low voltage distribution network*

The trajectories of the low voltage distribution network was planned according to the physical characteristics of the community (landing track, vegetation, existing paths, etc.) obtained during the visit to the community. The LVDN was planned in a radial form, aerial way, and using a 1F2C configuration. Annex A.6 shows the design of the LVDN from the PV system to the dwellings, as well as the trajectory of the distribution lines.

The sizing of the electrical conductors for the LVDN were determined based on guidelines and regulations of two electricity distribution companies (CENTROSUR, EERRSSA)[16].

These regulations state the following:

- The sizing of the LVDN must consider a life cycle of 10 years;
- The maximum limit of voltage drop from the PV generation system to the farthest dwelling should not exceed 5%;
- The minimum conductor size to be used will be 4 AWG and the maximum will be 3/0;

[16] CENTROSUR and EERRSSAA are two electricity distribution companies that operate in the city of Cuenca and Loja respectively. Guidelines and regulations were taken from the following web sites: http://www.centrosur.gob.ec/ | http://www.eerssa.com/

- The Duplex (2x6) electrical conductor will be used for the dwellings connection;
- The size of the neutral conductor will be related according to the gauge of the phase conductor 4(4), 2(4), 1/0(4), 2/0(2), 3/0(2).

The voltage drop calculation must consider the incidence of the projected maximum unit demand (DMUp), distribution of subscribers, special loads, public illumination, and distances at each connection point. DMUp are established according to the area of the lots for the urban sector and the type of consumers for the rural sector. Table 3-4 shows the DMUp established for rural areas by the two electrical distribution companies.

*Table 3-4: DMUp for rural areas established by CENTROSUR and EERSSA*

| Sector | Costumer | CENTROSUR | EERRSSA |
|---|---|---|---|
| | | DMUp (10años) | DMUp (10años) |
| City outskirts | F | 1,02 | 0,6 |
| Parish center | G | 0,84 | 0,5 |
| Rural | H | 0,65 | 0,4 |

The energy consumption of most dwellings in the community is very low. The total power required of the user with greater number of electrical appliances is approximately 0,2kVA. For this reason, the design of the LVDN must be performed using the DMUp established by the EERSSA electric distribution company.

The voltage drop calculation is performed by the following procedure:

$$DMp = DMUp.N.F \quad (kVA)$$

$$F = N^{-0,0944} \qquad (4)$$

$$DD = DMp + Ce + A \quad (kVA)$$

Where:

- DMp = Maximum demand at the given point;
- DMUp = Projected maximum unit demand;
- N = Number of subscribers;
- F = Coincidence factor;
- DD = Design demand;
- Ce = Special loads;
- A = Public illumination.

The voltage drop is determined by the method of the apparent power momentum of each conductor, and using the values of voltage load factor (FDV) in kVA-m for the 1% of voltage drop. The voltage drop calculation is determined as follow:

$$\%\Delta V = \frac{DD.(distance)}{FDV} \qquad (5)$$

The FDV calculation for the electrical conductors used in the design of the LVDN are determined in Annex A.7.

In order to determine a suitable size of the electrical conductor in each of the sections of the distribution line, satisfying the voltage limit, and minimizing the implementation cost, a MATLAB program was developed. The program perform a linear search of the conductor size for each section, calculates the accumulated voltage drop in the farthest point, and if it meets the established voltage limit calculates the total implementation cost of the distribution line. Annex A.8 shows the flowchart of the algorithm to determine the conductor size configuration and the cost of the distribution line.

The simulation results show that line 1 and line 4 exceed the voltage drop limit when is used 120V as a supply voltage. Therefore, the distribution voltage of the LVDN will be 220V. This voltage does not represent any inconvenience, since most of the electrical appliances available in the dwellings of the community can be connected at 220V. Table 3-5 shows the conductor size; the voltage drop at the most distant point, and the implementation cost of each of the lines, as well as the total cost of the LVDN.

*Table 3-5: Size conductor of each of the lines and implementation cost of the LVDN (without public illumination system)*

| line 1 section | conductor size | line 2 section | conductor size | line 4 section | conductor size |
|---|---|---|---|---|---|
| P0-P1 | 1/0 | P0-P19 | 4 | P0-P24 | 4 |
| P1-P2 | 1/0 | P19-P20 | 4 | P24-P25 | 4 |
| P2-P3 | 1/0 | P20-P21 | 4 | P25-P26 | 4 |
| P3-P4 | 1/0 | P21-P22 | 4 | P26-P27 | 4 |
| P4-P5 | 1/0 | Voltage drop | 2,26% | P27-P28 | 4 |
| P5-P6 | 1/0 | cost | $ 343 | P28-P29 | 4 |
| P6-P7 | 1/0 | **line 3** | **conductor** | P29-P30 | 4 |
| P7-P8 | 2 | **section** | **size** | Voltage drop | 4,9% |
| P8-P9 | 2 | P0-P31 | 4 | cost | $ 512 |
| P9P-10 | 2 | P31-P32 | 4 | **line 5** | **conductor** |
| P10-P11 | 2 | Voltage drop | 0,95% | **section** | **size** |
| P11-P12 | 4 | cost | $ 146 | P0-P33 | 4 |
| P12-P13 | 4 | **line 6** | **conductor** | P33-P34 | 4 |
| P13-P14 | 4 | **section** | **size** | P34-P35 | 4 |
| P14-P15 | 4 | P0-P33 | 4 | P35-P36 | 4 |
| P15-P16 | 4 | P33-P41 | 4 | P36-P37 | 4 |
| P16-P17 | 4 | P41-P42 | 4 | P37-P38 | 4 |
| P17-P18 | 4 | Voltage drop | 2,82% | Voltage drop | 3,17% |
| Voltage drop | 4,97% | cost | $ 278 | cost | $ 497 |
| cost | $ 1.613 | | | | |
| **Total cost of the LVN** | | | | $ 9.415,60 | |
| **Cost per kW** | | | | $ 619,46 | |

The proposed LVDN considers the placement of 10 luminaires for public illumination. Therefore, a new load profile for the community must be determined. Figure 3.12 shows the new daily load curve for the Yuwints community.

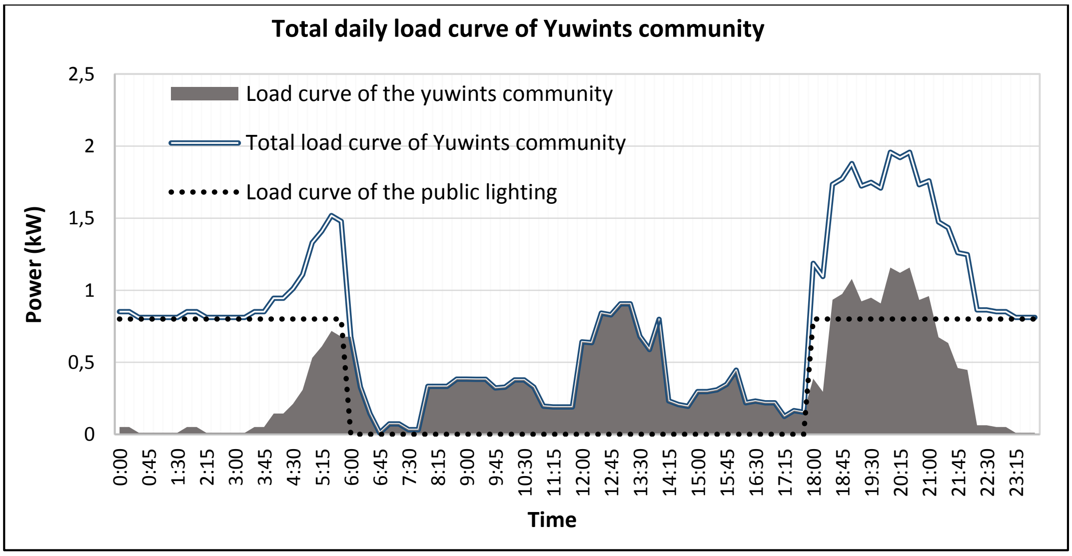



*Figure 3.12: Total daily load curve for the Yuwints community*

The load profile is modified in such a way that the period with the highest consumption occurs when there is no solar radiation (see Figure 3.12).

The new conductor size configuration of the LVDN does not change dramatically, and the total cost of the LVDN is $ 9450,60. Table 3-6 shows the conductor size of each of the lines, the voltage drop and the total cost of the LVDN including the public illumination.

*Table 3-6: Size conductor of each of the lines and implementation cost of the LVDN (with public illumination system)*

| line 1 section | conductor size | line 2 section | conductor size | line 4 section | conductor size |
|---|---|---|---|---|---|
| P0-P1 | 1/0 | P0-P19 | 4 | P0-P24 | 2 |
| P1-P2 | 1/0 | P19-P20 | 4 | P24-P25 | 4 |
| P2-P3 | 1/0 | P20-P21 | 4 | P25-P26 | 4 |
| P3-P4 | 1/0 | P21-P22 | 4 | P26-P27 | 4 |
| P4-P5 | 1/0 | Voltage drop | 2,26% | P27-P28 | 4 |
| P5-P6 | 1/0 | cost | $ 343 | P28-P29 | 4 |
| P6-P7 | 1/0 | **line 3 section** | **conductor size** | P29-P30 | 4 |
| P7-P8 | 1/0 | | | Voltage drop | 4,86% |
| P8-P9 | 2 | P0-P31 | 4 | cost | $ 525 |
| P9P-10 | 2 | P31-P32 | 4 | **line 5 section** | **conductor size** |
| P10-P11 | 2 | Voltage drop | 0,95% | | |
| P11-P12 | 4 | cost | $ 146 | P0-P33 | 4 |
| P12-P13 | 4 | **line 6 section** | **conductor size** | P33-P34 | 4 |
| P13-P14 | 4 | | | P34-P35 | 4 |
| P14-P15 | 4 | P0-P33 | 4 | P35-P36 | 4 |
| P15-P16 | 4 | P33-P41 | 4 | P36-P37 | 4 |
| P16-P17 | 4 | P41-P42 | 4 | P37-P38 | 4 |
| P17-P18 | 4 | Voltage drop | 2,99% | Voltage drop | 3,51% |
| Voltage drop | 4,99% | cost | $ 278 | cost | $ 497 |
| cost | $ 1.634 | | | | |
| **Total cost of the LVN** | | | | $ 9.450,60 | |
| **Cost per kW** | | | | $ 621,75 | |

Furthermore, additional consumption due to losses in the LVDN must be increased to the total daily load profile of the community. The daily power losses in the distribution network are calculated according to the equivalent load at the end of the line, with N loads distributed at different locations of the line [38]. The formulation is presented as follows:

$$P_T = \frac{\sum_{n=1}^{N} L_n P_n}{L} \quad (5)$$

Where:

- $P_T$ = Equivalent load at the end of the line [kW];
- $L_n$ = Distance from power supply for load n [km];

- $P_n$ = Load n [kW];
- $L$ = Total distance from power supply to end of the line [km].

The power losses are determined by

$$P_{loss} = \left(\frac{P_T}{V}\right)^2 r \qquad (6)$$

Where:

- $P_{loss}$ = Power loss in the line [kW];
- $V$ = Voltage of supply network [kV];
- $r$ = Resistance of the line conductor.

Table 3-7 shows the power losses at each hour of the LVDN.

*Table 3-7: Total daily power losses of the LVDN*

| Time | Total Power required (kWh) | Power Loss (kWh) | % Power Loss | Total Power required/day (kWh) | Total Power Loss/day (kWh) | % Total Power Loss/day |
|---|---|---|---|---|---|---|
| **0:00** | 0,362533613 | 0,0011979 | 0,3304246 | **10,7238408** | **0,050192106** | **0,468042254** |
| **1:00** | 0,362533613 | 0,0011979 | 0,3304246 | | | |
| **2:00** | 0,365180672 | 0,00122204 | 0,3346391 | | | |
| **3:00** | 0,359886555 | 0,00117422 | 0,3262741 | | | |
| **4:00** | 0,387531621 | 0,00130123 | 0,3357733 | | | |
| **5:00** | 0,552511091 | 0,00203454 | 0,3682355 | | | |
| **6:00** | 0,793506118 | 0,00371459 | 0,4681233 | | | |
| **7:00** | 0,086239286 | 4,0579E-05 | 0,0470535 | | | |
| **8:00** | 0,102558824 | 0,00034011 | 0,331621 | | | |
| **9:00** | 0,331529412 | 0,00355396 | 1,0719908 | | | |
| **10:00** | 0,330855533 | 0,00352179 | 1,0644494 | | | |
| **11:00** | 0,297822932 | 0,00275219 | 0,9241014 | | | |
| **12:00** | 0,251661818 | 0,00112563 | 0,4472803 | | | |
| **13:00** | 0,579645659 | 0,00238362 | 0,4112193 | | | |
| **14:00** | 0,501910118 | 0,00136453 | 0,2718672 | | | |
| **15:00** | 0,150520297 | 0,00012475 | 0,0828804 | | | |
| **16:00** | 0,223828227 | 0,00027448 | 0,1226296 | | | |
| **17:00** | 0,148735402 | 0,00012404 | 0,0833937 | | | |
| **18:00** | 0,479752512 | 0,00171757 | 0,3580126 | | | |
| **19:00** | 0,900874319 | 0,00468975 | 0,5205774 | | | |
| **20:00** | 1,002480705 | 0,00571727 | 0,5703123 | | | |
| **21:00** | 1,049954586 | 0,00621192 | 0,5916366 | | | |
| **22:00** | 0,719132834 | 0,00312404 | 0,4344181 | | | |
| **23:00** | 0,38265505 | 0,00128347 | 0,3354123 | | | |

The total daily power losses are 0,0501 kWh, representing only the 0,47% of the total power required by the community per day (see Table 3-7). Therefore, the power losses can be neglected.

Chapter 4

# 4. Simulations

The calculation of the power electrical supply system for the Yuwints community, is performed through the information processing in chapter 3. The most suitable option of energy supply for the community is determined comparing the NPC of stand-alone home system and the centralized system. The total NPC by using stand-alone home systems is determined from the NPC of each individual system in the community *e.g.* dwellings, school, and health center. On the other hand, the total NPC for the centralized system is obtained from simulations performed in Homer Energy, considering the implementation cost of the LVDN.

The electric supply through stand-alone home systems is carried out considering two scenarios:

a) Using the individual load profile of the school, the health center, and the representative load curve for each of the dwellings in the community;
b) Using the individual load profile of the school, the health center, and the categorized load profile for the dwellings according to the energy consumption (*load profile with higher consumption, and load profile with average consumption in the community*).

The electric supply through a centralized system also considers two scenarios:

a) Using the total load profile of the community without a public illumination system;
b) Using the total load profile of the community with a public illumination system.

## 4.1. Stand-alone home system modeling

One of the objectives of this research is to provide energy exclusively from renewable sources. Despite the solar resource is the major renewable source in the area, a PV-Wind-battery scheme is used to determine an optimum system, that satisfies the energy requirements at the lowest cost. Figure 4.1 shows the schematic diagram in Homer Energy software. The scheme consist of a PV system, two types of wind turbines, a storage system, and a power inverter.

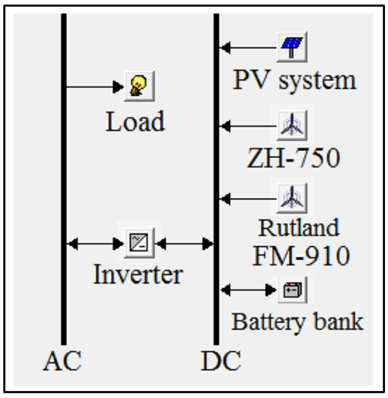



*Figure 4.1: Individual power system configuration*

### 4.1.1. Homer input summary

#### *4.1.1.1. Electric load profile*

The data of the daily load profile of the school, the health center, and the representative dwelling have been entered based on the values presented in section 3.2.5, and 3.3.1 respectively. Despite it has been assumed a constant load profile throughout the year, Homer can add hourly and daily randomness to this profile, and make it more realistic. In this case 5% and 10% randomness has been added respectively. Figure 4.2 shows the daily load profile, and the monthly average load for the school and the health center.

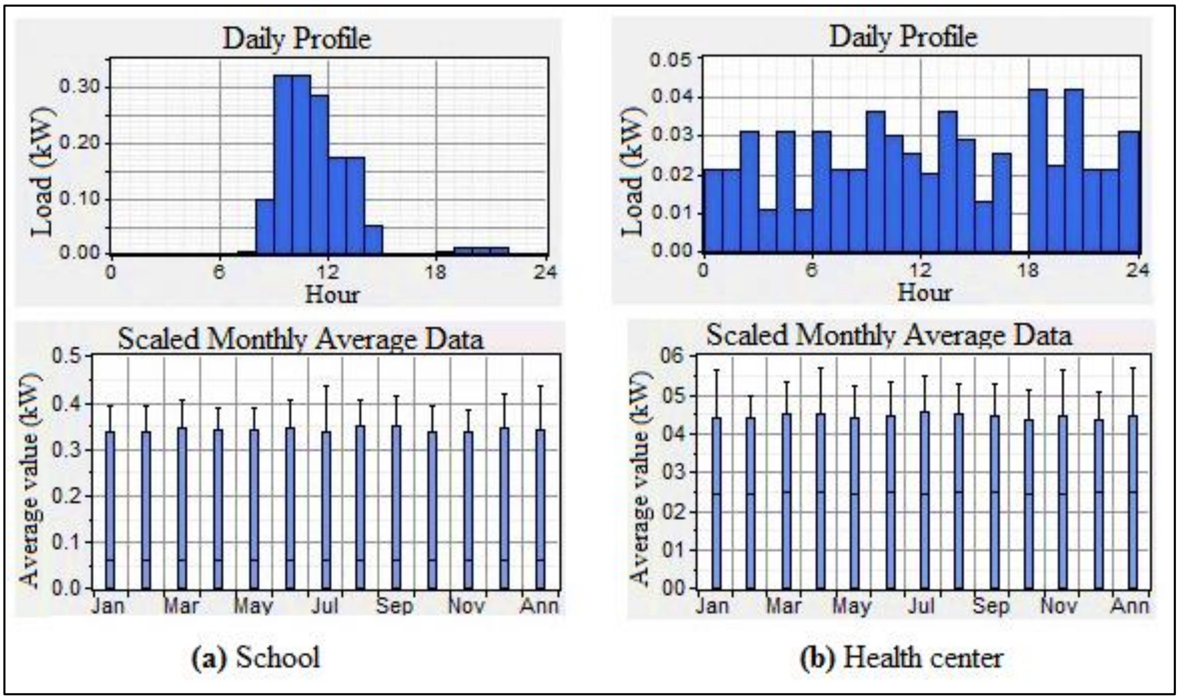



*Figure 4.2: Daily load profile and monthly average load for the school and the health center*

Figure 4.3 shows the daily load profile and the monthly average load of the representative dwelling and the dwellings categorized according to the energy consumption.

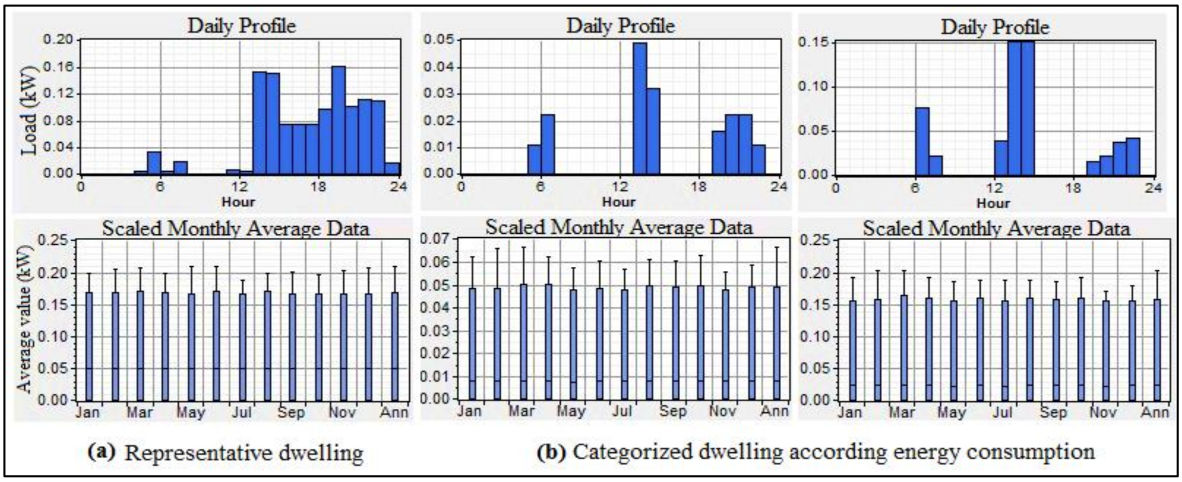


Figure 4.3: Daily load curve and monthly average load for: (a) Representative dwelling, (b) Categorized dwellings according to energy consumption

#### 4.1.1.2. Solar resource and wind speed data

The monthly average solar radiation data, as well as the monthly average wind speed for Yuwints community are shown in Figure 4.4.

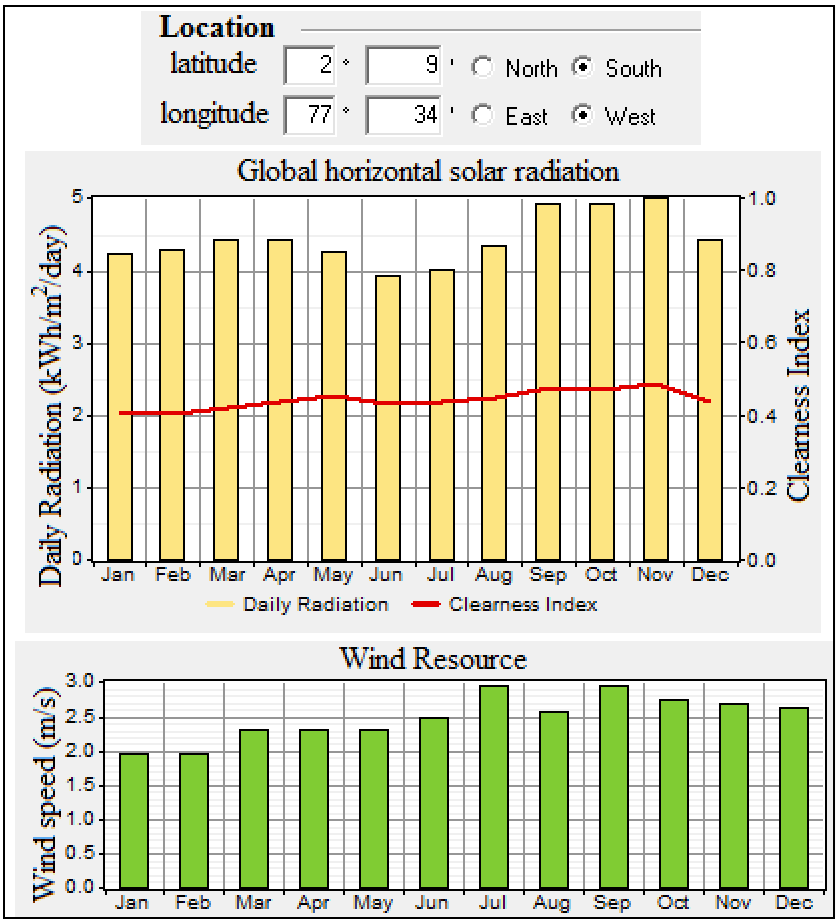


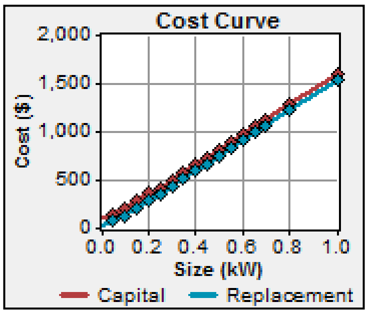
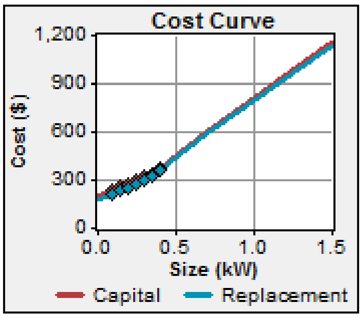
Figure 4.4: Monthly average of solar radiation and wind speed of Yuwints

Yuwints receives an annual average of solar radiation of $4{,}43kW/m^2/day$, and an annual average of wind speed of $2{,}48m/s$.

#### *4.1.1.3. Costs of the system components*

In order to obtain adequate results in the simulation, it is convenient consider actual costs of the system components and materials. Table 4-1 summarizes the size and costs of the system components used as inputs to the Homer hybrid model.

*Table 4-1: Component cost of the hybrid system*

<table>
<tr><th>Component</th><th>Size</th><th>Capital cost $</th><th>Replacement cost $</th><th>O & M cost $</th><th>Cost curve of the PV system and Inverter</th></tr>
<tr><td rowspan="7">PV system</td><td>30 W</td><td>127</td><td>62</td><td>10</td><td rowspan="9">
</td></tr>
<tr><td>50 W</td><td>148</td><td>83</td><td>10</td></tr>
<tr><td>100 W</td><td>199</td><td>134</td><td>10</td></tr>
<tr><td>140 W</td><td>267</td><td>202</td><td>10</td></tr>
<tr><td>200 W</td><td>367</td><td>302</td><td>10</td></tr>
<tr><td>250 W</td><td>423</td><td>358</td><td>10</td></tr>
<tr><td>300 W</td><td>502</td><td>437</td><td>10</td></tr>
<tr><td>Wind turbine (ZH 750)</td><td>900 W</td><td>2336</td><td>1736</td><td>200</td></tr>
<tr><td>Wind turbine (FM910-4)</td><td>180 W</td><td>2280</td><td>2200</td><td>200</td></tr>
<tr><td rowspan="3">Battery</td><td>200 Ah/12V</td><td>500</td><td>500</td><td>5</td><td rowspan="7">
</td></tr>
<tr><td>55 Ah/12V</td><td>200</td><td>200</td><td>5</td></tr>
<tr><td>225 Ah/6V</td><td>366</td><td>366</td><td>5</td></tr>
<tr><td rowspan="4">Inverter</td><td>180 W</td><td>271</td><td>247</td><td>5</td></tr>
<tr><td>350 W</td><td>341</td><td>320</td><td>5</td></tr>
<tr><td>700 W</td><td>603</td><td>582</td><td>5</td></tr>
<tr><td>1500 W</td><td>1162</td><td>1141</td><td>5</td></tr>
</table>

The cost of the charge controller, the electrical connection wire, and auxiliary components of the stand-alone home system are included in the cost of the inverter.

### 4.1.2. Simulation results

The simulations were performed for various configurations and electrical capacities of the hybrid system components. Each configuration must meet the system energy requirements at each moment. Homer Energy calculates and display in ascending order the total NPC of all feasible systems.

The simulations were executed using the three types of batteries presented in Table 4-1, and different levels of DC voltage for the battery system (6V, 12V, 24V). Table 4-2 summarizes the most economical alternatives for the electrical supply of the dwellings (*considering the two study scenarios*), the school, and the health center. Annex B.1 shows the simulation results of the individual systems according to the type of battery and voltage level of the DC bus.

Table 4-2: Simulation results of the stand-alone home systems

| | PV (kW) | ZH 750 | Batt | Inv (kW) | Initial capital | O&M ($/yr) | Total NPC | COE ($/kWh) |
|---|---|---|---|---|---|---|---|---|
| (a) | Dwelling with the single (representative) load profile | | | | | | | |
| | 0,9 | | 3 | 0,25 | $ 2848 | 160 | $ 4898 | 0,882 |
| | 0,85 | 1 | 3 | 0,25 | $ 5105 | 404 | $ 10266 | 1,85 |
| (b) | Dwellings with higher than average energy consumption | | | | | | | |
| | 0,5 | | 1 | 0,25 | $ 1484 | 93 | $ 2670 | 1,041 |
| | 0,5 | 1 | 1 | 0,25 | $ 3820 | 337 | $ 8125 | 3,167 |
| (c) | Dwellings with lower than average energy consumption | | | | | | | |
| | 0,1 | | 1 | 0,1 | $ 803 | 75 | $ 1767 | 2,058 |
| | 0,1 | 1 | 1 | 0,1 | $ 3139 | 322 | $ 7249 | 8,444 |
| (d) | Health center | | | | | | | |
| | 0,35 | | 2 | 0,1 | $ 1551 | 105 | $ 2855 | 1,035 |
| | 0,6 | 1 | 1 | 0,1 | $ 3916 | 345 | $ 8324 | 3,021 |
| (e) | School | | | | | | | |
| | 1,1 | | 2 | 0,45 | $ 3182 | 147 | $ 5059 | 0,743 |
| | 1,1 | 1 | 2 | 0,45 | $ 5518 | 393 | $ 10541 | 1,548 |

As shown in the optimization results, Homer suggest that the optimal hybrid system for each of the stand-alone home systems of the community are:

*Scenario (a):*

- The HS for the dwelling with the representative load profile consists of 900W PV system and 3 batteries of 225 Ah/6V. The initial investment cost is $ 2848 with operating cost of $ 160 per year, and the total NPC of this system is $ 4898. This hybrid system can supply electricity at a cost of 0,882 $/kWh;
- The HS for the health center is composed of 350W PV system and 2 batteries of 225 Ah/6V. The investment cost is $ 1551 with operating cost of 102 $/year. The total NPC for this system is $ 2855, and the cost of electricity (COE) is 1,035 $/kWh;
- The renewable system for the school consist of a 1,1 kW PV system and 2 batteries of 200 Ah/12V. The initial investment cost is $ 3182, the operating cost is 147 $ per year, the total NPC is $ 5059, and the COE is 0,743 $/kWh.

*Scenario (b)*:

- The HS for the school and the health center are the same as scenario (a);
- The HS for dwellings with energy consumption higher than average consumption consist of 500W PV system and 1 battery of 225 Ah/6V. The investment cost is $ 1484 with operating cost of 93 $/year. The total NPC for this system is $ 2670;
- The hybrid system for the dwellings with energy consumption lower than average consumption is composed of 100W PV system and 1 battery of 225 Ah/6V, the

initial investment cost is $ 803 with operating cost of $ 75 per year. The total NPC of this system is $ 1767.

The total NPC of the electrical supply system for the Yuwints community through stand-alone home systems is determined for each study scenario.

For the scenario (a), the total NPC is calculated by:

$$\boxed{Total_{NPC} = 34 \times \mathrm{NPC}_{(\text{representative dwelling})} + \mathrm{NPC}_{(\text{schoool})} + \mathrm{NPC}_{(\text{health}-\text{center})}}$$

$$Total_{NPC} = (34 \times 4898) + 5059 + 2855 = \$\,174446$$

For the scenario (b), the total NPC is calculated by:

$$\boxed{\begin{aligned} Total_{NPC} = {} & 21 \times \mathrm{NPC}_{(\text{average consumption dwelling})} + 13 \times \mathrm{NPC}_{(\text{highest consumption dwelling})} \\ & + \mathrm{NPC}_{(\text{schoool})} + \mathrm{NPC}_{(\text{health}-\text{center})} \end{aligned}}$$

$$Total_{NPC} = (21 \times 1767) + (13 \times 2670) + 5059 + 2855 = \$\,79731$$

The electricity supply by using a representative load profile for all dwellings in the community (scenario-a), supposes a high total cost. Most of the dwellings in the community have low energy consumption, therefore the hybrid system for these dwellings would be oversized.

The electricity supply by using two load profiles according to the energy consumption of the dwellings (scenario-b), represents a better option. The total NPC through this electrical supply option decrease $ 94715 compared with the total NPC of the system in scenario-a. Another viable option is to size all dwellings by using the hybrid system of the dwelling with higher consumption in the community, then the total NPC will be $ 98694.

## 4.2. Centralized system modeling

Like the individual systems, the schematic diagram for the centralized system is composed by a PV-wind-battery power system (see figure 4.1).

### 4.2.1. Homer input summary

#### *4.2.1.1. Electric load profile*

Figure 4.5 shows the load profile without consider the public illumination system and the load profile with public illumination system. 5% and 10% of hourly and daily randomness were assigned to these load profiles.

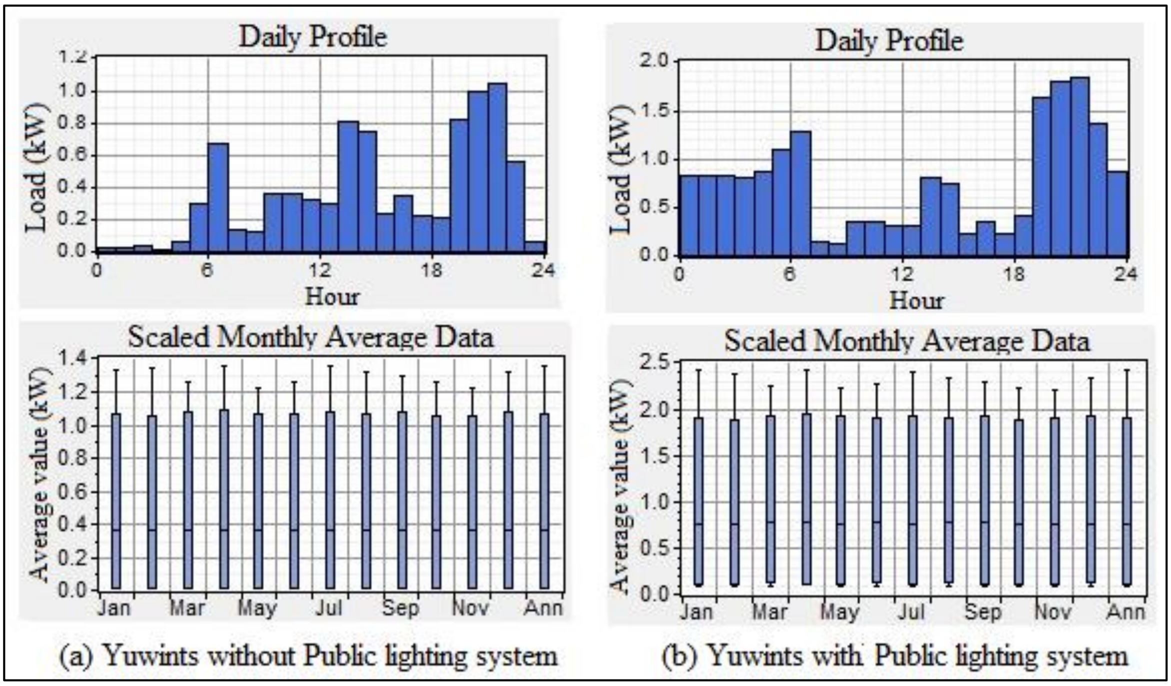



*Figure 4.5: Daily load curve and monthly average load of the centralized system for: (a) System without public illumination (b) System with public illumination*

#### *4.2.1.2. Solar resource and wind speed data*

The data of the solar radiation and wind speed are the same as for the stand-alone home systems (see Figure 4.4).

#### *4.2.1.3. Cost of the system components*

The capital, operation, and maintenance costs for photovoltaic panels, wind turbines, and batteries are the same as for the stand-alone home systems. However, the cost of the inverter is higher, since the cost of the LVDN as well as the components necessary for dwelling connections must be included in the cost of the inverter. Table 4-3 shows the inverter costs for the centralized system.

*Table 4-3: Power inverter cost for the centralized system.*

| Power inverter cost | size | capital cost ($) | Replacement cost ($) | O & M cost ($) |
|---|---|---|---|---|
| System without Public illumination | 2000 W | 12640,69 | 5824 | 200 |
| | 3000 W | 13950,25 | 7133,58 | 200 |
| Total system including Public illumination | 2000 W | 12675,69 | 5835,69 | 200 |
| | 3000 W | 13985,25 | 7145,25 | 200 |

The LVDN is projected for 10 years, therefore at the end of this time interval, the micro-network will have various modifications *e.g*. conductor size replacement, electric poles, and auxiliary equipment replacement, etc. For this reason, the replacement cost has been estimated as the sum of the power inverter cost and the third part of the cost of the LVDN.

### 4.2.2. Simulation results

The simulations were performed using the three types of batteries presented in Table 4-1, as well as different levels of DC voltage for the battery system (12V, 48V, 96V). Table 4-4 summarizes the most economical alternatives for the electrical supply of the community through a centralized system. Annex B.2 shows the simulation results of the centralized systems according to the type of battery, and voltage level of the DC bus.

*Table 4-4: Simulation results of the centralized system*

| | PV (kW) | ZH 750 | Batt | Inv (kW) | Initial capital | O&M ($/yr) | Total NPC | COE ($/kWh) |
|---|---|---|---|---|---|---|---|---|
| **(a)** | **Yuwints community without public illumination** | | | | | | | |
| | 6 | | 22 | 2 | $ 30201 | 1232 | $ 45944 | 1,134 |
| | 6 | 1 | 22 | 2 | $ 32537 | 1474 | $ 51378 | 1,268 |
| **(b)** | **Yuwints community considering public illumination** | | | | | | | |
| | 10,5 | | 66 | 3 | $ 42984 | 2378 | $ 73378 | 0,86 |
| | 10,5 | 1 | 66 | 3 | $ 45320 | 2620 | $78815 | 0,924 |

As shown in the optimization results, Homer suggests that the optimum hybrid system for the electric supply of the community are:

Scenario (a)

- The hybrid system consists of 6kW PV system and 22 batteries of 225 Ah/6V. The initial investment cost is $ 30201 with operating cost of $ 1232 per year, and the total NPC of this system is $ 45944. This hybrid system can supply electricity at a cost of 1,134 $/kWh.

Scenario (b)

- The hybrid system is composed of 10,5kW PV system and 66 batteries of 225 Ah/6V. The investment cost is $ 42984 with operating cost of 2378 $/year. The total NPC for this system is $ 73378 and the COE is 0,86 $/kWh.

The hybrid system for scenario (b), requires 4,5 kW of PV generation and 44 additional batteries, involving an increase of $ 27434 of the NPC compared to the hybrid system for scenario (a). This is because the public illumination system works during the periods of absence of solar radiation, increasing the number of batteries and PV modules. An illumination system in rural areas provides several advantages such as safety, mobility, recreational activities, etc. However, the need for a illumination system in the whole community, or at strategic locations require further analysis from a social point of view.

Chapter 5

# 5. Conclusions and Future work

This chapter summarizes the main results and methodologies proposed for the electrical supply of the Yuwints community. The conclusions are divided into discussion, main contributions, and future work.

## 5.1. Discussion

### 5.1.1. Methodology of the electrical supply for the Yuwints community

Chapter 3 was dedicated entirely to process the information of the Yuwints community and establish a methodology for its electrical supply. For this purpose, two options of electrical supply were evaluated, which are:

- Through stand-alone home PV-Wind-Battery systems for each of the dwellings;
- Through a centralized PV-Wind-Battery system for the entire community.

It was preferred a centralized system as an alternative of electrical supply, since the total number of dwellings and its physical distribution within the community allowed a properly sizing of the system, in addition to provide a lower implementation cost. On the other hand, although stand-alone home systems are the most widely used option in the Amazon, the total cost was higher than the centralized system. However the cost was reduced considerably by categorizing the dwellings according to their energy consumption and sizing a hybrid system for each of the categories.

### 5.1.2. Optimum placement of the PV array for the centralized system

An optimization model for determining a suitable location of the PV system is described in section 3.3.2.1. This methodology considers the physical characteristics of the community, the number and location of the dwellings, as well as the importance of the electrical supply. The optimum placement point determined provided several advantages, such as minimization of the distance from the generation system to consumers, reduction of the cable diameter of the LVDN, as well as the total cost of the system.

## 5.2. Conclusions

The main contribution of this research work is the techno-economic comparison of stand-alone home PV-Wind-Battery systems and a centralized PV-Wind-Battery system as an alternative to electrical supply for an isolated community in the Ecuadorian Amazon. The main features of the methodology proposed for determining the best option of electrical supply are:

- The total cost of the electrical supply, by using stand-alone home systems could be reduce considerably if the dwellings are classified according to their energy consumption, and the design of the hybrid system is made for each category.
- Optimum location of the PV system contributes to minimize the distance of the distribution lines, improve voltage levels at the farthest points, and reduce the total cost of the system.
- The sizing of the electric conductor in each of the sections of the LVDN by using a linear search, allow to decrease the cable diameter in the farthest points, keeping the adequate voltage levels, and reducing the total cost of the system.
- Simulations by using the microgrid optimization software Homer Energy, allow to evaluate the techno-economic feasibility of several hybrid systems and design an optimal system to fulfill the energy requirements according to the availability of the renewable resources. The simulation result provide a hybrid system at the lowest NPC.

The result of the present study proposes the Centralized Photovoltaic System as the best option of electrical supply for the community, allowing a full coverage of the load and guaranteeing a safe operation of the system. The electrical supply through a CPVS system requires a distribution network, which may or may not be integrated by a public illumination system. From the data in Table 4-4, it is apparent that the more economically option of electricity supply is through the centralized system shown in Table 4-4(a). The sizing of this system does not consider the additional energy consumption of the public illumination. However, there is the necessity to place public luminaires at strategic points such as PV generation system, landing track, health center, and recreational areas, etc., which justifies the system shown in Table 4-4(b) to be considered as the most suitable option to provide electricity to the community.

### 5.3. Future work

Access to electricity is a global priority, especially in remote regions, where the grid extension is not feasible, or it is costly and harmful to the environment. According to the result of this work, the following research activities are proposed:

- Simulation of the low voltage network of the community, adding distributed PV generation at different points, in order to improve the voltage level and reduce the diameter of the electric conductor
- Analysis of the electrical supply of the community through stand-alone home PV system for the farthest dwellings, and through a CPVS for the zones with greater concentration of dwellings

- Exploration of the proposed methodology to determine an optimal hybrid system in nearby communities, and if it is feasible to interconnect them, in order to have a more robust network
- Design of the electric diagrams of the CPVS of the community, integrating protection and control systems of the LVDN

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# Appendices

## A.1. **Renewable resources in Ecuador**

<u>Average global insolation of Ecuador</u>

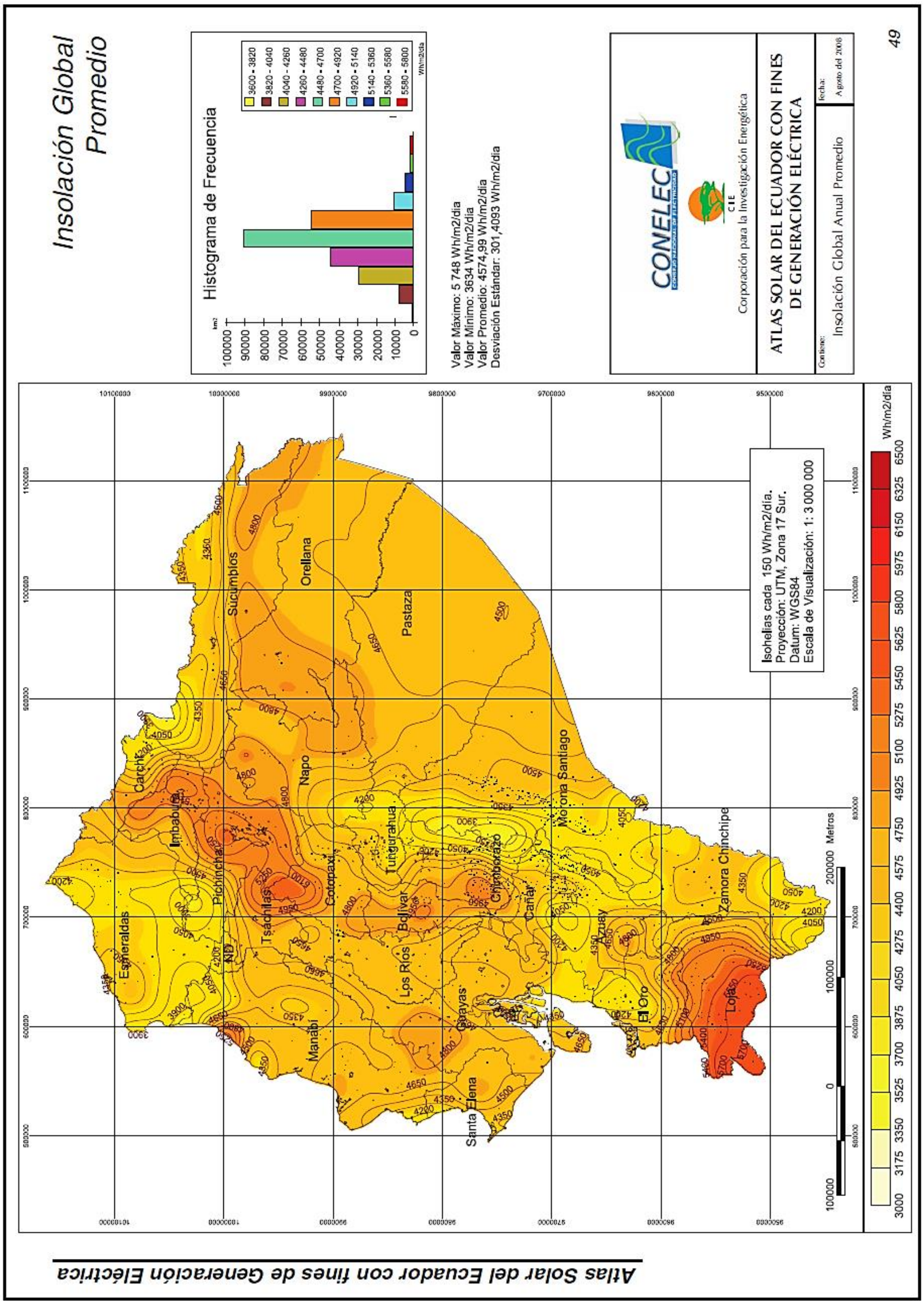

*Figure A.1. 1: Average global insolation of Ecuador*

<u>Feasible short-time potential map of wind resource of Ecuador</u>

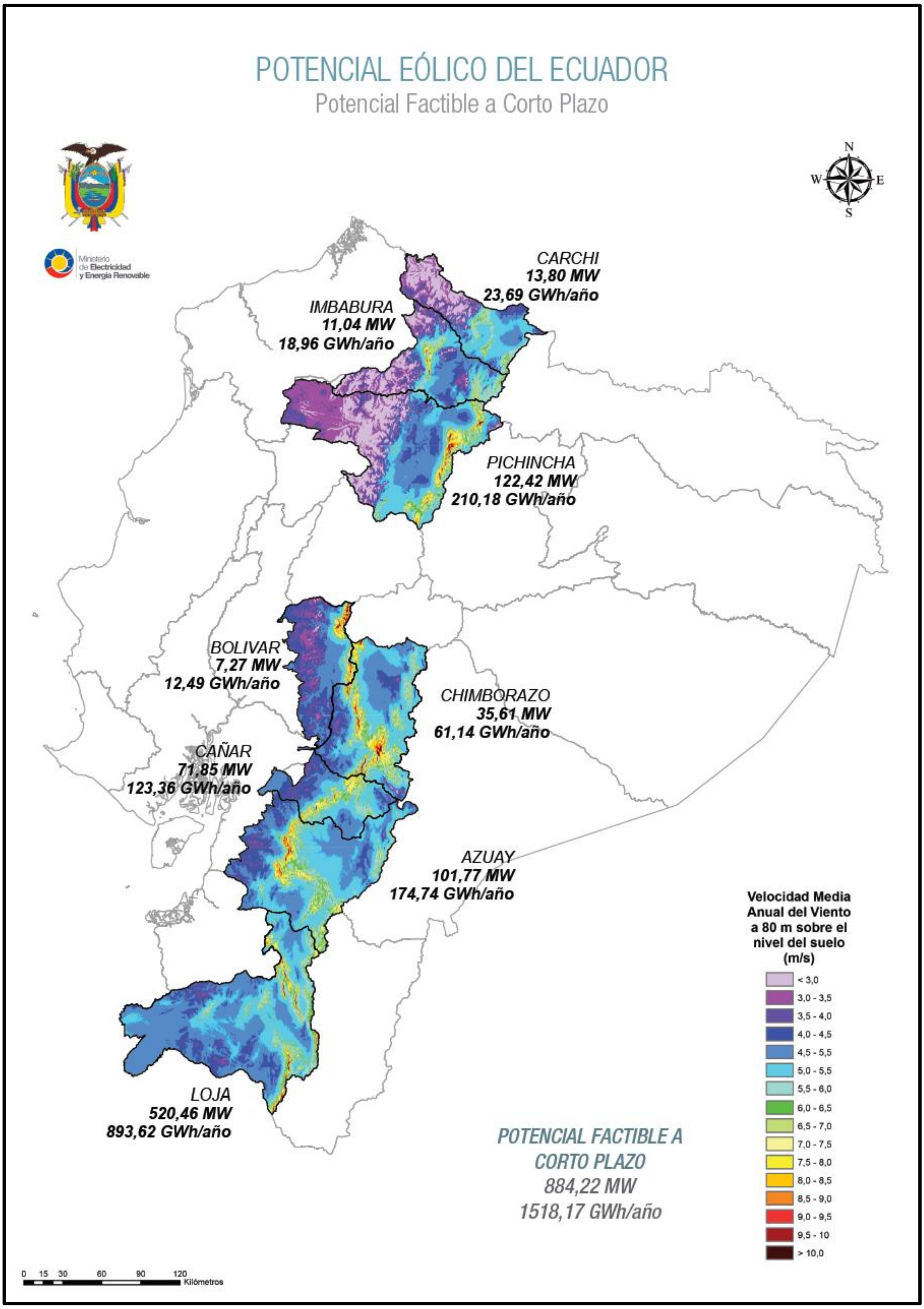


*Figure A.1. 2: Feasible short-time potential map of wind resource of Ecuador*

## A.2. **Calculation methodology of the representative number of surveys for the Yuwints community and the survey model developed.**

*Sample size for a finite and known population*

$$n = \frac{k^2.N.p.q}{e^2(N+1)+k^2.p.q} \quad where$$

n: *Sample size*
N: *Population size*
e: *Expected error (1%-10%)*
p: *Success probability of the parameter to be evaluated, if not known (p = 0.5)*
q: *failure probability q=(1-p)*
k: *Constant depend on table A3.1*

| k | 1.15 | 1.28 | 1.44 | 1.65 | 1.96 | 2.24 | 2.58 |
|---|---|---|---|---|---|---|---|
| Confidence level | 0,75 | 0,8 | 0,85 | 0,9 | 0,95 | 0,97 | 0,99 |

Used values for determining the sample size (n):

| n | N | k | p | q | E |
|---|---|---|---|---|---|
| 28 | 34 | 2.24 | 0.5 | 0.5 | 0.09 |

**MODELO DE ENCUESTA**

USO DE ENERGÍA MEDIANTE SISTEMAS FOTOVOLTÁICOS EN LA REGIÓN AMAZÓNICA - ÁREA DE CONCESIÓN CENTROSUR

Encuesta N°: ______________________
Fecha: ______________
Comunidad: ______________________
Código: ______________
Nombre del Usuario: ______________________

P1) N° de integrantes en la vivienda:
______________________

P2) ¿Cuánto es el pago mensual de uso del sistema?
______________________

P3) ¿Qué tipo de energía utiliza para la cocción de alimentos?

a) Leña: ______________________
b) Gas: ______________________
c) Otro tipo de energía especifique: ______________________

P4)

| Iluminación | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | Mañana | | Tarde | | Noche | |
| Luz | foco N° | Desde | Hasta | Desde | Hasta | Desde | Hasta |
| Fluorescente Compacta 12V en DC 11W | 1 | | | | | | |
| | 2 | | | | | | |
| | 3 | | | | | | |

P5)

| Artefactos - Usos | | | | | | | |
|---|---|---|---|---|---|---|---|
| Artefactos | Potencia | Mañana | | Tarde | | Noche | |
| | | Desde | Hasta | Desde | Hasta | Desde | Hasta |
| Radio | 6 W | | | | | | |
| TV | | | | | | | |
| DVD | | | | | | | |
| Computador | | | | | | | |
| Otros | | | | | | | |

P6) ¿Tiene previsto adquirir más equipos eléctricos especifique?

a) Iluminación N° de focos ______________________
b) Artefactos Cuáles ______________________
OBSERVACIONES: ______________________

*Figure A.2. 1: Survey model*

## A.3. **Renewable electrical equipment provided by national distribution companies (Proviento S.A and Renova energía)**

*Table A.3.1: Cost of electricity generation technologies*

| Proviento S.A | | | Renova Energía | | |
|---|---|---|---|---|---|
| **Photovoltaic panels** | **Power range** | **Price (IVA not included) $** | **Photovoltaic panels** | **Power range** | **Price (IVA not included) $** |
| **EXMORK** | | | Tynsolar/Zimpertec/ Sunlink | 10W/12V | 22,05 |
| Polycrystalline | 5Wp/12V | 20 | Sunlink | 20W/12V | 29,93 |
| Polycrystalline | 15Wp/12V | 40 | Tynsolar/Zimpertec/ Sunlink | 30W/12V | 55,13 |
| Polycrystalline | 25Wp/12V | 50 | Victron energy | 30W/12V | 89,78 |
| Polycrystalline | 50 Wp/12V | 90 | Zimpertec | 45W/12V | 77,18 |
| **SIMAX** | | | Sunlink | 50W/12V | 74,42 |
| Monocrystalline | 90 Wp/12V | 120 | Tynsolar | 50W/12V | 102,53 |
| Polycrystalline | 100 Wp/12V | 120 | Sunlink | 85W/12V | 115,76 |
| Monocrystalline | 120 Wp/12V | 160 | Sunlink | 100W/12V | 144,9 |
| Polycrystalline | 140 Wp/12V | 180 | Sunset | 120W/12V | 214,2 |
| Monocrystalline | 150 Wp/12V | 200 | Tynsolar | 140W/12V | 272,87 |
| Monocrystalline | 190Wp/24V | 265 | Sunset | 145W/12V | 329,68 |
| Polycrystalline | 250 Wp/24V | 320 | Sunlink | 150W/12V | 207,9 |
| Monocrystalline (MPPT system only) | 230 Wp/30V | 290 | Sunlink | 195W/24V | 275,63 |
| Polycrystalline | 300 Wp/24V | 390 | Pansonic | 250W/24V | 513,14 |
| **Wind turbines** | **Power range** | **Price (IVA not included) $** | Sunlink | 250W/24V | 339,02 |
| ZONHAN ZH750 | 750W/12-24Vdc | 1550 | AlmadenEurope | 250W/24V | 404,78 |
| ZONHAN ZH1.5 | 1500/24Vdc | 2000 | Sunlink | 300W/24V | 406,78 |
| MARLEC FM 910-4 | 180W/12-24Vdc | 2200 | | | |
| MARLEC FM 1803-2 | 850W/12-24Vdc | 4500 | | | |

An important aspect in rural electrification is to reduce installation costs, therefore, local raw material could be used for the subjection and adaptation of photovoltaic modules, wind turbine, batteries, cabling, etc.

The prices considered for the structures and supports from distributing companies are shown in the table A.3.2.

*Table A.3.2: Cost of structures and support components for the hybrid system*

| Structures and supports | |
|---|---|
| **PV modules structure** | Price $ |
| Mast and support structure (1650x1000) | 80 |
| PV floor structure 1Unit (1650x1000) | 65,73 |
| PV floor structure 3Unit (1650x1000) | 126 |
| PV floor structure 5Unit (1650x1000) | 182 |
| **Wind turbine tower** | |
| Unsupported tower 13m | 2430 |
| Freestanding tower 13m | 1470 |
| **Battery structure (sunlight)** | |
| 1 row rack 24V translucent battery (198x119x640) 20kg | 230 |
| 1 row rack 12V translucent battery (198x119x640) 20kg | 140 |
| 1 row rack 12V for translucent battery (198x119x505) | 130 |

The available conditioning power system technologies in the local market, as well as the associated costs are presented in the table A.3.3.

*Table A.3.3: Cost of equipment for the conditioning of the power system*

| Proviento S.A | | | Renova Energía | | |
|---|---|---|---|---|---|
| **Charge controller** | **Power range** | **Price $** | **Charge controller** | **Power range** | **Price $** |
| | **MORNINGSTAR** | | | | |
| Sunsaver SS | 12V/6-10-20A | 75-110-140 | Phocos ECO | 12V/10A | 32,34 |
| Sunsaver SS | 24V/20A | 150 | Phocos CML | 12-24V/10A | 59,61 |
| Solar Home SHS | 12V/6-10A | 45-60 | Phocos CMLup(USB, ROHS) | 12-24V/10A | 58,25 |
| Sunlight SL | 12V/10-20A | 125-170 | Phocos CML | 12-24V/15A | 75,75 |
| ProStar 15 | 12-24V/15-30A | 130-195 | Phocos CML | 12-24V/20A | 85,71 |
| Sunsaver MPPT-15 | 12-24V/15A | 380 | Phocos CMLsolid | 12-24V/30A | 109,4 |
| ProStar MPPT -25M | 12-24V/25-40A | 590-750 | Phocos CX | 12-24V/10A | 83,63 |
| ProStar MppT-40M | | | Phocos CX | 12-24V/20A | 126,38 |
| Pro Star con pantalla | 12-24V/15-30A | 230-280 | Phocos CX | 12-24V/40A | 176,56 |
| TriStar | 12-24-48/45-60A | 250-330 | Victron Energy BlueSolar MPPT | 12-24V/15A | 212,46 |
| TriStar MPPT | 12-24-36-48V/60A | 950 | Victron Energy BlueSolar MPPT | 12-24V/30A | 382,73 |
| | | | Victron Energy BlueSolar MPPT | 12-24V/50A | 576,45 |
| | | | Victron Energy BlueSolar MPPT | 12-24-36-48V/35A | 559,13 |
| **Power inverter** | **Power range** | **Price $** | **Power inverter** | **Power range** | **Price $** |
| **ZONHAN** | 12-24Vdc/1500VA/115Vac-60Hz | 290 | Phocos Pure Sine Solar Inverter | 12Vdc/110Vac-60hz/350W | 249,72 |
| **EXMORK** | 24Vdc, 2000W, 110Vac-60Hz | 500 | Phocos Pure Sine Solar Inverter | 24Vdc/110Vac-60hz/350W | 266,4 |
| **EXMORK** | 12V/500VA/110VAC-60Hz | 200 | Phocos Pure Sine Solar Inverter | 12-24Vdc/110Vac-60hz/700W | 512,66 |
| **POWERSTARS** | 12-24Vdc/1000W/110-220VAC-60Hz | 450 | Phocos Pure Sine Solar Inverter | 48Vdc/110Vac-60hz/700W | 582,27 |
| **POWERSTARS** | 24-48Vdc/2000W/110-220VAC-60Hz | 700 | Phocos Pure Sine Solar Inverter | 24-48Vdc/110Vac-60hz/1500W | 1071,63 |
| **POWERSTARS** | 48Vdc/4000W/110-220VAC-60Hz | 1200 | Studer AJ | 12Vdc/115Vac-60hz/275W | 548,1 |
| **MORNINGSTARS** | 12Vdc/300-600VA/110VAC-60Hz | 350 | Studer AJ | 24Vdc/115Vac-60hz/350W | 793,67 |
| **SAMLEX AMERICA** | 12Vdc/450VA/110VAC-60Hz | 80 | Studer AJ | 12Vdc/115Vac-60hz/500W | 841,05 |
| **SAMLEX AMERICA** | 24-48Vdc/1000VA/110VAC-60-50Hz | 690 | Studer AJ | 24Vdc/115Vac-60hz/600W | 1388,19 |
| **SAMLEX AMERICA** | 12Vdc/1500W/110VAC-60Hz | 690 | Victron Energy Phoenix | 12Vdc/110Vac-60hz/180W | 181,91 |
| **SAMLEX AMERICA** | 48Vdc/3000W/110VAC-60Hz | 1790 | Victron Energy Phoenix | 24Vdc/110Vac-60hz/180W | 233,99 |
| **SUNNY ISLAND SMA** | 48Vdc/6000W/110Vac/60hz | 8000 | Victron Energy Phoenix | 12Vdc/110Vac-60hz/350W | 258,3 |
| | | | Victron Energy Phoenix | 24Vdc/110Vac-60hz/350W | 429,38 |
| | | | Victron Energy Phoenix | 12-24Vdc/110Vac-60hz/750W | 673,64 |
| | | | Victron Energy Phoenix | 24Vdc/110Vac-60hz/1200W | 853,34 |
| | | | Victron Energy MultiPlus | 24-12Vdc/120Vac-60hz/2000W | 2397,94 |
| | | | Victron Energy MultiPlus | 12-24Vdc/110Vac-60hz/3000W | 3212,29 |
| | | | Victron Energy Quattro | 48Vdc/110Vac-60hz/3000W | 3955,25 |

The available batteries in the local market, as well as the associated costs per unit are presented in the table A.3.4.

*Table A.3.4: Cost of batteries for stand-alone systems*

| Proviento S. A | | | Renova Energía | | |
|---|---|---|---|---|---|
| Battery | **Power range** | **Price $** | **Photovoltaic panels** | **Power range** | **Price $** |
| **Sunbright battery** | | | Ritar power AGM | 12Vdc/12Ah- @ C10h | 44,89 |
| Battery sbb AGM | 12Vdc/20Ah- @ C20h | 80 | Ritar power AGM | 12Vdc/18Ah- @ C10h | 54,34 |
| Battery sbb GEL | 12Vdc/55Ah- @ C10h | 190 | Ritar power AGM | 12Vdc/48Ah- @ C10h | 155,93 |
| Battery sbb GEL | 12Vdc/100Ah- @ C10h | 300 | Ritar power GEL | 12Vdc/40Ah- @ C10h | 165,38 |
| Battery sbb GEL | 12Vdc/150Ah- @ C10h | 440 | Ritar power AGM | 12Vdc/100Ah- @ C10h | 314,21 |
| **Ultracell** | | | Ritar power GEL | 12Vdc/100Ah- @ C10h | 382,73 |
| UCG20-12 Deep cycle GEL | 12Vdc/150Ah- @ C10h | 90 | Ritar power AGM | 12Vdc/150Ah- @ C10h | 496,13 |
| UCG20-12 Deep cycle GEL | 12Vdc/55Ah- @ C10h | 245 | Ritar power AGM | 6Vdc/200Ah- @ C10h | 326,03 |
| UCG20-12 Deep cycle GEL | 12Vdc/85Ah- @ C10h | 280 | Ritar power GEL | 12Vdc/260Ah- @ C10h | 913,5 |
| UCG20-12 Deep cycle GEL | 12Vdc/100Ah- @ C10h | 330 | Ritar power AGM | 2Vdc/350Ah- @ C10h | 181,13 |
| UCG20-12 Deep cycle GEL | 12Vdc/150Ah- @ C10h | 490 | Trojan AGM | 12Vdc/89Ah- @ C20h | 708,75 |
| **ENERPRO** | | | Trojan AGM | 12Vdc/100Ah- @ C20h | 1110,38 |
| Krawer GEL SM200 | 12Vdc/210Ah | 531,2 | Power sonic | 12Vdc/100Ah- @ C20h | 336 |
| Toyama GEL | 12Vdc/200Ah | 531,2 | Famma battery AGM | 12Vdc/12Ah | 72,15 |
| Bulls power widson GEL | 12Vdc/200Ah | 531,2 | Famma battery AGM | 12Vdc/18Ah | 78 |
| Toyama AGM/GEL | 12Vdc/110Ah | 294,55 | Magna battery AGM | 12Vdc/12Ah- @ C20h | 72,15 |
| Rittar AGM/GEL | 12Vdc/100Ah | 294,67 | Magna battery AGM | 12Vdc/100Ah- @ C20h | 540 |

A.4. **Physical distribution of dwellings in the Yuwints community**

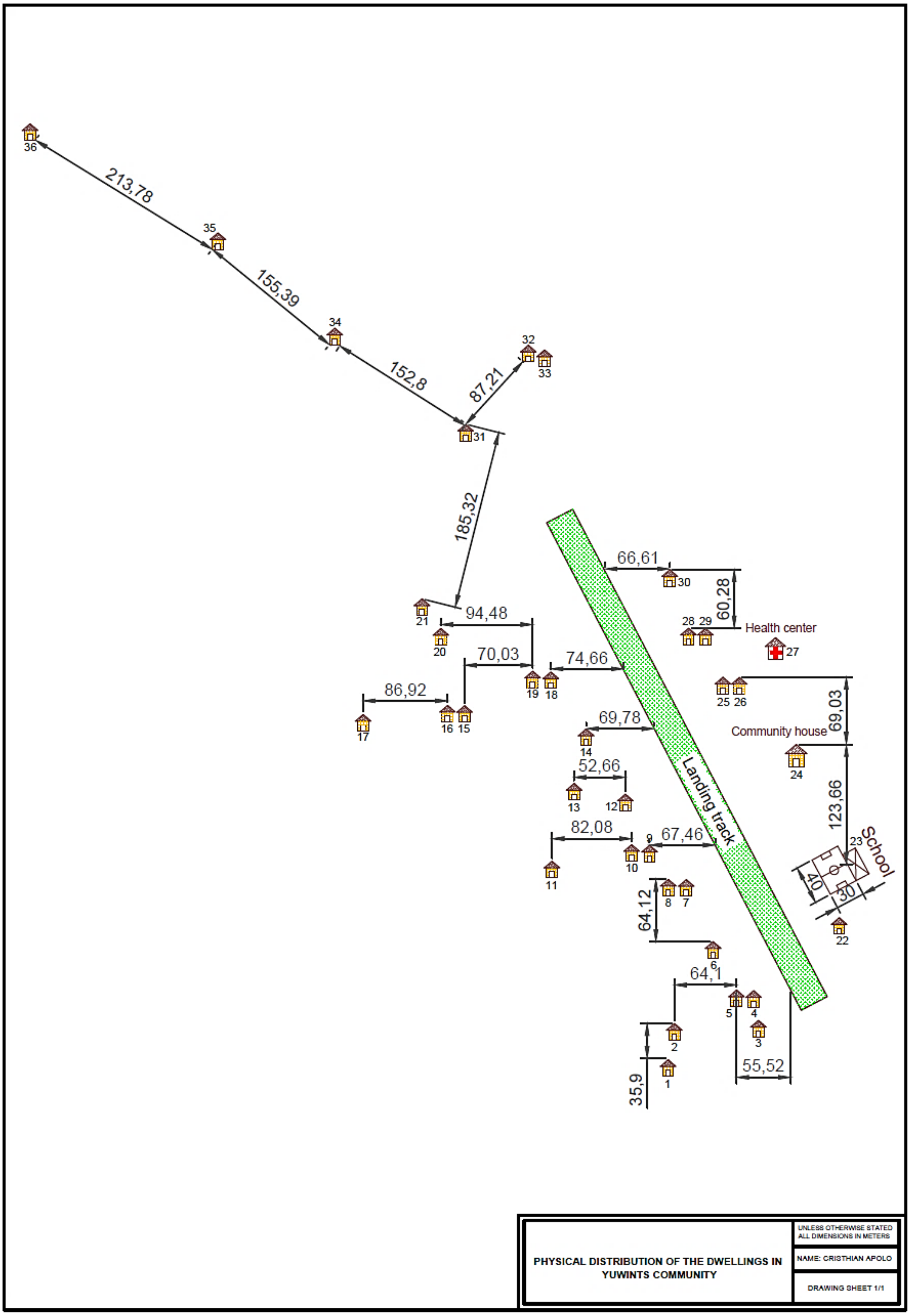


*Figure A.4. 1: Physical distribution of dwellings in Yuwints*

## A.5. **Algorithm to determine the optimum location of the PV generation system**

```
function optimal_location_PVsystem()
  clear;
  clc;
  close all;
  x = -21 : .01 : 21;
  xy = viviendas();
  nh=length(xy);
  Z0 = [-1,1];
  W=weight_important_dwellings();
  [punto1 P]=pesos();
  punto2=second_point();
  Z = fmincon(@(Z) costo3(Z,xy,P,W),Z0, [], [], [], [], [], [], @(Z) restriction3(Z));
  punto3=Z;

  y=landing_track(x);
plot(x, y,'k',x, -y,'k', xy(:,1), xy(:,2),'m.', punto1(1), punto1(2),     'c.',punto2(1),punto2(2),'r.',punto3(1),punto3(2),'b*',
'LineWidth', 1); grid on
  axis equal
  title('Optimal location of PV system for Yuvientza community','color','k');
  xlabel('eje x','color','w');
  ylabel('eje y','color','w');
  set(gcf,'color',[1 1 1]);%,'menubar','none');
  legend('Landing track','landing track','Dwellings','first point','second point','third point');
  set(gca,'color',[0.9 1 0.7]);

punto1
punto2
punto3
end

function f3 = costo3(Z,xy,P,W)
   nh = length(xy);
   f3 = 0;
               for k = 1 : nh
                  f3 = f3 + ((Z(1) - xy(k,1))^2 + (Z(2) - xy(k,2))^2)*P(k)*W(k);
              end
end

function [c, ceq] = restriction3(Z)
   c = [];
   ceq = 98115.64*Z(1)^2 + 450*Z(2)^2 - 40076018.54;
end

function punto2=second_point()
  xy = viviendas();
  nh=length(xy);
  X0 = [-1,-5];
  W=weight_important_dwellings();
  [punto1 P]=pesos();

  X = fmincon(@(X) costo2(X, xy,P),X0, [], [], [], [], [], [], @(X) restriction2(X));
  punto2=X;
end

function f2 = costo2(X, xy,P)
   nh = length(xy);
   f2 = 0;
            for k = 1 : nh
                f2 = f2 + ((X(1) - xy(k,1))^2 + (X(2) - xy(k,2))^2)*P(k);
            end
end

function [c, ceq] = restriction2(X)
   c = [];
   ceq = 98115.64*X(1)^2 + 450*X(2)^2 - 40076018.54;
end

function [punto1 P]=pesos()
  xy = viviendas();
  nh=length(xy);
  Y0 = [-1,-5];

  Y = fmincon(@(Y) costo1(Y, xy),Y0, [], [], [], [], [], [], @(Y) restriction1(Y));
```

```
  punto1=Y;
          for k = 1:nh
              P(k) =1/sqrt((Y(1)-xy(k,1))^2 + (Y(2)-xy(k,2))^2);
          end
end

function f1 = costo1(Y, xy)
  nh = length(xy);
  f1 = 0;
  for k = 1 : nh
     f1 = f1 + ((Y(1) - xy(k,1))^2 + (Y(2) - xy(k,2))^2);
  end
end

function [c, ceq] = restriction1(Y)
  c = [];
  ceq = 98115.64*Y(1)^2 + 450*Y(2)^2 - 40076018.54;
end

function y = landing_track(x)
  y = sqrt( (40076018.54 - 98115.64*x.^2) / 450 );
end

function xy = viviendas()
  xy = [-168,-280;-145,-250;-67,-287;-57,-258;-72,-249;-70 -194;
        -65,-124;-82,-115;-83,-85;-99,-66;-179,-43;-80,-17;
        -122,17;-85,61;-185,140;-200,148;-282,180;-90,130;
        -106,39;-170,222;-173,258;56,-231;104,-176;96,-59;
        64,43;79,35;129,50;56,104;71,96;67,166;-50,396;
        45,439;57,427;-123,457;-185,689;-304,878];
end

function W = weight_important_dwellings()
W=[1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 5 1 1 1 3 1 1 1 1 1 1 1 1 1];
End
```

A.6. **Design of the Low Voltage Network for the Yuwints community**

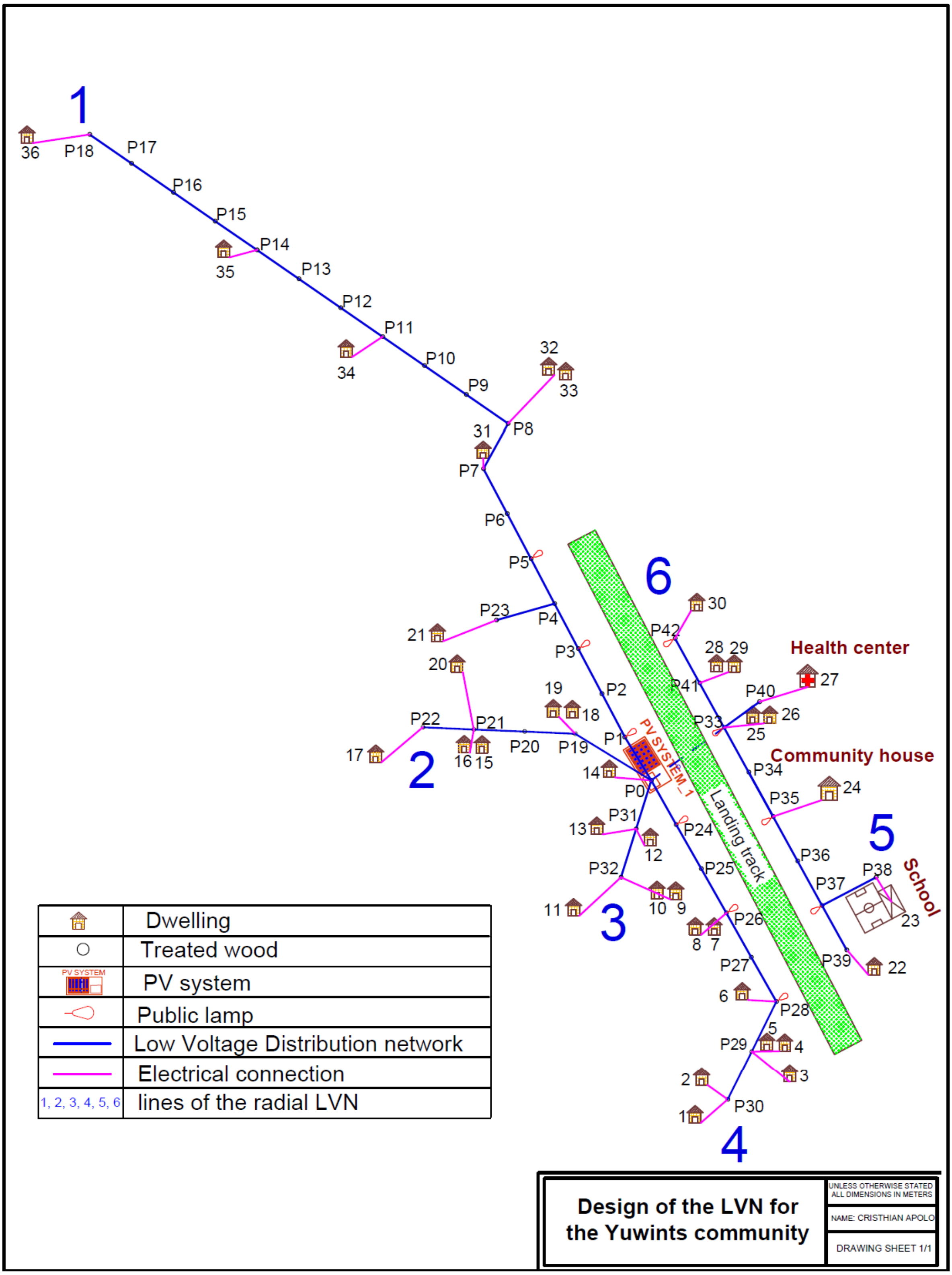


*Figure A.6. 1: Design of the low voltage network for the Yuwints community*

## A.7. **FDV calculation for the LVDN conductors**

The electric characteristics of the conductors to use in the LDVN are present in table A.7.1.

*Table A.7. 1: Electric characteristics of ACSR electric conductors*

| Characteristics of ACSR electric conductor | | | | | | |
|---|---|---|---|---|---|---|
| size AWG or MCM | N° strands | amperes capacity (A) | RMG mm | R to 50°C ohm/km | Xl ohm/km | Z ohm/km |
| **2** | 1-6 | 183 | 1,2741 | 1,012 | 0,545 | 1,149 |
| **4** | 1-6 | 139 | 1,332 | 1,565 | 0,542 | 1,656 |
| **1/0** | 1-6 | 240 | 1,3594 | 0,654 | 0,54 | 0,848 |
| **2/0** | 1-6 | 275 | 1,5545 | 0,53 | 0,53 | 0,750 |
| **3/0** | 1-6 | 316 | 1,8288 | 0,429 | 0,518 | 0,673 |

$$FDV = \frac{10 * kV_{(f-n)}^{2} * F}{k * (r * \cos(\emptyset + x * sen(\emptyset))}$$

Where:

| configuration | K | F |
|---|---|---|
| **1F2C** | 2 | 1 |
| **1F3C** | 1 | 2 |
| **2F2C** | 1 | 2 |
| **2F3C** | 1 | 2 |
| **3F3C** | 1 | 3 |
| **3F4C** | 1 | 3 |

The result of the calculation for each electric conductor by using a voltage of 110V and 220V, are shown in table A.7.2.

*Table A.7. 2: Calculation results for ACSR electric conductors*

| Configuration | FDV | | | | | Pf |
|---|---|---|---|---|---|---|
| **1F2C** | Size of the ACSR electric conductor | | | | | **0,95** |
| **Voltage V** | 2 | 4 | 1/0 | 2/0 | 3/0 | 4/0 |
| **120** | 64 | 44 | 92 | 108 | 127 | 153 |
| **220** | 214 | 147 | 307 | 362 | 426 | 513 |

A.8. **Flowchart and MATLAB code to determine the conductor size configuration for each of the lines and total cost of the LVDN.**

Flowchart of the algorithm for determining the size of the conductors in the Low Voltage Line.

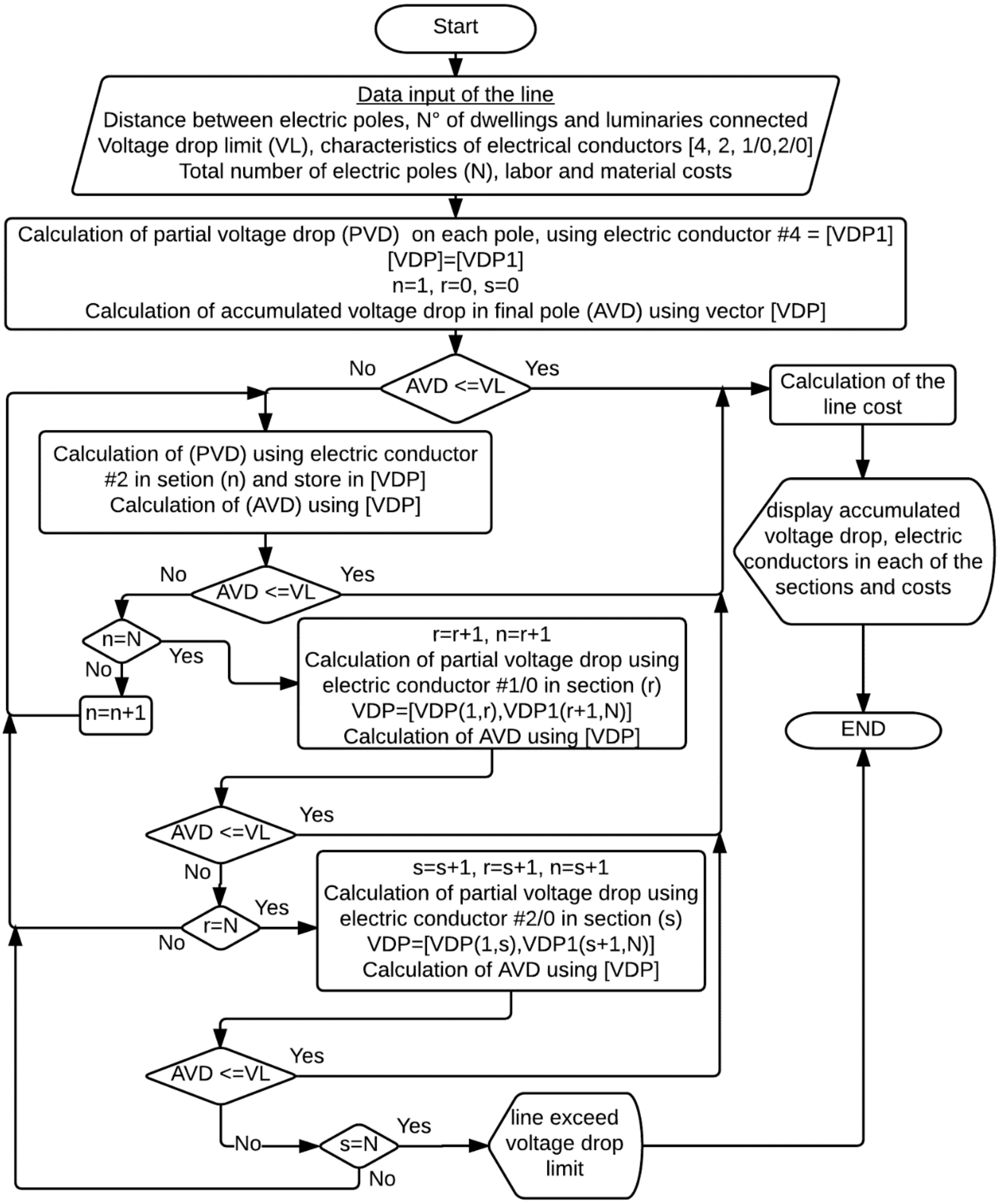


*Figure A.8. 1: Flowchart of the algorithm for sizing the electric conductors in a distribution line*

## MATLAB code for the conductor size configuration of the line 1.

```
function [C1 u1 VDA3]=calculo_linea1()

   DMUp=0.4;
   DL=(0.08/0.9);
   limite=5;
   datos=informacion_L1();
   FDV=conductor();
   [Cmat Cman]=costos();
   N=length(datos);
   L=length(FDV);

d=demanda(DMUp,DL,datos);
VDP1 = caidatension(datos,FDV,1,d); % Partial voltage drop in line 1 using conductor # 4
[VDP VDA] = caidatension(datos,FDV,5,d);
limitemaximo=VDA(N-1,1); % Maximum limit of voltage drop with conductor 3/0

for m=1:L
   [VDP VDA] = caidatension(datos,FDV,m,d);
       if VDA(N-1,1) < limite
               if m==1
                  [u1 C1]=costolinea(datos,Cmat,Cman,VDP,d);
                  VDA3=VDA(N-1,1);
               end
           M=m;
        break
       end

       if (m==L & VDA(N-1,1) > limite)
               disp('line exceeds voltage limit');
               disp(' The maximum limit can be reduced in the line is'), limitemaximo
               M=0;
       end
end
%-----------------------------------------------------------------------------------------
VDP=VDP1;
if (M > 1)
v=0;r=0;s=0;t=0;w=1;n=1;q=2;

 while(1)

   VDA1=caidaacumulada(VDP); % Calculation of accumulated voltage drop from VDP values
        %-----------------------------------------
        if (VDA1 <= limite)
           [u C]=costolinea(datos,Cmat,Cman,VDP,d); %calculates and stores the cost of
           v=v+1;                                   %the different configurations for
               if (v == 1)                          %line conductors, provided they meet
                  u1=u;                             %the established voltage limit
                  C1=C;
                  VDA3=VDA1(N-1,1);
               else
                       if (u < u1)
                          w=w+1;
                          u1(w)=u;
                          C1(:,w)=[C];
                          VDA3(w)=VDA1(N-1,1);
                       end
               end
        end
        %------------------------------------------
    if VDA1(N-1,1) > limitemaximo
            VDP(n)= (d(n,1)*datos(n+1,1))/FDV(q,2); %calculates partial V.D in (n)
            n=n+1;
                                                    % section using conductor # 2
        if (n == N)
             VDA1=caidaacumulada(VDP);

               if VDA1(N-1,1) > limitemaximo
                   if (M >= 2)
                       %-------------------------------------------
                             if (VDA1 <= limite)
                                 [u C]=costolinea(datos,Cmat,Cman,VDP,d);
                                  v=v+1;
                                  if (v == 1)
```

```
                  u1=u;
                  C1=C;
                  VDA3=VDA1(N-1,1);
              else
                  if (u < u1)
                      w=w+1;
                      u1(w)=u;
                      C1(:,w)=[C];
                      VDA3(w)=VDA1(N-1,1);
                  end
              end
        end
        %--------------------------------------
r=r+1;
n=r;  % Calculates partial V.D using 1/0 conductor in (r) section
VDP(r)= (d(r,1)*datos(r+1,1))/FDV(3,2);
 if r < (N-1)
          for i=r+1:N-1           % changes partial V.D using #4
              VDP(i,1)=VDP1(i,1);  % conductor from (r+1) section
          end
     n=n+1;
     q=2;
 else
     VDA1=caidaacumulada(VDP);
     s=s+1;
   %-----------------------------------------------
          if (VDA1 <= limite)
              [u C]=costolinea(datos,Cmat,Cman,VDP,d);
              v=v+1;
                 if (v == 1)
                    u1=u;
                    C1=C;
                    VDA3=VDA1(N-1,1);
                 else
                    if (u < u1)
                        w=w+1;
                        u1(w)=u;
                        C1(:,w)=[C];
                        VDA3(w)=VDA1(N-1,1);
                    end
                 end
          end
    %-----------------------------------------------
     if VDA1(N-1,1) > limitemaximo
         VDP(s)= (d(s,1)*datos(s+1,1))/FDV(4,2); % V.D with 2/0
         if s < (N-1)
             for i=s+1:N-1
                 VDP(i,1)=VDP1(i,1);
             end
             n=s+1;
             q=2;
             r=s;
         else
             VDA1=caidaacumulada(VDP);
             t=t+1;
     %-----------------------------------------------
             if (VDA1 <= limite)
                 [u C]=costolinea(datos,Cmat,Cman,VDP,d);
                 v=v+1;
                 if (v == 1)
                     u1=u;
                     C1=C;
                     VDA3=VDA1(N-1,1);
                 else
                     if (u < u1)
                        w=w+1;
                        u1(w)=u;
                        C1(:,w)=[C];
                        VDA3(w)=VDA1(N-1,1);
                     end
                 end
             end
    %-------------------------------------------------
             if VDA1(N-1,1) > limitemaximo
                 VDP(t)= (d(t,1)*datos(t+1,1))/FDV(5,2);% V.D 3/0
                     if t < 18
                         for i=t+1:N-1
```

```
                                                        VDP(i,1)=VDP1(i,1);
                                                    end
                                                 n=t+1;
                                                 s=t;
                                                 r=t;
                                                 q=2;
                                                end
                                        else
                                           break
                                        end
                                    end
                                else
                                  break
                                end
                           end
                        end
                   else
                     break
                   end
             end
        else
           break
        end
 end
end
C1,u1,VDA3
end

function [VDP VDA]=caidatension(datos,FDV,m,d)
 p=0;
 N=length(datos);
       for i=1:N-1
             for k=1:N-1
                 VDP(k,1) = (d(k,1)*datos(k+1,1))/FDV(m,2);
             end
       p = p + VDP(i);
       VDA(i,1) = p;
       end
end

function [u C]=costolinea(datos,Cmat,Cman,VDP,d)
 u=0;
 N=length(datos);
    for i=1:N-1
    FDVF(i,1)= round((d(i,1)*datos(i+1,1))/VDP(i,1));

    if (FDVF(i,1)==147.0000)
        C{i,1}='conductor 4';
        Costo(i,1)= datos(i+1,1)*(Cmat(1,1)+Cmat(1,1)+Cman(1,1)+Cman(1,1));
    elseif (FDVF(i,1)==214.0000)
        C{i,1}='conductor 2';
        Costo(i,1)= datos(i+1,1)*(Cmat(2,1)+Cmat(1,1)+Cman(2,1)+Cman(1,1));
    elseif (FDVF(i,1)==307.0000)
        C{i,1}='conductor 1/0';
        Costo(i,1)= datos(i+1,1)*(Cmat(3,1)+Cmat(1,1)+Cman(3,1)+Cman(1,1));
    elseif (FDVF(i,1)==362.0000)
        C{i,1}='conductor 2/0';
        Costo(i,1)= datos(i+1,1)*(Cmat(4,1)+Cmat(2,1)+Cman(4,1)+Cman(2,1));
    elseif (FDVF(i,1)==426.0000)
        C{i,1}='conductor 3/0';
        Costo(i,1)= datos(i+1,1)*(Cmat(5,1)+Cmat(2,1)+Cman(5,1)+Cman(2,1));
    end
    u=u+Costo(i,1);

    end
end

function VDA1=caidaacumulada(VDP1)
p=0;
N=length(VDP1);
for i=1:N
    p=p+VDP1(i);
    VDA1(i,1)=p;
end
end
```

```
function d=demanda(DMUp,DL,datos)
N=length(datos);
for j=1:N
    for k=1:N
    g=0;
    f=0;
        for i=k+1:N
        g = g + datos(i,2);
        f = f + datos(i,3);
        end
        usuarios(k,1)=g;    % Number of users downstream of post i
        luminarias(k,1)=f; % Number of luminaries downstream of post i
    end
    d(j,1)=DMUp*usuarios(j,1)^(1-0.0944)+luminarias(j,1)*DL; % Demand in each section
 end
end

function [Cmat Cman]=costos()
 Cmat=[0.47;0.7;1.09;1.4;1.71;0.53;102.97];
 Cman=[0.26112;0.2989;0.33671;0.3745;0.41229;0.25081;12];
end

function FDV = conductor()
 FDV=[44,147;64,214;92,307;108,362;127,426];
end

function datos_L1 = informacion_L1()
     % distancia    viviendas    luminarias
 datos_L1 =[0,1,0;50,0,1;50,0,0;50,0,1;50,1,0;50,0,1;50,0,0;50,1,0;50,2,0;50,0,0;50,0,0;
           50,1,0;50,0,0;50,0,0;50,1,0;50,0,0;50,0,0;50,0,0;50,1,0];
end
```

## B.1. **Simulation results of the individual systems of the Yuwints community**

**(a)** *Representative dwelling*

| Battery | PV (kW) | ZH | RTL | N° Batt | Conv. (kW) | Initial Capital | Operating Cost ($/yr) | Total NPC | COE ($/kWh) | Ren. Frac. | Batt. Lf. (yr) | Voltage System |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 200Ah 12V | 0.70 | | | 3 | 0.25 | $ 2,934 | 189 | $ 5,347 | 0.963 | 1.00 | 8.4 | 12V |
| | 0.95 | | | 2 | 0.25 | $ 2,829 | 199 | $ 5,374 | 0.968 | 1.00 | 5.9 | 24V |
| 55Ah 12V | 0.90 | | | 7 | 0.25 | $ 3,150 | 283 | $ 6,773 | 1.221 | 1.00 | 5.7 | 12V |
| | 0.85 | | | 8 | 0.25 | $ 3,271 | 281 | $ 6,864 | 1.237 | 1.00 | 6.4 | 24V |
| 225Ah 6V | 0.90 | | | 3 | 0.25 | $ 2,848 | 160 | $ 4,898 | 0.882 | 1.00 | 8.3 | 6V |
| | 0.70 | | | 4 | 0.25 | $ 2,898 | 165 | $ 5,012 | 0.903 | 1.00 | 10.0 | 12V |
| | 0.70 | | | 4 | 0.25 | $ 2,898 | 165 | $ 5,012 | 0.903 | 1.00 | 10.0 | 24V |

**(b)** *School*

| Battery | PV (kW) | ZH | RTL | N° Batt | Conv. (kW) | Initial Capital | Operating Cost ($/yr) | Total NPC | COE ($/kWh) | Ren. Frac. | Batt. Lf. (yr) | Voltage System |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 200Ah 12V | 1.10 | | | 2 | 0.45 | $ 3,182 | 147 | $ 5,059 | 0.743 | 1.00 | 10.0 | 12V |
| | 1.10 | | | 2 | 0.45 | $ 3,182 | 147 | $ 5,059 | 0.743 | 1.00 | 10.0 | 24V |
| 55Ah 12V | 1.60 | | | 4 | 0.45 | $ 3,772 | 145 | $ 5,626 | 0.826 | 1.00 | 10.0 | 12V |
| | 1.20 | | | 6 | 0.45 | $ 3,540 | 179 | $ 5,823 | 0.855 | 1.00 | 10.0 | 24V |
| 225Ah 6V | 1.45 | | | 2 | 0.45 | $ 3,467 | 131 | $ 5,142 | 0.755 | 1.00 | 10.0 | 6V |
| | 1.45 | | | 2 | 0.45 | $ 3,467 | 131 | $ 5,142 | 0.755 | 1.00 | 10.0 | 12V |
| | 0.85 | | | 4 | 0.45 | $ 3,251 | 184 | $ 5,605 | 0.823 | 1.00 | 10.0 | 24V |

**(c)** *Health center*

| Battery | PV (kW) | ZH | RTL | N° Batt | Conv. (kW) | Initial Capital | Operating Cost ($/yr) | Total NPC | COE ($/kWh) | Ren. Frac. | Batt. Lf. (yr) | Voltage System |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 200Ah 12V | 0.45 | | | 1 | 0.10 | $ 1,477 | 114 | $ 2,939 | 1.066 | 1.00 | 6.2 | 12V |
| | 0.25 | | | 2 | 0.10 | $ 1,661 | 118 | $ 3,167 | 1.149 | 1.00 | 10.0 | 24V |
| 55Ah 12V | 0.50 | | | 3 | 0.10 | $ 1,656 | 155 | $ 3,638 | 1.320 | 1.00 | 5.2 | 12V |
| | 0.40 | | | 4 | 0.10 | $ 1,698 | 153 | $ 3,659 | 1.328 | 1.00 | 6.8 | 24V |
| 225Ah 6V | 0.35 | | | 2 | 0.10 | $ 1,551 | 102 | $ 2,855 | 1.035 | 1.00 | 10.0 | 6V |
| | 0.35 | | | 2 | 0.10 | $ 1,551 | 102 | $ 2,855 | 1.035 | 1.00 | 10.0 | 12V |
| | 0.25 | | | 4 | 0.10 | $ 2,125 | 155 | $ 4,109 | 1.490 | 1.00 | 10.0 | 24V |

**(d)** *Dwelling with the average energy consumption in the community*

| Battery | PV (kW) | ZH | RTL | N° Batt | Conv. (kW) | Initial Capital | Operating Cost ($/yr) | Total NPC | COE ($/kWh) | Ren. Frac. | Batt. Lf. (yr) | Voltage System |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 200Ah 12V | 0.10 | | | 1 | 0.10 | $ 937 | 83 | $ 2,002 | 2.332 | 1.00 | 10.0 | 12V |
| | 0.10 | | | 2 | 0.10 | $ 1,437 | 118 | $ 2,943 | 3.428 | 1.00 | 10.0 | 24V |
| 55Ah 12V | 0.15 | | | 1 | 0.10 | $ 722 | 85 | $ 1,810 | 2.109 | 1.00 | 5.1 | 12V |
| | 0.10 | | | 2 | 0.10 | $ 837 | 85 | $ 1,926 | 2.243 | 1.00 | 9.3 | 24V |
| 225Ah 6V | 0.10 | | | 1 | 0.10 | $ 803 | 75 | $ 1,767 | 2.058 | 1.00 | 10.0 | 6V |
| | 0.10 | | | 2 | 0.10 | $ 1,169 | 102 | $ 2,473 | 2.881 | 1.00 | 10.0 | 12V |
| | 0.10 | | | 4 | 0.10 | $ 1,901 | 155 | $ 3,885 | 4.525 | 1.00 | 10.0 | 24V |

**(e)** *Dwelling with the highest energy consumption in the community*

| Battery | PV (kW) | ZH | RTL | N° Batt | Conv. (kW) | Initial Capital | Operating Cost ($/yr) | Total NPC | COE ($/kWh) | Ren. Frac. | Batt. Lf. (yr) | Voltage System |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 200Ah 12V | 0.45 | | | 1 | 0.20 | $ 1,518 | 99 | $ 2,786 | 1.086 | 1.00 | 8.4 | 12V |
| | 0.25 | | | 2 | 0.20 | $ 1,702 | 125 | $ 3,296 | 1.284 | 1.00 | 10.0 | 24V |
| 55Ah 12V | 0.50 | | | 3 | 0.20 | $ 1,697 | 128 | $ 3,335 | 1.300 | 1.00 | 7.3 | 12V |
| | 0.60 | | | 2 | 0.25 | $ 1,676 | 130 | $ 3,336 | 1.301 | 1.00 | 5.2 | 24V |
| 225Ah 6V | 0.50 | | | 1 | 0.25 | $ 1,484 | 93 | $ 2,670 | 1.041 | 1.00 | 8.3 | 6V |
| | 0.30 | | | 2 | 0.20 | $ 1,513 | 109 | $ 2,905 | 1.132 | 1.00 | 10.0 | 12V |
| | 0.25 | | | 4 | 0.20 | $ 2,166 | 162 | $ 4,237 | 1.651 | 1.00 | 10.0 | 24V |

*Figure B.1. 1: Simulations result of the stand-alone home systems for the community*

## B.2. **Simulation results of the centralized systems of the Yuwints community**

**(a)** *Yuwints community without public lighting*

| Battery | PV (kW) | ZH | RTL | N° Batt | Conv. (kW) | Initial Capital | Operating Cost ($/yr) | Total NPC | COE ($/kWh) | Ren. Frac. | Batt. Lf. (yr) | Voltage System |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 200Ah 12V | 6.0 | | | 16 | 2 | $ 30,149 | 1,476 | $ 49,015 | 1.210 | 1.00 | 6.8 | 12V |
| | 6.0 | | | 16 | 2 | $ 30,149 | 1,476 | $ 49,015 | 1.210 | 1.00 | 6.8 | 24V |
| | 6.0 | | | 16 | 2 | $ 30,149 | 1,476 | $ 49,015 | 1.210 | 1.00 | 6.8 | 48V |
| | 6.0 | | | 16 | 2 | $ 30,149 | 1,476 | $ 49,015 | 1.210 | 1.00 | 6.8 | 96V |
| 55Ah 12V | 7.0 | | | 44 | 2 | $ 32,529 | 2,072 | $ 59,020 | 1.457 | 1.00 | 5.3 | 12V |
| | 7.0 | | | 44 | 2 | $ 32,529 | 2,072 | $ 59,020 | 1.457 | 1.00 | 5.3 | 24V |
| | 7.0 | | | 44 | 2 | $ 32,529 | 2,072 | $ 59,020 | 1.457 | 1.00 | 5.3 | 48V |
| | 6.0 | | | 56 | 2 | $ 33,349 | 2,051 | $ 59,567 | 1.470 | 1.00 | 6.7 | 96V |
| 225Ah 6V | 6.0 | | | 22 | 2 | $ 30,201 | 1,232 | $ 45,944 | 1.134 | 1.00 | 8.9 | 12V |
| | 6.5 | | | 20 | 2 | $ 30,259 | 1,242 | $ 46,140 | 1.139 | 1.00 | 8.2 | 24V |
| | 6.0 | | | 24 | 2 | $ 30,933 | 1,216 | $ 46,481 | 1.146 | 1.00 | 9.7 | 48V |
| | 8.0 | | | 16 | 2 | $ 31,165 | 1,273 | $ 47,438 | 1.171 | 1.00 | 6.6 | 96V |

**(b)** *Yuwints community with public lighting*

| Battery | PV (kW) | ZH | RTL | N° Batt | Conv. (kW) | Initial Capital | Operating Cost ($/yr) | Total NPC | COE ($/kWh) | Ren. Frac. | Batt. Lf. (yr) | Voltage System |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 200Ah 12V | 10.5 | | | 49 | 3.00 | $ 43,328 | 3,088 | $ 82,801 | 0.971 | 1.00 | 7.0 | 12V |
| | 10.0 | | | 52 | 3.00 | $ 44,038 | 3,043 | $ 82,936 | 0.972 | 1.00 | 7.4 | 24V |
| | 8.5 | | | 60 | 3.00 | $ 45,668 | 2,913 | $ 82,909 | 0.972 | 1.00 | 8.6 | 48V |
| | 9.5 | | | 56 | 3.00 | $ 45,248 | 2,971 | $ 83,227 | 0.975 | 1.00 | 8.0 | 96V |
| 55Ah 12V | 14.0 | | | 124 | 3.00 | $ 49,158 | 4,918 | $ 112,022 | 1.313 | 1.00 | 5.0 | 12V |
| | 14.0 | | | 124 | 3.00 | $ 49,158 | 4,918 | $ 112,022 | 1.313 | 1.00 | 5.0 | 24V |
| | 14.0 | | | 124 | 3.00 | $ 49,158 | 4,918 | $ 112,022 | 1.313 | 1.00 | 5.0 | 48V |
| | 13.0 | | | 136 | 3.00 | $ 49,978 | 4,900 | $ 112,621 | 1.320 | 1.00 | 5.5 | 96V |
| 225Ah 6V | 10.5 | | | 66 | 3.00 | $ 42,984 | 2,378 | $ 73,378 | 0.860 | 1.00 | 9.0 | 12V |
| | 11.0 | | | 64 | 3.00 | $ 43,042 | 2,389 | $ 73,576 | 0.862 | 1.00 | 8.7 | 24V |
| | 11.0 | | | 64 | 3.00 | $ 43,042 | 2,389 | $ 73,576 | 0.862 | 1.00 | 8.7 | 48V |
| | 11.0 | | | 64 | 3.00 | $ 43,042 | 2,389 | $ 73,576 | 0.862 | 1.00 | 8.7 | 96V |

*Figure B.2. 1: Simulations result of the centralized system for the community*