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Planning of rural electrification with mini hydro-power systems in the Cimitarra basin (Colombia)

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ABSTRACT

On the 25th September 2015 the 2030 Agenda for Sustainable Development was adopted by 193 world leaders, the Sustainable Development Goal (SDG) 7.1 aimed to ensure universal access to affordable, reliable and modern energy services by 2030.
The world still remains off-track in its effort to achieve SDG 7.1, even if in 2018 the number of people without electricity access fell below 1 billion for the first time ever. In rural areas the access rate is just 75% as the isolated and scattered distribution of rural communities makes grid extension a non-economically viable option.
In this context, distributed generation systems based on renewable energy reveal themselves as promising solutions to this challenging task.

The thesis aims to provide a useful method for planning off-grid rural electrification with run-off-river mini-hydro for the Cimitarra river basin (Colombia). The geographical area was chosen since it has been already object of study of a specific project of Ingegneria Senza Frontiere together with l'Asociacion Campesina del Valle del Rio Cimitarra.
The starting point was represented by the Master Thesis of Mattia Manara, a colleague who developed the implementation of the algorithm for the Dudh Kosi river basin (Nepal).
A semi-distributed hydrological model was implemented and coupled with a hydroelectric module, used to design various possible electrification schemes.
The results show that mini-hydro is a very promising technology, able to satisfy the energy demand of more than 85% of the population without reaching exceeding costs. However, due to the lack of a storage systems, for few days a year some plants are not able to provide all the energy required.

The model proved to be an effective tool to support the planning of rural electrification based on the hydro-electricity and the results could be further improved through the development of hybrid micro-grid.

SOMMARIO

Il 25 Settembre 2015 193 Nazioni hanno adottato la nuova Agenda per lo Sviluppo Sostenibile del 2030; l'obiettivo (SDG) 7.1 si prefiggeva come scopo quello di assicurare entro il 2030 l'accesso a livello globale ad un servizio di energia elettrica sostenibile, affidabile e moderno.

Tuttavia, si rimane ancora distanti da questo obiettivo, anche se nel 2018 si è raggiunto un traguardo importante: per la prima volta nella storia, il numero di persone prive di accesso al servizio di energia elettrica è sceso sotto il miliardo. Le maggiori difficoltà si incontrano nelle regioni rurali, dove la distribuzione dei villaggi è molto sparsa e per questo motivo in molti casi non è economicamente sostenibile la connessione diretta alla rete elettrica, il che si traduce in una copertura media del 75%.

In questo contesto la generazione distribuita basata su fonti rinnovabili rappresenta senza subbio una valida alternativa per il raggiungimento dell'obiettivo preposto.

Questa tesi mira a fornire un metodo utile per pianificare l'elettrificazione rurale di tipo off-grid tramite il mini-idroelettrico ad acqua fluente nel contesto colombiano del bacino del fiume Cimitarra. La scelta del sito geografico deriva dalla presenza di un altro progetto realizzato da Ingegneria Senza Frontiere in collaborazione con l'Asociacion Campesina del Valle del Rio Cimitarra.

Il punto di partenza per questa analisi è stato il lavoro di tesi specialistica del mio collega Mattia Manara, che ha precedentemente studiato la problematica calata nel contesto himalayano del bacino Dudh Kosi.

Il modello si presenta come modello idrologico semi-distribuito accoppiato con un modulo idroelettrico in grado di valutare diversi possibili schemi di micro-grid.

I risultati confermano il potenziale delle soluzioni di mini-idroelettrico, in grado di garantire fino al'85% di copertura dei bisogni energetici mantenendo un costo dell'energia competitivo. Tuttavia, data l'assenza di sistema di accumulo nelle reti elettriche più

performanti, in alcuni giorni dell’anno gli impianti non saranno in grado di evadere la richiesta di energia.

Il modello risulta essere uno strumento risolutivo efficace e di potenziale supporto per la pianificazione dell’elettrificazione rurale basata su tecnologia idroelettrica. Inoltre, si possono individuare dei punti di miglioramento per ulteriori sviluppi che potrebbero essere indagati tramite la pianificazione di reti ibride e non più dipendenti dalla sola risorsa idrica.

CONTENTS

ACRONYMS

SDG	Sustainable Development Goals
IEA	International Energy Agency
UNFCCC	United Nation Framework Convention on Climate Change
NDC	National Determined Contributions
IRENA	International Renewable Energy Agency
ISA	Interconexion Electrica S.A.
NIZ	Non-Interconnected Zones
IPSE	Instituto de Planificacion y Promocion de Soluciones Energetica
SIN	National Interconnected System
NBI	Basic Needs Index
ENSO	El Niño Southern Oscillation
SST	Sea Surface Temperature
IDEAM	Instituto de Hidrología, Meteorología y Estudios Ambientales
UPME	Unidad de Planeacion Minero Energetica
RES	Renewable Energy Sources
SHP	Small Hydro Power
BIRD	
CFT	Cross Flow Turbine
PAT	Pump as Turbine
MHP	Micro Hydro Power
SHP	Small Hydro Power
ICIMOD	International Centre for Integrated Mountain Development
SUI	Sistema Unico de Informacion

SDE	Daily Energy Surpul
LCOE	Levelized Cost of Energy
DEM	Digital Elevation Model
NASA	National Aeronautics and Space Administration
METI	Japan’s Ministry of Economy, Trade and Industry
DANE	Departamento Administrativo Nacional de Estadística

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CHAPTER 1

1. INTRODUCTION

1.1 BACKGROUND AND OBJECTIVES OF STUDY

The provision of secure and affordable energy, even though not sufficient alone to reduce poverty, is essential to foster human development and economic growth. The link between energy access and sustainable development was officially recognized by the United Nations in September 2015 when 193 countries adopted the 2030 Agenda for Sustainable Development, a set of 17 goals aimed at ending poverty, protecting the planet and ensuring prosperity for everyone. For the first time, energy occupied a central place among the world's development priorities as indicated in the SDG 7.1: "ensure universal access to affordable, reliable, sustainable, and modern energy for all."

Despite the great progresses done in 2018, year ended with the number of people without electricity access below 1 billion for the first time ever, the world still remains off-track in its effort to achieve SDG 7.1. The rate of access is above 95% in urban areas, whereas it falls down to just 75% in rural areas (IEA 2018). The difficulty of serving rural inhabitants lies in a combination of complex topography and low population density which can make the extension of the main grid not economically viable (Nerini et al. 2016).

However, assessing this problem only with the aim of promoting energy access around the world would be a huge mistake, indeed it can not be denied any longer the major importance gained by the climate change issue. The current, and the future, socio-economic development paths (governance, technology, populations, economic growth) will have to face this phenomenon as it has severe and deep impacts on both human and natural systems. On the 12th of December 2015, 196 Parties to the UNFCCC adopted the Paris Agreement, a new legally-binding framework for an internationally coordinated effort to tackle climate change both actively, through national determined contributions (NDCs), and passively, by

enhancing << *adaptive capacity, strengthening resilience and reducing vulnerability to climate change* >> (Paris Agreement 2015)**.**
Considering all these different topics, decentralized solutions look a promising way to deal with electrification problem even in the most remote areas. Moreover, technological changes are promoting their development, putting these solutions in the condition to play a significant role in accelerating the pace of electrification (IRENA 2016).

Apart from Brazil, there is no country in Latin America that can rely on a greater hydroelectric potential than Colombia (Arias-Gavaria et al. 2017). According to statistics of Interconexión Eléctrica S.A (ISA), the country has a global hydroelectric potential of about 93000 MW of which 25000 MW the INEA estimated to be technically exploitable. Therefore, there is great interest in the implementation of both large and small hydropower plants (Pacheco and Rodigruez 2015).
The objective of this study is the Cimitarra basin, a region already explored in a previous study developed by Ingegneria Senza Frontiere with the collaboration of l'Asosciacion Campesina del Valle del Rio Cimitarra whose aim was the revitalization of rural enterprise. The water system is a tributary of the major Andean river Magdalena, it is located in the middle of Colombia in a flat region characterised by tropical climate. In this region the percentage of electrification exceed 90% both in urban and rural areas. However fuel incidence in energy production in rural areas has the same percentage. This is an alarming signal of no sustainable electrification process taking place.
This thesis aims to propose an alternative solution to this urgent problem.

Despite this relevant potential a large portion of Colombia territory is located outside the SIN, namely in the Non-Interconnected Zones (NIZ).
According to the Institute for Planning and Promoting Energy Solutions for Non-Interconnected Zones (IPSE for its abbreviation in Spanish) there are 90 municipalities in Colombia belonging to the NIZ, covering about 52% of the National territory, which include 32 departments, 5 departmental capitals, 39 municipal capitals and 1448 localities. Likewise, the National Interconnected System (SIN) connects 48% of the national territory and serves 97% of the population (Vides-Prado, 2018); in terms of the number of households that have access to the electricity grid in Colombia, it is currently provided with 12.1 million, 4 million

more than 2005, represented by 95.8% of the total Colombian population (Mamaghani and Escandon 2016).
Besides this, the percentage of unsatisfied basic needs (NBI) is 71%, whereas for the rest of the country is 28%. Even though the demand for off-grid energy is substantial, the feasibility of satisfying this demand is challenging as some regions have as few as two people per km^2 (Gaona, Trujillo and Guacaname 2015).

In this context, small and micro hydropower implementations, developed both through off-grid or mini-grid solutions, looks like a promising way to satisfy the demand and need for energy access in the NIZ, especially in the Andean territories where grid costs would be prohibitively high and nearly technically unfeasible (Wiemann 2014).

Following the path of a previous colleague, this study aims at extending and verifying the potential of the developed tool, borne for planning the best design of off-grid mini-hydro power plants at a regional level, in a different context.
As study area the Cimitarra river basin, located in the central Colombia, was chosen. The region was selected due to the virtual absence of operating hydro-power plants and the very low population density, a singularity given the importance of the Antioquia department.
The steps followed are hereafter summarized:

- Implement and calibrate a hydrological model based on the meteorological data available in the area;
- Estimate the energy demand related to the self-consumption of the inhabitants and the limited economic activities (almost only agriculture);
- Implement a hydroelectric model to size a small hydro plant and evaluate its cost on the bases of the energy required by the neighbouring villages;
- Implement a heuristic optimisation model aimed at providing a technically feasible solution to serve the greatest share of the population;

1.2 THESIS STRUCTURE

This thesis is composed of six chapters, whose content is hereafter summarized.

Chapter 2 presents the study area. In particular, the main physical and socio-economical characteristics are presented; this is done both at national level and in more detailed way for the Cimitarra catchment.

Subsequently, the energetic overview of Colombia is presented, a chapter is entirely dedicated to the hydroelectricity resource, aiming to introduce the context in which this study is developed.

Chapter 3 describes the modelling approach adopted. Firstly, the hydrological model and its characteristics are analyzed and secondly, the approach used for sizing the various hydro-power plants (aka the hydro-power module) is presented. A stand-alone chapter is dedicated to the optimization technique adopted, with a detailed description of the underlying assumptions of the methodology.

Chapter 4 is dedicated to the input data utilized in the study. Among them, particularly important are the climatic variables (temperature and precipitation); thus, they are presented in a detailed way.

In Chapter 5 the obtained results are reported and discussed. Firstly, the results of the hydrological calibration for the control run 1982 - 1990 are shown. Finally, the results from the optimization technique are presented together with a sensitivity analyses on the major parameters involved.

Chapter 6 sums up the achievements of the study, analyses the limitations in the adopted approach and suggests future developments

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CHAPTER 2

2. STUDY AREA

In the following chapter the study area is presented; in each paragraph, a general framework of the country is provided followed by a more detailed analysis of the Cimitarra catchment. Colombia is firstly framed from a physical point of view, with a particular focus on the climate and the impact of such a various orography. Subsequently, the energy overview is presented alongside with a completely dedicated chapter to hydroelectricity and different technical solutions to exploit such a relevant potential when it comes to tackle rural electrification problem.

2.1 GEOMORPHOLOGY

Colombia is a South America country located between latitudes 12°26’ N and 4°12’ N and longitudes 66°50’ E and 79°02’ E and bordering Antilles in North, Venezuela and Brazil in the East, Perú and Ecuador in the South, Pacific Ocean in the West and Panama in the North-West. With a total area of 1141748 km^2 Colombia is the 26th largest country in the world and the 4th in South America.

From the physiographic point of view, Colombia can be subdivided in two main regions: The Western one, with high mountains and the plane Eastern one.
The first region is characterized by three mountainous different complexes, the so called: Cordillera Oriental, Cordillera Central and Cordillera Occidental. The last one is the shortest and its mountains have relatively high peaks. The Cordillera Central region is characterized by volcanos and peaks profusion, like the Nevado del Hulia, which nearly reaches 5700 m, assuring itself the highest active volcano in Colombia. Nevertheless, the largest mountainous region of the country is the Cordillera Oriental, here in the Sierra Nevada de Santa Marta raises the highest peak of Colombia, the Pico Cristóbal Colon 5775 m.
The Eastern region is named Llano Orientales, it covers almost the 60% of the whole Colombia extension, and is characterized by tropical forest spread out (Paris et al. 2017).

Figure 2.1: *Colombia Map (DEMIS)*

Colombia has four main drainage systems: The Pacific drain, the Caribbean drain, the Orinoco Basin and the Amazon Basin. The main rivers of Colombia are Magdalena, Cauca, Guaviare, Atrato, Meta, Putumayo and Caquetá (Hydrography of Colombia 2014).

The Cimitarra basin is located in the South-East of Antioquia department, the region in Colombia with the highest hydropower potential, it is a flat land characterized by tropical climate. The water system is a tributary of the Magdalena, the Andean major river in Colombia, which flows across the country. The Cimitarra Fault is a sinistral oblique thrust fault in the departments of Antioquia, Bolívar and Santander in central Colombia. The fault has a total length of 136,5 km and runs across the Middle Magdalena Valley and Central Ranges of the Colombian Andes (Paris et al. 2017). The basin object of study is a region of 2950 km^2.

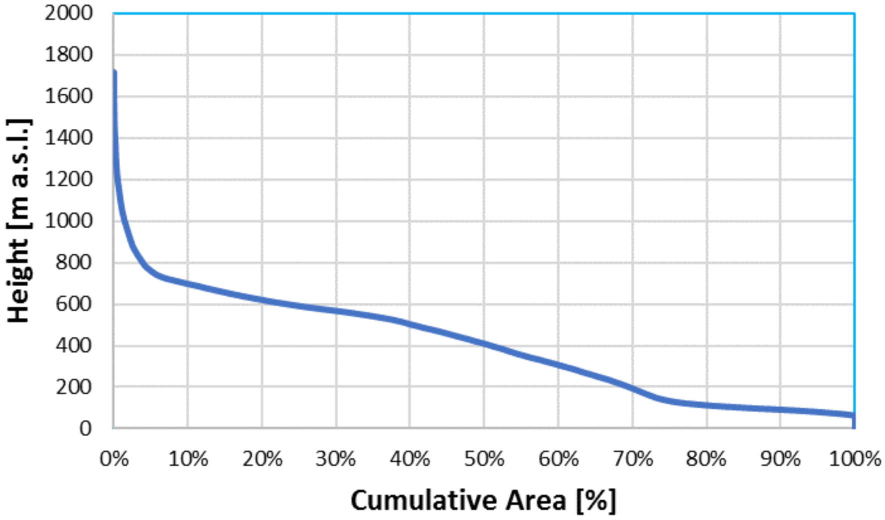

Figure 2.2: *Hypsographic curve of the Cimitarra catchment*

2.2 CLIMATE

The classification commonly used in the Andean regions is developed by considering the climate altitude dependency imposed by the complex orography and it is here reported: lower lands (tierras calientes), tierras templadas (1000 – 2200 m a.s.l.), tierras frìas (around 3000 m a.s.l.) and tierras heladas (Franco 1952).

More specifically, the climate of Colombia is characterized for being tropical, presenting variations within six main natural regions and depending on the altitude, temperature, humidity, winds and rainfall.

As a result of the combination of all these drivers a wide spectrum of climate zones is derived, which ranges from the tropical rainforests to savannas, steppes, deserts and mountain climate.

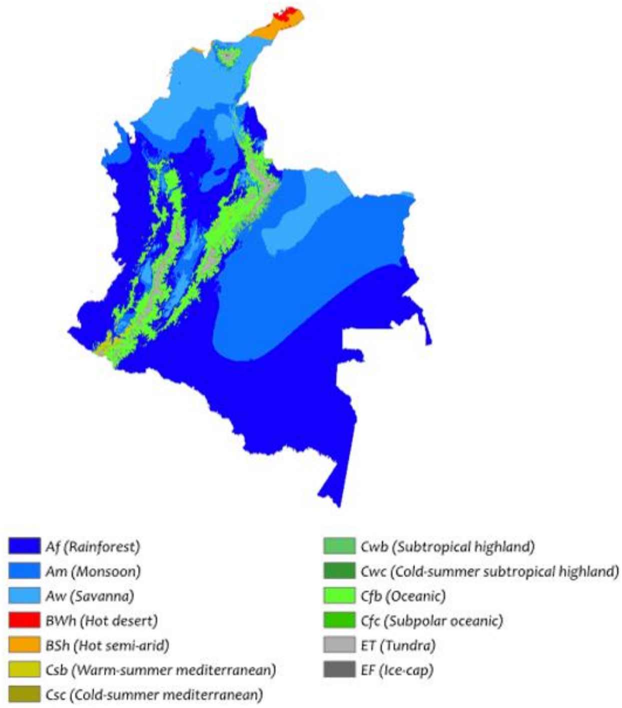

Figure 2.3: *Climate Types of Colombia (WorldClim)*

In addition to this, Andes influences the local atmospheric circulation patterns. Indeed, the Eastern regions are subjected to Trade Winds, which are seasonal and foster the growth of the Amazon region trough almost continuous precipitations. The Andean region climatic conditions, especially in the highest areas, are no longer dependent on Trade Winds but they are characterized by tropical climate, with rainy summers and dry winters. Tropical climate also affects temperatures in the area, a strange result is that solid precipitations are expected only at altitudes major than 4000 m.

Precipitations are abundant almost all-around Colombia as in the west and east regions they can reach 3000 – 4000 mm per year and even 8000 mm in the Pacific region. The inner plateau region and some northern region represent an exception with their 500 – 10000 mm. The same considerations can be proposed regarding temperature and orography relationship. According to the equatorial climate, temperature is almost constant in the eastern region (26-27 °C) and it slowly decreases moving to the plateau regions or even higher. Simply consider that in Medellín, 1487 m a.s.l., temperature is around 20-21 °C and in Bogotá, next to the tierras frias, around 13-14 °C (Arango Cano 1955).

Eventually, Colombia climate trends are subject to El Niño Southern Oscillation (ENSO), El Niño is the warm phase and La Niña is the cool phase. ENSO is associated with a band of warm ocean water that develops in the central and east-central equatorial Pacific, including the area of the Pacific coast of South America. The ENSO is the cycle of warm and cold sea surface temperature (SST) of the tropical central and eastern Pacific Ocean. El Niño is accompanied by high air pressure in the western Pacific and low air pressure in the eastern Pacific. La Niña induces SST in the eastern Pacific below average and air pressure high in the eastern and low in western Pacific. Even if the periodicity of the phenomenon is not constant phases are known to be close to four year, with a wide range of variability from two to even seven years (Trenberth et al. 2007).
Cimitarra basin lies the central region of Colombia, in an almost flat area, thus the climate can be considered tropical, with very little changes depending on the locality of the basin itself.

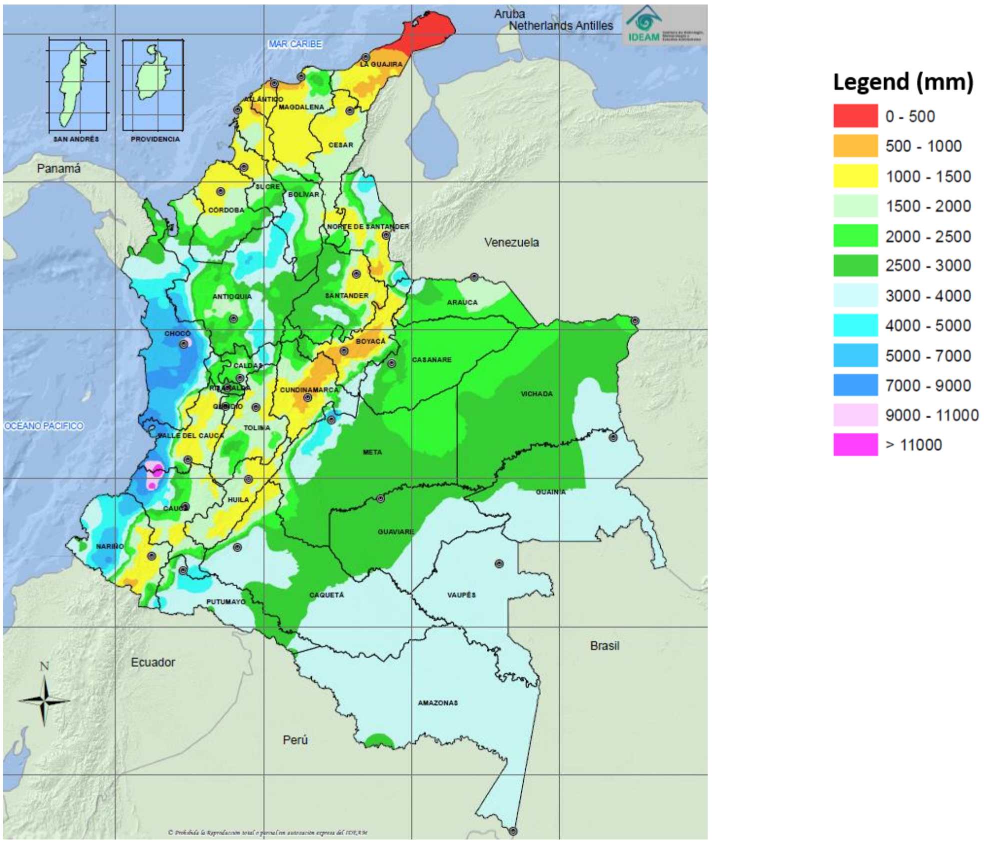

Figure 2.4: *Colombia Annual Precipitation Map (IDEAM Colombia Precipitation Atlas)*

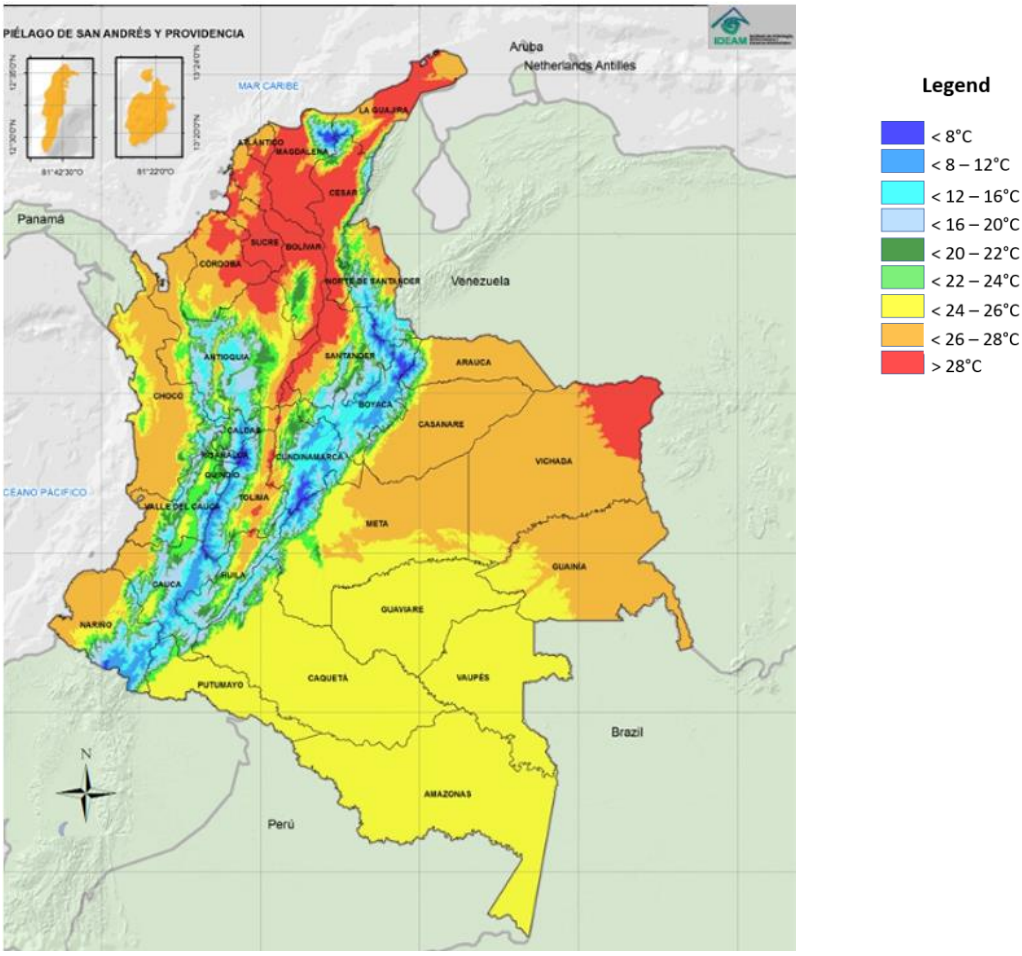

Figure 2.5: *Colombia Average Temperature Map (IDEAM Colombia Temperature Atlas)*

2.3 POPULATION AND ENERGY CONSUMPTIONS

If all around the world it is common to hear about developing countries, steep energy demand increases and so on, Colombia is quite different. The Andean country is in the midst of a demographic transition resulting from steady declines in its fertility, mortality, and population growth rates. The birth rate has fallen from more than 6 children per woman in the 1960s to just above replacement level in 2016 as a result of increased literacy, family planning services, and urbanization. However, income inequality is among the worst in the world, and more than a third of the population lives below the poverty line.

The demographic trend shows a quite low 1,22% urbanization rate. However, population distribution is already significantly unbalanced, 80,8% of the total population live in urban areas (cities like Medellin, Cali, Barranquilla has more than 2 million people and Bogotá is by far the most crowed with its nearly 11 million inhabitants). On the other hand the remaining 20% of the total population is spread over the 60% of the vast grasslands and llanos of the South and East regions, making the population highly scattered and isolated.

Colombia heavily depends on energy and mining exports, making it vulnerable to fluctuations in commodity prices. Colombia is Latin America's fourth largest oil producer and the world's fourth largest coal producer, third largest coffee exporter, and second largest cut flowers exporter.

This country together with Peru and Ecuador are called "Andean Countries". This region is home to approximately 95 million people (Wold Bank, 2015) and have experienced steady economic growth over the last two decades as evidenced by average GDP growth rate from 3% to 5% from 1990 to 2012 (Mauro F. Chavez-Rodriguez, 2018). According to the World Bank, in 2012 its GDP amounted to US $ 380 billion, making Colombia one of the fastest growing economies in Latin America (Wienmann 2014). However, declining oil prices, foreign investments and exploitation, insurgent attacks on oil pipeline and narcotrafficking hindered Colombia's economy, which slowed from an averaged GDP growth of +3% during the past decade to +1% in 2017.

In 2016 the GDP composition by sector was: 7,2% agriculture, 30,8% industry, 62,1% services with a labour force distribution of 17% agriculture, 21% industry and 62% services (The World Factbook Archive 2019).

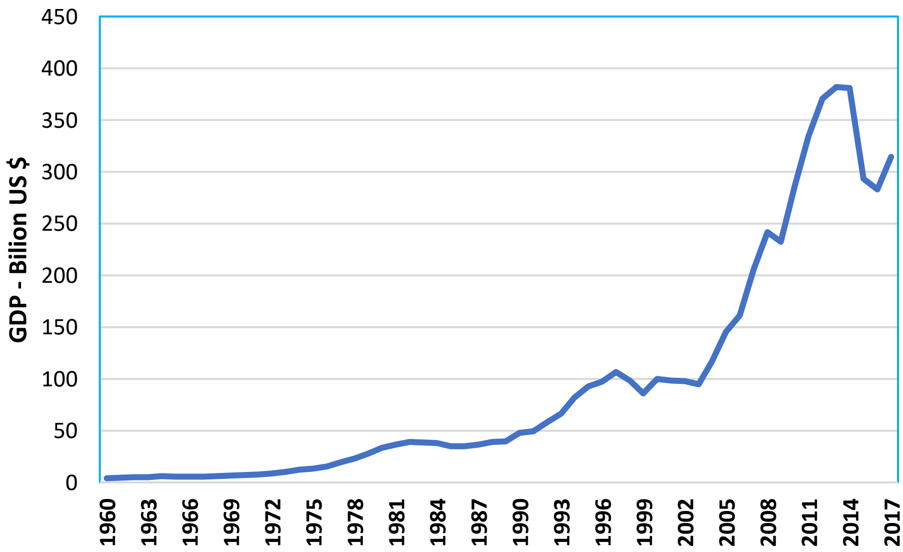

Figure 2.6: *Colombia GDP trend (World Bank Data)*

2.4 COLOMBIA ENERGY CONTEXT OVERVIEW

This section is dedicated to give a deeper insight about Colombia energy context, aiming to ensure a more complete understanding of Colombia energy mix and its peculiarities when compared with other countries of South America.

In this analysis, it will be assumed that installed power quantities associated to the SIN can be considered representative of Colombia energy trends, given the limited importance of NIZ contribute in absolute quantity.

As mention before, with 1141748 km^2 of surface, Colombia is the 4th country of Latin America for extension and it is also the 5th considering the installed power, which was equal to 15673 MW back in the 2014 (UPME 2016). On one hand, the energy mix shows how hydropower is important in Colombian economy, which is no surprise as this country boasts the second largest hydropower potential in the Southern America. On the other hand, it shows how much this country is reliant on this specific resource.

Eventually, the National energy production breakdown reflects the same trends described above.

Country	**2010**	**2011**	**2012**	**2013**	**2014**
Brazil	112.399	117.135	120.973	126.755	133.930
Argentina	32.847	33.810	35.023	35.531	35.354
Venezuela	24.882	25.754	27.523	30.292	30.980
Chile	16.954	18.423	18.118	18.289	19.298
Colombia	14.247	14.427	14.414	14.558	15.673
Perù	8.613	8.556	9.699	11.051	11.203
Paraguay	8.818	8.818	8.818	8.833	8.833
Ecuador	5.143	5.232	5.454	5.498	6.023
Uruguay	2.667	2.677	2.843	3.177	3.585
Bolivia	1.645	1.682	1.654	1.676	1.865
Southern America	228.215	236.514	244.519	255.660	266.744

Table 2.1: *Southern America country installed capacity [MW] (CIER and UPME*)

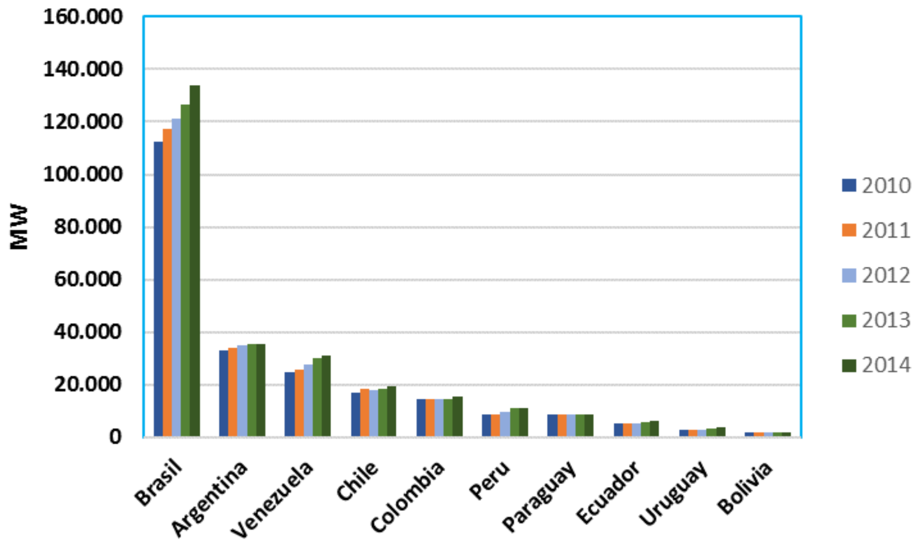

Figure 2.7: Southern America country installed capacity *[MW] (CIER and UPME*)

Year	Hydro	Coal	Gas	Wind	Other	Total
2012	9.778	997	2.484	18	1.136	14.414
2013	9.876	1.002	1.850	18	1.812	14.558
2014	10.920	1.172	1.848	18	1.714	15.673
2015	11.501	1.348	1.668	18	1.949	16.484

Table 2.2: *Energy Production from 2012 to 2015 [GWh] (UPME 2016)*

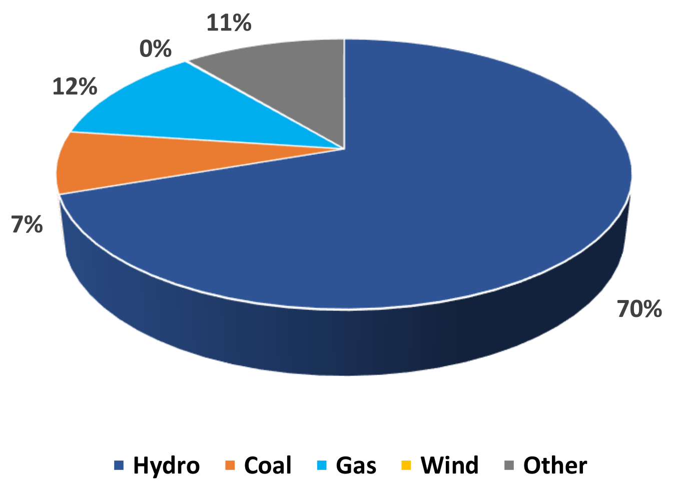

Figure 2.8*: Energy Production 2014 [GWh] (UPME 2016)*

The NIZ reality, and more in general the rural dimension, is something quite different for what the Colombia global energy mix might suggest. In the NIZ almost 90% of power generation corresponds to diesel plants and only the remaining percentage represent the RES contribution (Gaona, Trujillo and Guacaname 2015).

The aim of this Master Thesis stems from the combination of this consideration and the fact that a large portion of the country is still rural territory or NIZ. Given this, there is a problem linked to the sustainable electrification process in Colombia and another issue bounded to the scattered population distribution on the territory.

As the Colombia sustainable electrification problem is becoming more distinct, it should be equally clearer why distributed generations, micro-grids and micro – mini power plants are the most suitable alternative for this task.

Even if hydropower looks like the only renewable resource available, and it will have a dedicated section, this is not true at all as Colombia benefits of great potential both for photovoltaic and wind installations. Biomass and geothermal energy were not taken into account as the first one has low energy density but high transportation costs whereas the second has only few regions suitable for such installations.

2.4.1 PHOTOVOLTAIC ENERGY

Colombia has a high potential for solar energy and relevant opportunities because solar radiation throughout the country is mostly uniform during the year (4.5 kWh/m^2/day in average, higher than the world one of 3.9 kWh/m^2/day). However, estimations showed that the installed solar capacity is by far less than 20 MWp and the main powerplants corresponded to private systems and business applications, regardless of the outstanding radiation potential of NIZ regions, which can reach even 6 kWh/m^2/day. Some examples of NIZ potential are the Amazonas, the largest area in Colombia (more than 100000 km^2), average radiation of 3.5–4.0 kWh/ m^2/day but only 600 kWp installed. Finally, Antioquia, third department by number of inhabitants and La Guajira, department with the highest radiation at national level 5.5-6 kWh/ m^2/day, have nearly no photovoltaic installations.

In all these areas photovoltaic implementation would enable local people to meet their lighting, refrigeration and leisure needs, allowing them to expand their capacities and improve their life quality, but in the last decade only IPSE carried out photovoltaic, reaching a total of 2.25 MWp in 23 departments (Rodriguez-Urrego D. and Rodriguez-Urrego L. 2018).

Unfortunately, the inability to deliver surplus energy to the grid, the fossil fuel subsidy policies oriented, the lack of a case report inventory and the high investment and O&M costs hinder the spread of this technology.

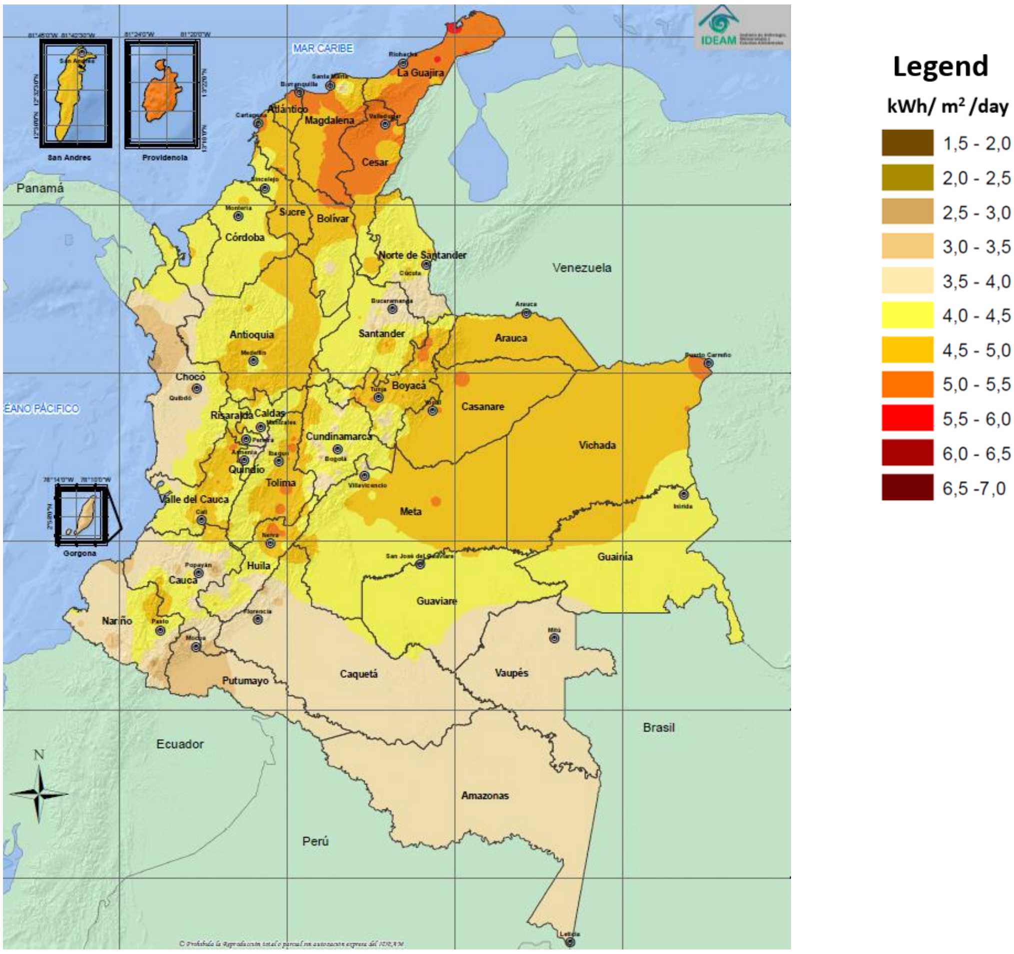

Figure 2.9: *Colombia Global Horizontal Irradiation (IDEAM Global Horizontal Irradiation Atlas)*

2.4.2 WIND ENERGY

Wind regime in Colombia is considered among the best in South America, the coastal regions have been classified under class 7 winds (10 m/s), only by utilizing half of its total

technical wind energy potential, the country would be able to match the entire electricity demand. Moreover, wind in particular has been shown to serve as a good complementary energy source to existing hydro generation. In fact, higher average wind speeds have been found to coincide with droughts caused by El Niño (Gomez-Navarro and Perez 2018). Nevertheless, until 2013 there was only one operating power plant, settled in Guajira.
As mentioned before, the possibility to connect the wind farm to the grid together with a RES policy system would foster the spread of this technology.

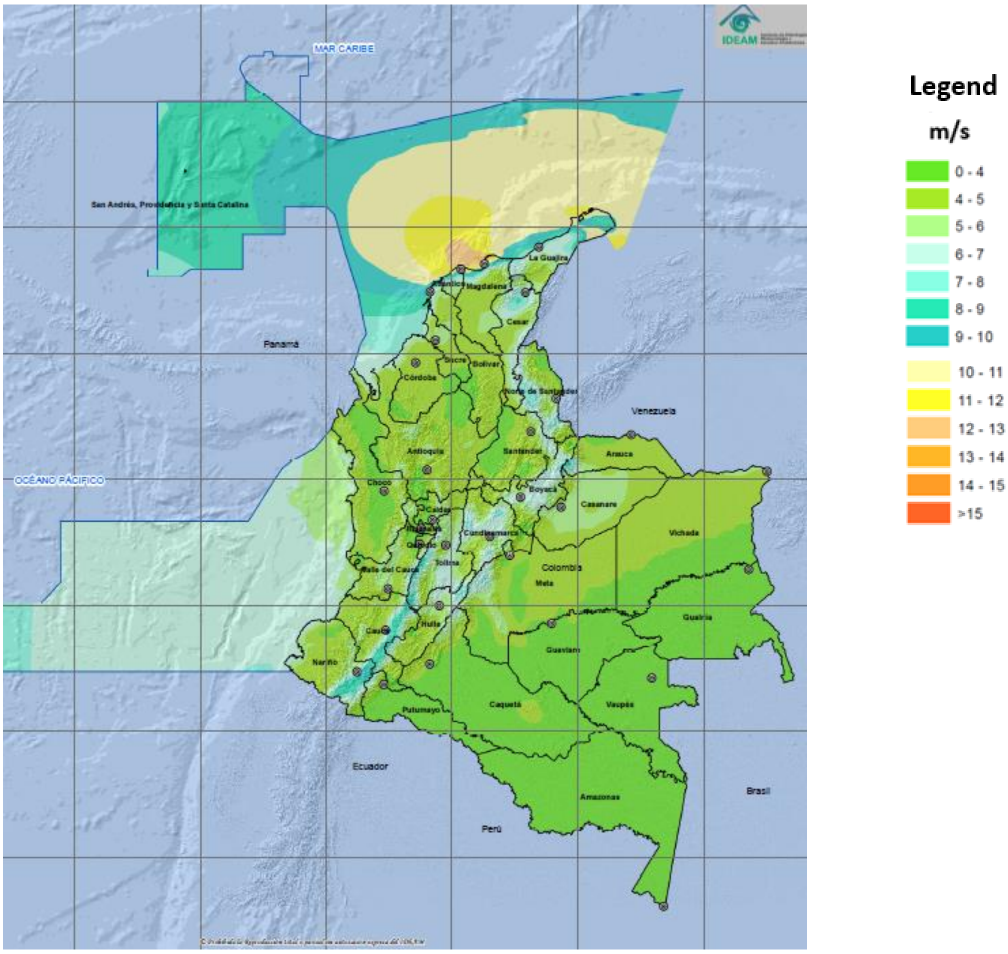

Figure 2.10: *Colombia Wind Map (IDEAM Colombia Wind Atlas)*

To conclude, the obstacles to the development of these technologies can be summarized as follow:

- Technical barriers: since there is nearly no background, investors must pay for accurate information and/or accept a degree of risk about the components, quality and post selling assistance. In addition to this, the power plant will not be able to communicate with the grid but it will have to deliver electricity locally, preventing an optimal management of the investment

- Economic barriers: there is no structured system to help and promote these kinds of technologies but the subsidy policies are still fossil fuel oriented. In this way, the investment cost and the operation and maintenance cost remain prohibitive for the vulnerable communities belonging to the NIZ when considered low income.
- Social barriers: there is lack of coordination between the ministry and private companies, non-profit making organizations, foreign investors or local communities, which leads to a lack of defined framework for these technologies.

2.4.3 HYDROPOWER

As already mentioned in Chapter 1.1, Colombia has the second greatest hydroelectric potential in the Southern America, indeed only Brazil potential is more significant. The Interconexiòn Eléctrica S.A (ISA) estimated a global potential equal to 93000 MW, of which 25000 MW can be considered technically exploitable, according to INEA. At the current status only 180 MW were installed, which is equivalent to 0.72% of the available potential, this raises great interest and leaves space for upcoming hydropower implementations both large and small (Pacheco and Rodigruez 2015). In particular, the bank energy projects of the Mining and Energy Planning Unit (UPME) shows that the country can reach a Small Hydro Power (SHP) installed capacity of 1.8 GW by 2020 and 2.1 GW by 2030, if all current projects materialize (Arias-Gavaria et al. 2017).

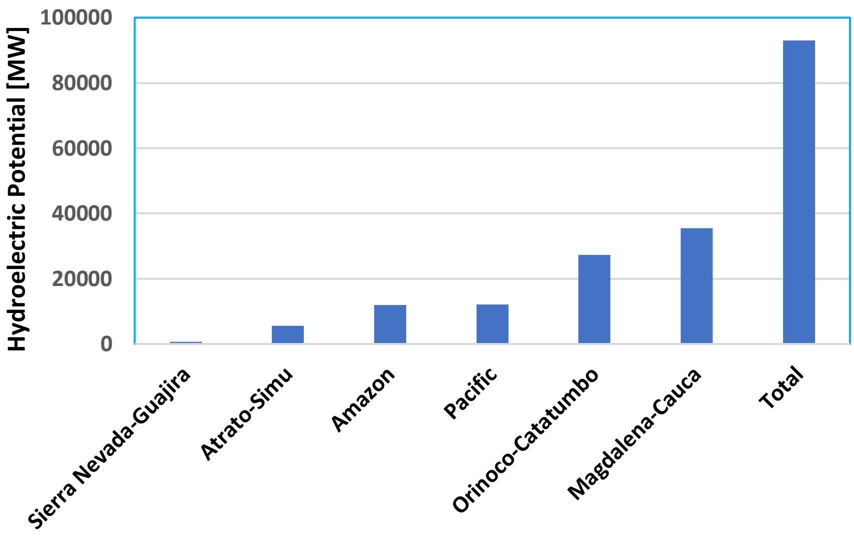

Figure 2.11: *Hydro-Energy potential in Colombia by region (Pacheco and Rodriguez 2015)*

One of the reasons that led to the choice of Antioquia department as region of interest was its hydro-electricity potential, the highest in the country, thanks to the combination of its natural waterfalls, mighty rivers and stable geological conditions.

In 2010, Antioquia presented 45 operating hydroelectric plants. That means 3803 MW, which corresponded to 28.6% of the country's total capacity (13279 MW) (BIRD 2011), of which six plants were built with a total potential of 3503 MW. The remaining identified potential is found at different development phases: 6.8 MW were at the feasibility phase and 1 MW at the design phase (Duque 2014).

According to 2010 data, Northern and Eastern Antioquia's sub-regions possess the highest hydroelectric potential. The Northern region offers 8062.3 MW (34%) mainly composed of the Cauca, Porce, Grande and Guadalupe rivers basins. The Eastern one has 5806.4 MW (24%) corresponding to Nare, Guatapé, San Carlos and Samaná Norte rivers basins (Duque 2014).

A comparison between Antioquia region's potential and the Latin American countries is reported. As showed in Figure 2.12, Antioquia held the ninth position over the Central American countries and three South American ones.

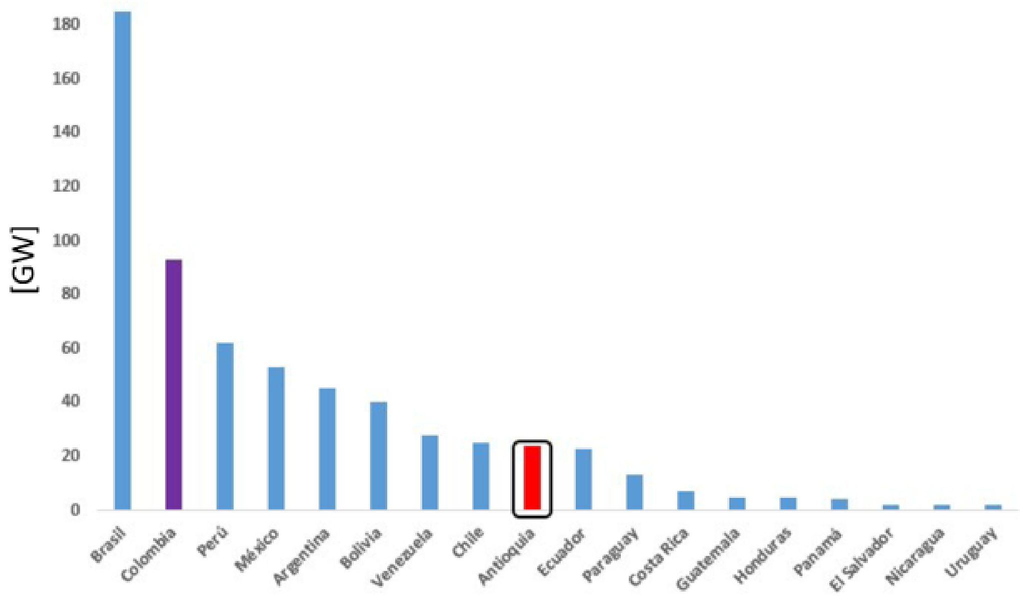

Figure 2.12: *Hydroelectric potential in Latin America (Duque et al. 2016)*

2.5 MICRO- HYDROPOWER

The Colombian hydroelectric potential was estimated equal to 93000 MW, of which 25000 MW can be considered technically exploitable. This particular condition leaves space for the development of hydroelectric power systems of any size. In Colombia, the UPME has adopted the IEA definition of SHP plants, that addresses a plant capacity less than or equal to 20 MW and that operates at run-of-river, with no water storage. SHP plants with smaller capacities are typically classified as Pico, Micro and Mini hydropower plants with upper installed capacity limits of 10 kW, 100 kW and 1 MW respectively (Pacheco and Rodigruez 2015). In particular, micro and mini hydropower plants have been built across the country in the NIZ and rural regions. In 2015 only the 4.8 % of the power installed in the Andean country derived from Small plants, of which 85% was SHP, this context did not undergo any significant variations, thus the Master Thesis focuses on innovative solutions to face sustainable electrification process in rural areas of the country.

2.5.1 MICRO HYDROPOWER STRUCTURE

Hydropower plants are of three types:

- Impoundment: this is a large hydropower system which uses a dam to store river water in reservoir and use it to generate electricity, according to the demand
- Diversion: a diversion facility channels a portion of a river through a canal or penstock. This system may not require the use of a dam.
- Run-of-river: the system uses water within the natural flow range and it requires little or no impoundment

In the 20th century, the development of hydroelectric power involved the building of large dams and huge artificial lakes. SHP systems are mainly 'run of river,' so they involve construction of a quite small dam or barrage, usually just a weir, and in most of the cases little or no water is stored. Generally, for low-head installations (head < 5 m), water enters the turbine almost directly from the weir and then run back into the river, guaranteeing a minimal environmental impact on the local ecosystem. Starting from flow duration and head estimation, several quantities must be defined before going through the choice process of components and design. Following the description reported in Kengne Signe Micro-Hydro case study (Kengne Signe, Hamandijida and Nganhou 2017) the components from the weir to the turbine are listed:

1. Weir: a weir is a low wall or dam across the stream to be gauged with a notch through which all the water may be channelled. Its strength lies in its anchoring on the banks and the stability of its foundation. Several types of notch can be used such as rectangular, Vee or trapezoidal. All materials available and cheap on site must be used, common solutions are metal plate, concrete and hard wood with sharp edges.
2. Water intake: at the inlet of the supply line avoids turbulence and stops heavy or light debris with the screen, threshold and chicane. The inlet water level must be below the water level to prevent air from entering the line.
3. Supply channel: the most important thing to consider while constructing the headrace open channel is to make slope of canal only slightly elevated because higher slope

can lead to higher velocity of water which can then cause erosion in the channel surface.

4. Loading room (fore bay): serves as a regulating and decanting tank.
5. Penstock: supplies the turbine with pressurized water from the loading room.
6. The tailrace: the restitution channel or leakage channel serves to bring water from the turbine outlet to the river.

Flood gate and trash screen are the complement equipment that are placed in intake and forebay. Flood gate is used to maintain the power plant, and the trash rack is used to separate trash from water before it comes to the turbine.

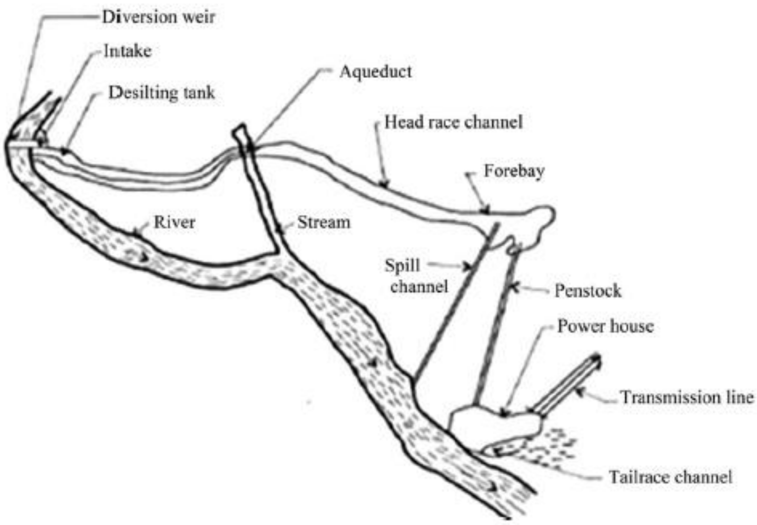

Figure 2.13: *Typical small hydro site layout (Singal et al. 2010)*

2.5.2 TURBINE SELECTION

The water turbine is one of the key and costly elements of micro-hydro power plants depending on the particular requirements of any given site. The current micro-hydro conversion system is based on impulse turbines and on reaction turbines. Micro-hydropower generation efficiency is generally in the range of 60–80% (Elbatran and Yaakob 2015). These machines generate very reliable power though with very simple designs and fabrications. Nevertheless, the selection of micro-hydropower turbines for achieving the most efficient and best result is rather difficult, as most turbines are designed for higher systems.

As it is well-known the selection of any type of hydropower turbine for a project is based on the head and the flow volume of water at the site. The head, usually measured in metres or units of pressure, is the vertical distance that water falls and it may be influenced by the characteristics of the channel or pipe through which the water flows. In the determination of head, both the gross head (i.e. the vertical distance between the top of the penstock that conveys the water under pressure and the point where the water discharges from the turbine) and net head are considered. Net head (H) is the difference between gross head (H_g) and losses due to friction, turbulence in the piping (ΔH_{AB}) and the energy required from the water to exit the plant (Okot 2013).

$$H = H_g - \Delta H_{AB} \tag{1}$$

There are two main categories of hydro turbines in use: impulse and reaction turbines.

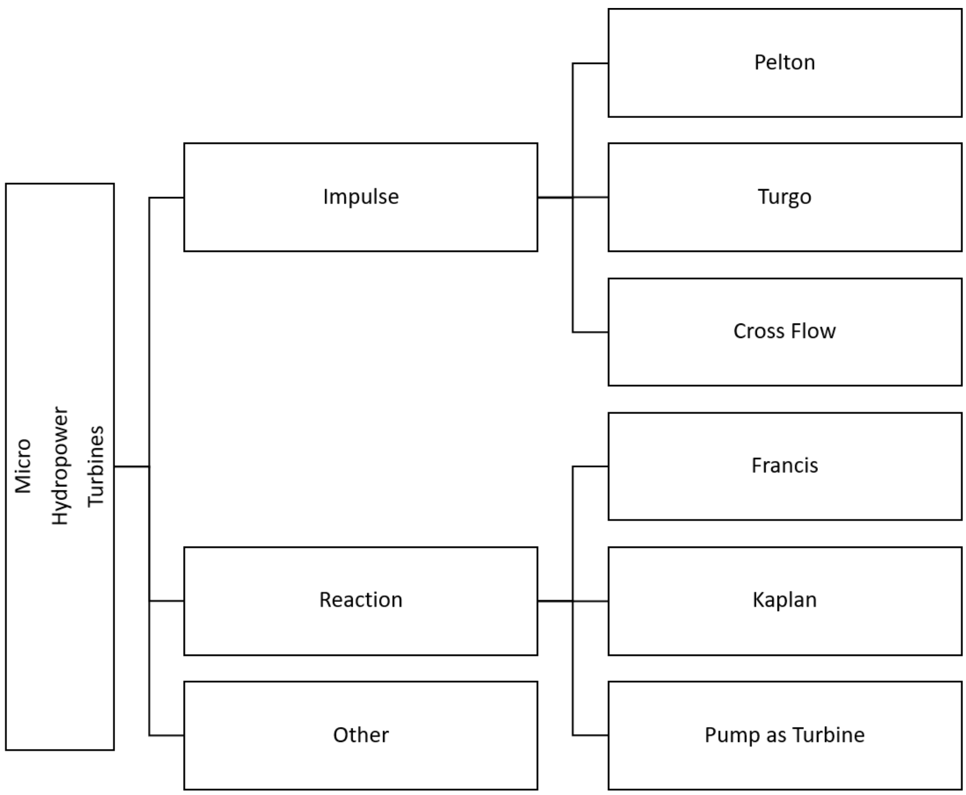

Figure 2.14: *Micro-hydropower turbines classification (Elbatran 2015)*

IMPULSE TURBINE

These machines are usually applied in systems with high head and low flow, they use the kinetic energy of water to drive the runners, which operate in air and are moved by jets of water, which remains at atmospheric pressure before and after making contact with the runner blades. However, recent applications in low head micro-sites have proven this technology effectiveness also in this field, making them an acceptable alternative practice in many countries.

There are three common types of impulse turbine: Pelton, Cross-flow and Turgo.

- Pelton Turbine: this form of turbine has a wheel containing a series of split buckets (vanes) set around the rim. Buckets are hit by jets of high-pressure water, supplied by nozzles coaxial with the runner, jets are split and deflected almost through 180°. The flow control is granted by the needle (or spear) and the deflection plates motion, together they also regulate the pressure level in the pipeline avoiding dangerous overpressures (Dossena et al. 2015).
- Cross-Flow Turbine (CFT): CFT has a drum-like rotor and uses an elongated, rectangular-section nozzle which is directed against curved vanes on a cylindrically shaped runner. This turbine is less efficient than the others, mainly because water flows twice through the blades, introducing significant shock losses in the passage from one stage to another. Nevertheless, CFT are very flexible machines as they can cope with large water flows and low heads, indeed, they are the most suitable option for micro-low head application (Elbatran 2015).
- Turgo Turbine: this turbine is similar to the Pelton, but with different shape of buckets and the jet strikes the plane of the runner at an angle (typically 20%). Unlike the Pelton, the flow rate through a Turgo turbine is not limited by the discharged fluid interfering with the incoming jet, this allows Turgo to have higher power output with same diameter. Eventually, Turgo turbine has a higher running speed which makes a direct coupling of turbine and generator more likely, thus increasing the overall efficiency and decreasing maintenance. In addition to this, Turgo turbine with single jet is able to work efficiently in low head micro-hydro remote sites, giving the best performances in the range of 1.5 – 3.5 m. (Okot 2013).

REACTION TURBINE

Reaction turbine are generally appropriate for sites with lower head and higher flows compared with the impulse turbines. They generate electricity from the natural action of pressure and by moving water. The runner blades are profiled so that pressure differences across them impose lift forces, akin to those on aircraft wings, which cause the runner to rotate.

There are three common types of impulse turbine: Francis, Kaplan, Propeller.

- Francis Turbine: is the most common type of hydropower turbine in use. This turbine generally has radial or mixed radial/axial flow runner which is most commonly mounted in a spiral casing with internal adjustable guide vanes. Water flows radially inward into the runner and emerges axially, causing it to spin.
- Kaplan and Propeller Turbine: Kaplan turbine has adjustable blade pitch, swirl generator and snail shell as distributor whereas propeller are unregulated turbines, commonly used in small and mini hydro systems. These machines generally have an axial flow runner with three to six blades depending on the designed water head and are used to exploit low head (from 0.6 to 1.5 m) and high flow rates (from 0.0035 to 0.0130 m^3/s) (Kusakana, 2014). Due to the low cost and relative simplicity of the installation process these turbines have been implemented all over the world in many different conditions.

An alternative to these more common solutions is to use a centrifugal pump as turbine, with the direction of the flow reversed. This technical alternative brings in several advantages, especially for micro-hydro power generation. Indeed, PAT is practical and cost saving, almost 50% less than the corresponding turbine, it does not require special design, it is available in most developing countries, in wide range of standard size and they guarantee acceptable efficiency. However, PAT was not taken into account as it is more indicated in rural mountainous locations, highest efficiency between 13–75 m of gross head (Phrakonkam and Remy 2012).

Considering the different range of application in the Q vs H space of the turbines, the different respond to partial load conditions, the cost both of the turbine and the installation and the case studies reported in the references, the turbine type selected were Cross Flow, Francis, Kaplan and Propeller.

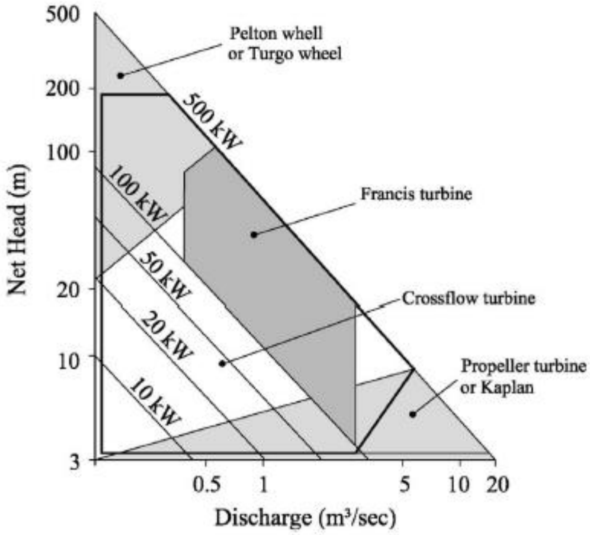

Figure 2.15: *Head-flow ranges of small hydro turbines (Okot 2013)*

2.5.3 MICRO HYDROPOWER ADVANTAGES

Compared to other renewable technologies like wind and solar power, some of the advantages that micro-hydroelectric power plants have are:

- High efficiency (70 – 90%), by far the best of all energy technologies, even more significant if the simplicity of MHP plants is considered
- High capacity factor (>50%) to compare with 10% for solar and 30% for wind power plants
- Slow rate of change, the output power varies only gradually from day to day, not from minute to minute

In addition to this MHP plants (up to 100 kW capacity) reveal to be also less capital intensive than SHP plants and they involve minor political decisions, reducing the difficulties during the implementation phase (Nasir 2014).

2.5.4 COMMUNITY INTEGRATION ROLE

The key finding of different studies was that local population must play a central role in the decisions to be taken in the development and implementation of the project, ideally they should undertake construction by themselves as much as possible in order to promote local learning and a feeling of local project "ownership". This central role will be even more important during operation and maintenance, thus it is suggested to set up a local committee to participate in the project and in the system construction (Kangne, Hamandojoda and Nganhou 2017). The interaction with user communities should go on after the installation of the power plant, the supplier should provide post-selling service, like technical support and evaluation meetings to bring up problems and suggestions.

Unfortunately, local communities often do not have sufficient technical capabilities to sustain and maintain MHP plant. Usually one or several people have been trained, but in many cases their knowledge is not transferred properly to their successors when they leave, but once the knowledge had been lost, it is very difficult to restore it, especially without any training facilities (Wouter 2010).

Thus, operation and maintenance are key factors to be considered when designing MHS. The survey (Murni et al 2012) showed that providing O&M training to increase capacity building in the community helps in reducing the cost and maintenance time. This finding is in line with result by the International Energy Agency that most renewable energy projects in developing countries that have not been sustainable in the long term have failed due to poor maintenance and monitoring (IEA 2003).

2.6 FLOW REGIME

Given the orography complexity of Colombia, precipitations strongly depend on the geographical area, in fact there are several natural regions from the savanna to the tropical rainforest, from the tropical desert to the Paramo (typical climate of regions around 3000 and 4000 meters) (see Figure 2.3). In many regions of the country the temperature through the whole year changes for about 1 °C, this means that precipitation is the most significant parameter to determine season change. Typically, winter is the driest season, precipitation can drop well below than 50 mm. In spring the precipitations start to increase, reaching their pick during summer. This rainy condition will last until the middle autumn, reducing gradually during winter.

However, it must be considered that this scheme might be different from region to region in absolute quantities or even trend. For example, close to the Atlantic coast precipitations are almost constant during all the year, apart from winter.

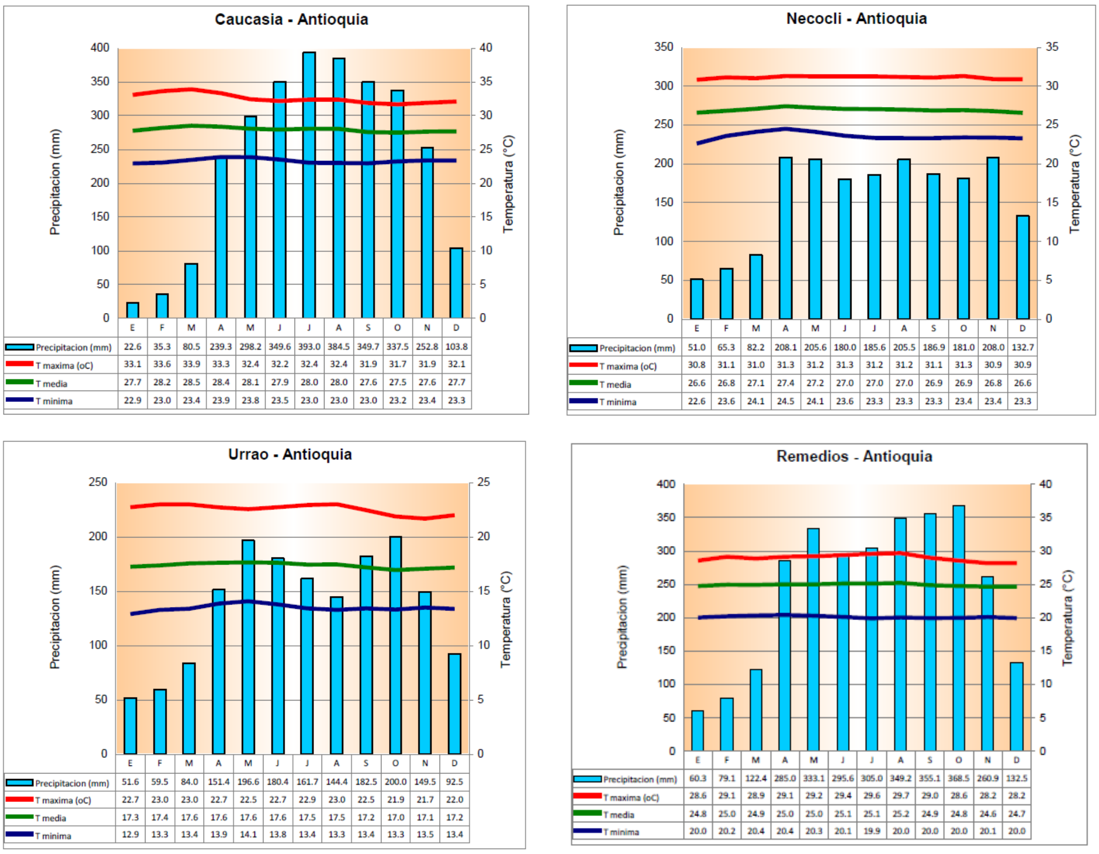

Figure 2.16: *Precipitation trend in Antioquia (IDEAM Precipitation Atlas)*

The Cimitarra basin is located in the South-Eastern region of the Antioquia department, and the water system object of study is a tributary of the Magdalena river, the major of the country. As mentioned before Colombia complex orography strongly influences the equatorial climate and precipitation trends, an example is shown in the Figure 2.16 above where different municipalities of the same departments are taken in account. Remedios better represents the basin characteristic, however it has to be noticed how different can be the rain trend depending on the geographical area.

CHAPTER 3

3. MODEL DESCRIPTION

The purpose of the present study is not only to support the rural electrification planning of the Cimitarra basin by means of micro hydro-power based mini-grids. But also to promote a sustainable rural development by tackling the alarming current condition, which shows a system nearly fully fuel reliant, in the NIZ almost 90% of power generation corresponds to diesel plants (Gaona, Trujillo and Guacaname 2015).
This is carried out by providing a general and scalable approach that is able to identify a solution that is both pseudo-optimal and technically feasible.

A hydrological model was used to describe the physical interactions among the atmosphere, the soil and the vegetation with the aim of reproducing the flow regime of the area in a distributed way and at a daily scale. Subsequently, this information was utilized to properly design the hydro-power plants as well as the electrical connection with the villages.

In this chapter, a detailed description of the hydrological and hydroelectric model is presented with a stand-alone chapter dedicated to the methodology used for the optimisation.

3.1 HYDROLOGICAL MODEL

Hydrological models are mathematic structures which aim is to reproduce the complex physical processes that happen inside a specific catchment with the ultimate purpose of replicating the system's response to spatial and temporal variation of the input.
Based on the type of relationships that are established between the input and the output variables, hydrological models can be classified into three main categories.

The so-called black-box or empirical models are systems that link outputs and inputs by means of empirical mathematical relationships, without considering the underlying physical processes of the catchment. Due to their empirical nature, these models are valid only within the boundaries of study area. On the contrary, white-box or physically-based models are based on a physical description of the system and they generally discretize processes based on energy and mass balance equations. By their nature, they require a large number of parameters and a huge amount of data for the calibration and have the import drawback of requiring high computational time. Finally, gray-box models represent a compromise between them: they describe physical processes with a simplified parametrization and semi-empirical relationships. In this way they are able to perform a physical description of the system while reducing the computational load.

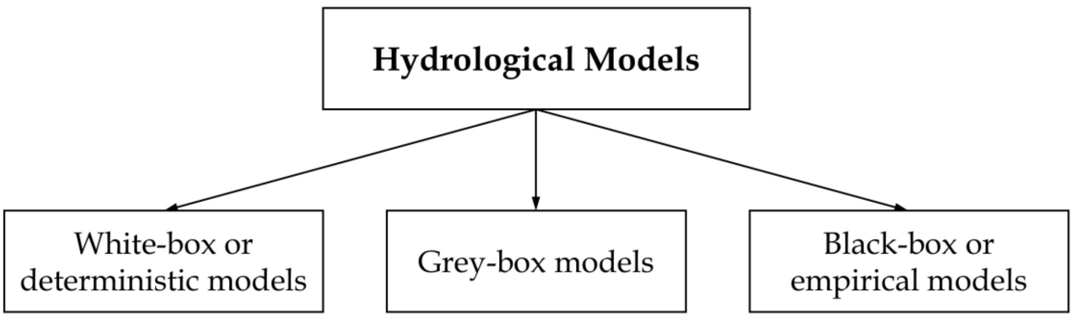

Figure 3.1: *Different types of hydrological models*

The model used in this study belongs to this last category. In fact, it puts in relationship the input variables (among which precipitation and temperature) with the output ones by means of a simplified parametrization of physical processes such as snow and ice melting, evapotranspiration, soil water content, surface runoff and groundwater discharge. However, in our case study nor snow neither ice melting was considered, give the catchment structure.

The spatial and temporal resolution were the trade-off results between a more accurate processes variability description and computational burden. Thus, the spatial domain (Area 2950 km^2) is discretized with a regular grid of 300 x 300 m and the simulations were carried out with a daily time step.

The hydrological model was derived from the more complex Distributed Hydrological Model (Wigmosta, Vail, and Lettenmaier 1994) and is based on a linear mass balance equation:

$$S^{\Delta t+t} = S^{t} + R + M_s + M_i - ET_{eff} - Q_g \tag{2}$$

where:

S = soil water content [mm/day]

R = precipitation [mm/day]

M_s = snow melting [mm/day]

M_i = ice melting [mm/day]

ET_{eff}= effective evapotranspiration [mm/day]

Q_g = groundwater discharge [mm/day]

Surface runoff Q_S is generated when the maximum soil water content S_{max} is exceeded:

$$Q_s = \begin{cases} S^{\Delta t+t} - S_{max} & \text{if } S^{\Delta t+t} > S_{max} \\ 0 & \text{if } S^{\Delta t+t} <= S_{max} \end{cases} \tag{3}$$

S_{max} is evaluated according to the Curve Number (SCS-CN) method:

$$S_{max} = S_0 \left(\frac{100}{CN} - 1\right) \tag{4}$$

where S0 = 254 mm. The CN map for the catchment (drawn up by Buizza, 2014) was estimated combining the land cover map realized by ICIMOD and soil data prepared by FAO.

The sub-superficial discharge Q_g recharging the groundwater reservoir by infiltration is expressed as a function of the soil water content S and the hydraulic conductivity K [mm/day] (Chen et al. 2005):

$$Q_g = K \left(\frac{S}{S_{max}}\right)^{k_g} \tag{5}$$

where k_g is the calibrated scale factor.

3.1.1 ICE AND SNOW MELTING

Even though the hydrological model implemented to analyze the specific Cimitarra catchment does not draw upon the Ice and Snow melting corresponding code sections, this paragraph is dedicated to a brief explanation of those physical processes.

Daily ice and snow melt are evaluated with a hybrid-approach (Pellicciotti et al. 2005) which combined the simplicity of the degree day method while also including the dependency on the solar radiation:

$$M = \begin{cases} DDF(T - T_0) + SRF(1-\alpha)G & \text{if } T > T_0 \\ 0 & \text{if } T <= T_0 \end{cases} \tag{6}$$

The first term represents the influence of the temperature gradient: whenever the mean air temperature T is greater than a threshold value, the rate of snow or ice melt M [mm/day] is proportional to the gradient and to DDF (degree day factor), a parameter that takes into account the complex process of heat transfer to ice caps and snow packs. Instead, the second term accounts for the additive effect of the solar radiation: the melting rate M is also proportional to the fraction of the distributed solar radiation G [W/m^2] absorbed by the terrain (α is the albedo, namely the ratio between the outgoing and the incoming shortwave radiation). The value of G is specific for each cell and hour of the day. Taking into account the effect of the topographical shading, it can be calculated considering the different contributions of direct solar radiation on a tilted surface, the diffuse radiation and the reflected radiation.

GLACIER DYNAMICS

Ice flow is driven by gravitational forces and thus by the weight of the ice mass itself which is acting on the sloped plain. In the hydrological model, the glacier flow was modelled as driven by a simplified force balance, proportional to the basal shear stress raised to n, the exponent of Glen's ow law which is equal to 3 in most cases (Oerlemans 2001). The value of basal sheer stress τ is derived at each time step considering the ice thickness $h_{ice;i}$, the local bedrock slope α and the ice density ρ. In order to compute for each cell the ice height loss Δ it is defined an average depth velocity v_{ice} according to the following formulation:

$$\Delta h_{ice,i} = \frac{h_{ice,i}\, v_{ice,i}\, dt}{l_{cell}\, ice_{\%,i}} \tag{7}$$

To avoid possible numerical instabilities a superior limit to ice flow velocity is set to 250 [m/y].

Finally, the ice loss is then shifted to downstream cells along three directions with a weight that depends on the local slope.

3.1.2 EVAPOTRANSPIRATION

The effective evapotranspiration term ET_{eff} is derived from the potential evapotranspiration ET_p. In this study, the Hargreaves-Samani formula was chosen (Hargreaves and Samani 1985):

$$ET_p = 0.0023\, R_a \sqrt{\Delta T}(T + 17.8) \tag{8}$$

where:

R_a = extraterrestrial radiation expressed as mm of water evaporated per day [mm/day]

ΔT = mean monthly temperature variation [°C]

T = mean daily temperature [°C]

Subsequently, the effective evapotranspiration ET_{eff} is computed as sum of the actual evaporation from the ground E_s and the actual transpiration from the vegetation T_s, both function of the potential evapotranspiration ET_p, the soil water content (θ) and the fraction of vegetated soil f_v:

$$E_s = \propto(\theta) ET_p (1 - f_v) \tag{9}$$

$$T_s = \beta(\theta) ET_p\, f_v \tag{10}$$

$$\propto(\theta) = 0.082\,\theta + 9.173\,\theta^2 - 9.815\,\theta^3 \tag{11}$$

$$\beta(\theta) = \begin{cases} \dfrac{\theta - \theta_w}{\theta_l - \theta_w} & if\ \theta > \theta_w \\ 0 & if\ \theta <= \theta_w \end{cases} \tag{12}$$

$$ET_{eff} = E_s + T_s \tag{13}$$

where θ_w represents the water content at wilting point and θ_s the water content at field capacity; the value of θ derives from the ratio between S and S_{max}.

3.2 HYDROELECTRIC MODEL

The sizing of an off-grid hydroelectric system differs significantly from the traditional approaches. In fact, traditional methodologies aim at selecting the most promising upstream dam location and downstream outlet point that enable to maximise the total amount of energy produced by the plant while minimising the costs (Bianchi 2013). However, most of these systems are run-of river applications (typical capacity factor 50%), thus they do not generally provide firm capacity, due to weather variations during the year. For this reason micro hydropower plants should be hybrid and combined with other energy sources to supply all the electricity needs, in order to provide a better living quality level (Pacheco and Rodigruez 2015).

With this configuration, all the power produced by the MHS should be used by the load and excess power is dumped. On the other hand, if the load is greater than the power available, blackouts or brownouts occur, however, a circuit breaker can be applied to limit consumption and avoid overloading (Murni and Whale 2012).

Eventually, high efficiency, the non capital-intensive profile of the investment, the environmental friendly nature of the plants put this technology in great advantage. Although these systems reveal themselves less susceptible to sudden variations minutes in minutes, the comparison between the temporal variation of the discharge and the energy demand variability is crucial for the optimal plant design and economic return.

The hydroelectric model represents an additional module of the hydrological model from which it receives as inputs the discharge series for each cell. In this module, firstly a pre-screening step is carried out. From this pre-screening all the technically feasible pairs of inlet and outlet points are selected. As a second step, the plants are sized to comply with the amount of energy required by the nearby villages. Lastly, the investment and operational costs are evaluated and the parameter LCOE (levelized cost of the electricity) is derived. The LCOE is then used as an objective function in the subsequent optimisation model.

3.2.1 PRE-SCREENING

Aim of the pre-screening step is to strongly reduce the computational burden in all the subsequent steps. This is done by selecting only a subset of all the possible pairs of inlet and outlet point according to the following constrains:

$$A_{basin} > A_{threshold} \tag{14}$$

$$H_{min} < \Delta H < H_{max} \tag{15}$$

$$dist_{in,out} < dist_{max} \tag{16}$$

where ΔH and $dist_{in,out}$ are respectively the gross head and the distance between the intake and the turbine while A_{basin} is the area of the catchment closed at the inlet point.
The values of H_{min} and H_{max} were selected according to the operating range of the chosen turbines.

Type	H min [m]	H max [m]	Q min [m^3/s]	Q max [m^3/s]
Cross Flow	5	200	0.2	10
Kaplan				
Francis				
Propeller				

Table 3.1: *Operation range of the chosen turbines*

3.2.2 DEMAND EVALUATION AND RESOURCE CHARACTERIZATION

For the evaluation of the energy demand the "Plan Indicativo de Expansiòn de Cobertura de Energia Electrica 2013 – 2017" (UPME 2013) was taken as reference. The UPME reported strategy rely on the analysis of all information from the Operadores de Red through "El Sistema Unico de Informacion (SUI)". As a result, the average monthly energy consumption for vivienda was estimated equal to 92 kWh/month. The distribution of rural villages was taken from the Database UPME (Database UPME 2018).
For what concern the water availability, the characterization was carried out by large dataset elaboration and analysis, taking as source the IDEAM database (2018).
Due to seasonal effect (Figure 2.3), the maximum nominal flow of the turbine has to be close to the minimum site value. In fact, the choice of a high nominal flow would require an excessive number of batteries to store the energy not provided by the hydroelectric plant when the discharge is minor than its nominal value. For this reason, the maximum nominal flow for each site $Q_{max,sitei}$ was selected as follows:

$$Q_{max,site_i} = \frac{\sum_{year=1984}^{1990} Q_{335,site_i}}{1984 - 1990} - EF_{site_i} \tag{17}$$

where:

$Q_{335,site_i}$ = flow amount reached or exceeded for 335 days in a year at site i [m^3/s]

EF_{site_i}= environmental flow at site i [m^3/s]

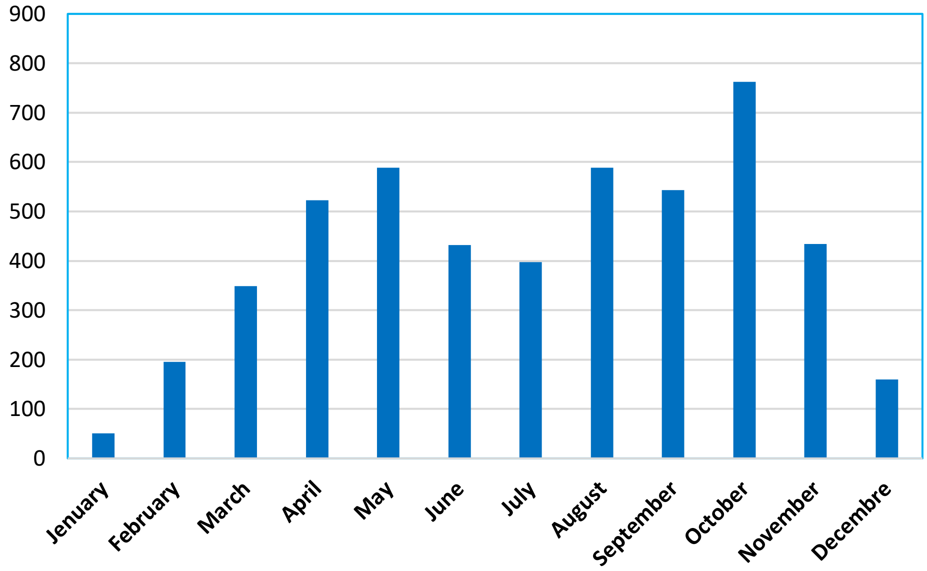

Figure 3.2:*Mean monthly discharge at Bagre el*

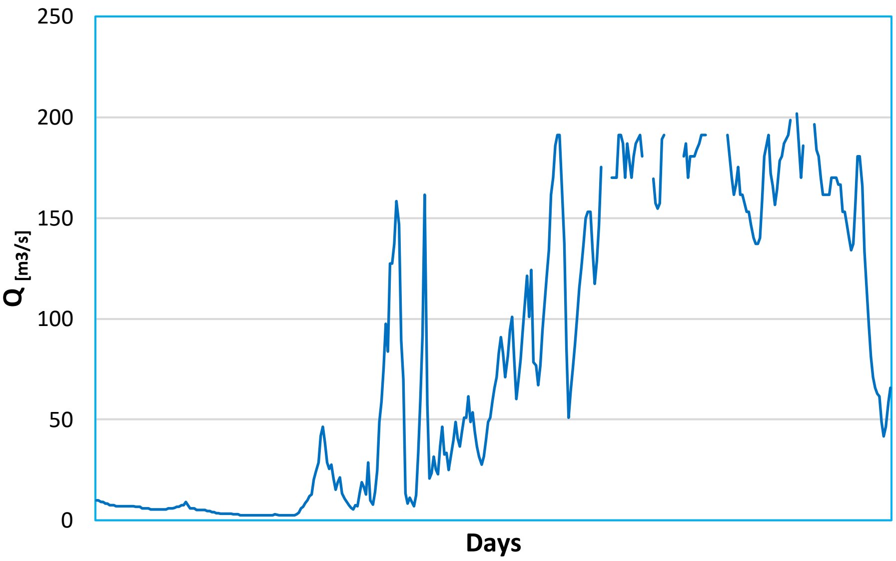

Figure 3.3: *Mean daily discharge at Bagre el*

3.2.3 SIZING PROCEDURE

At this stage of the analysis, all the pre-screened pair must be considered in the sizing procedure. In fact, a-priori it is not known neither where the plants will be located nor which and how many villages will be connected to it.

Therefore, for each pair the plant is firstly sized to provide energy to the closest village; in all the subsequent step, the grid is extended by connecting the demand point closest to the one of the nodes of the already created network which can be either the hydro-electric plant or an already connected village. In this way, the mini-grid is designed to assume a branched structure which is the typical distribution networks configuration.

At the end of the sizing procedure, for each pair n different nominal power $P_{nom,i}$ values will have been selected, according to the number of villages connected to the network. The consecutive steps of connecting and choosing the proper value of $P_{nom,i}$ continue as long as certain technical criteria are met, as shown in the flux diagram below.

At the end of the sizing, different plants will be connected to multiple villages with a physiological overlapping due to the approach chosen; the task of select a final configuration is left to the optimisation step.

The following paragraphs present the methods and hypotheses adopted for sizing the main components of the run-o_-river plants, namely the turbine, the penstocks, the electrical connection and the energy storage (Manara 2018).

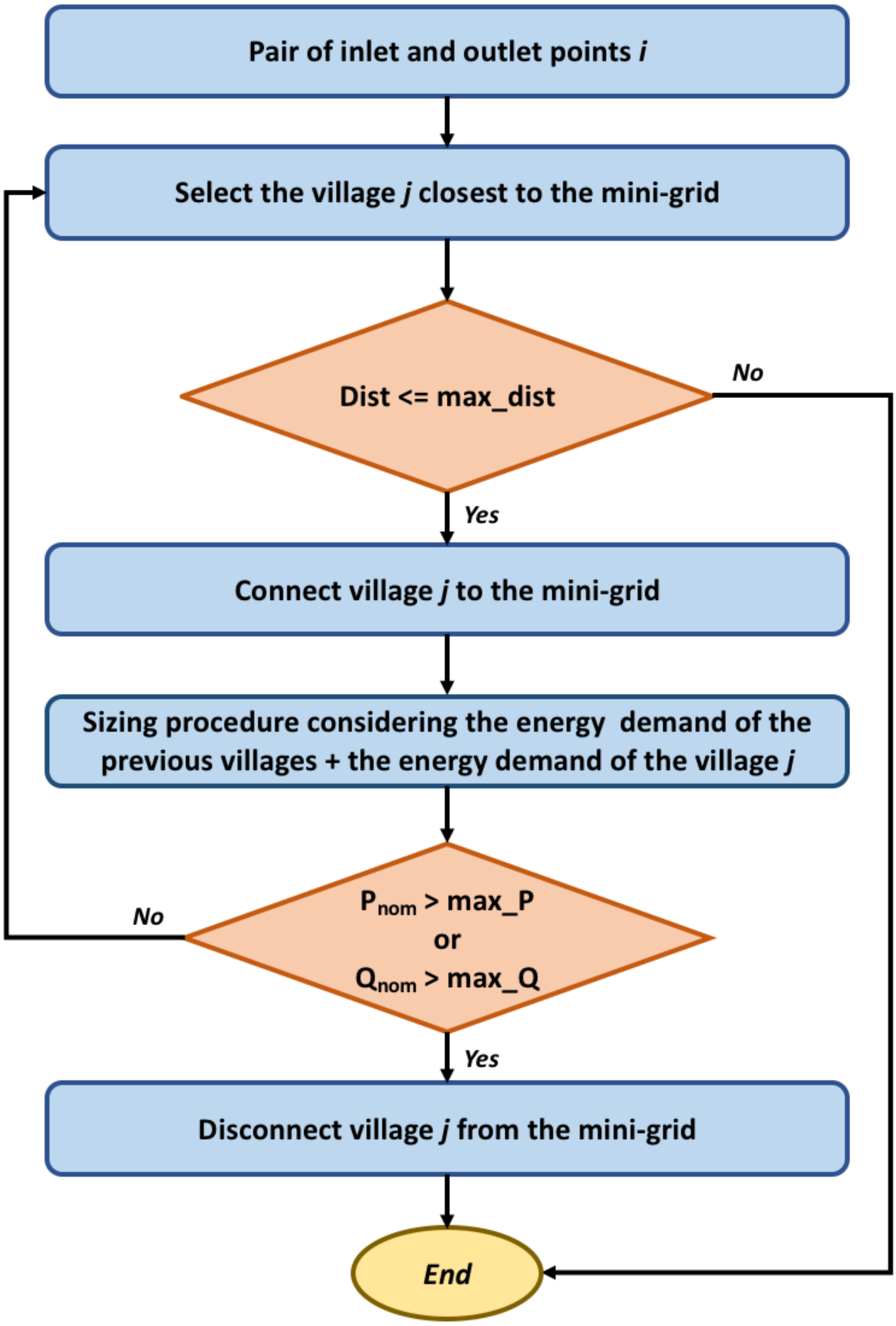

Figure 3.4: *Mini-grid creation scheme*

TURBINE

The general formula for the instant power P_t and the energy produced over a certain time span E_t are expressed by the well-known formulas:

$$P_t = \rho_w \, g \, Q_t \, \Delta H \, \eta_{hydr} \, \eta_{mech} \, \eta_{electr} \tag{18}$$

$$\eta_{hydr} = \eta_{hydr} \left(\frac{Q_t}{Q_{nom}} \right) \tag{19}$$

$$E_T = \int_T P_t dt \tag{20}$$

where:

Q_t = turbines working flow [m^3/s]

ΔH_{net} = effective pressure head of water across the turbine [m]

H_{hydr}, η_{mech}, η_{electr} = hydraulic, mechanical and electrical efficiency [%]

In the calculation η_{mech} and η_{electr} can be considered constant values; instead, η_{hydr} is dependent on the turbine's type as well as the ratio between the working flow and its nominal value, namely the partialization conditions under which the turbine works (Figure 3.5).

Finally, the working ow Q_t depends on its nominal value Q_{nom} and the discharge Q_i:

$$Q_t = \begin{cases} 0 & if \quad Q_i < Q_{\text{cut-off}} \\ Q_i - EF & if \quad Q_{\text{cut-off}} <= Q_i < Q_{\text{nom}} + EF \\ Q_{nom} & if \quad Q_i >= Q_{\text{nom}} + EF \end{cases} \tag{21}$$

where $Q_{cut\text{-}off}$ is the ow value under which the turbine is not able to produce power and EF is the value of environmental ow for the site considered. As explained in the Chapter 3.2.2 a maximum value of nominal flow was selected for each site in order to avoid an excessive energy storage which would be not realistic in the study context.

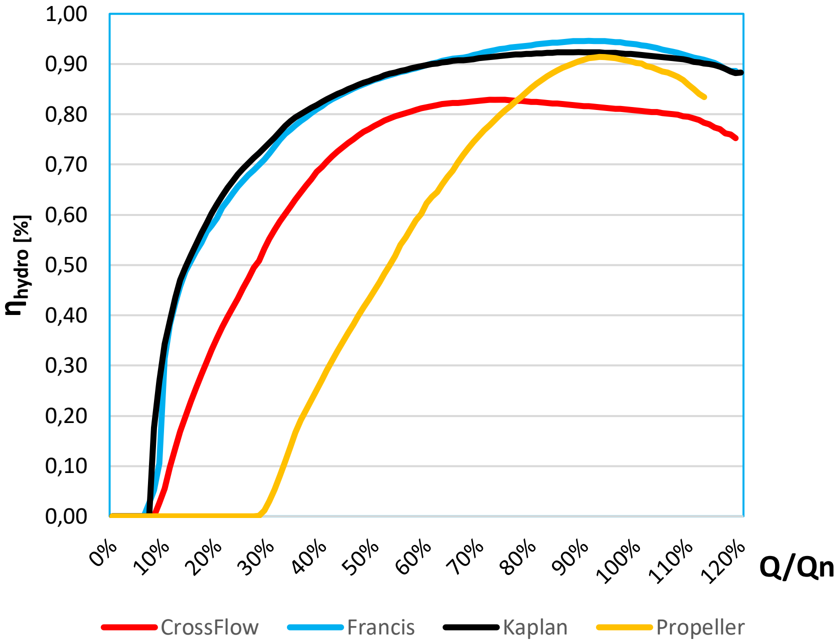

Figure 3.5: *Hydraulic efficiency under partialization conditons*

The sizing of the turbine is carried out by calculating an energy balance between the energy required (considered constant every day) and the variable energy produced by the turbine. However, the energy balance is computed only for a predefined number of days $n_{balance}$ during which there are the lowest discharge values. In this way, it is avoided the not realistic scenario in which the energy is stored throughout the whole year to be consumed only during few dry days. The greater amount of energy produced in the other days is assumed to be either dissipated or stored to balance the daily demand fluctuation, not considered in the study.

The sizing process is conducted by an iterative method: a first attempt value of P_{nom} is selected and then the energy balance is evaluated; if the energy produced is greater than required one the process ends; otherwise the value of P_{nom} is increased (with an incremental step of 1 kW) and the calculations are repeated.

PENSTOCKS

Penstocks supplies the turbine with the water already filtered by the flood gate and the trash screen. The choice of their diameter is fundamental since it impacts on both distributed pressure drops and the cost. The more the internal diameter increases the more the pressure drops are reduced and a greater amount of kinetic energy is conserved; on the other hand, a wider internal requires a greater thickness to contain the high pressures, which determines an increase of the costs.

The calculation of the pipes' diameter was based on the Manning formula, which was modified for considering the possibility of having different penstocks working in parallel. This option grants a greater reliability of the system and at the same time helps to contain the diameters. Inside the formula, the net head ΔH_{net} was calculated by imposing a maximum loss percentage e% over the gross head:

$$D_{theor} = \left(10.29\, n^2 \; \frac{L \left(\frac{Q}{n_l}\right)^2}{\Delta H_{gross}\; e\%} \right)^{\frac{3}{16}} \tag{22}$$

$$\Delta H_{net} = \Delta H_{gross}(1 - e\%) \tag{23}$$

where:

n = Manning coefficient dependant on the pipes’ material [$s/m^{1/3}$]

L = penstocks length [m]

Q = nominal flow [m^3/s]

N_l = number of penstocks working in parallel

ΔH_{net} = net head [m]

ΔH_{gross} = gross head [m]

D_{theor} = theoretical diameter [m]

The value of D_{theor} represents the minimum diameter necessary to contain the head losses at the maximum percentage value of e%. The commercial diameter is than evaluated by rounding up the value of D_{theor} according to commercial tables available on the markets (Figure 3.6). The model automatically chooses the option that minimizes the penstocks' cost; this is done by selecting a proper combination in terms of material, number and diameter for each site and each value of nominal flow.

	*PN 10 - SDR 17			*PN 12.5 - SDR 13.6			*PN 16 - SDR 11			*PN 25 - SDR 7.4		
Ø est [mm]	Thickness [mm]	Ø int [mm]	Cost [€/m]	Thickness [mm]	Ø int [mm]	Cost [€/m]	Thickness [mm]	Ø int [mm]	Cost [€/m]	Thickness [mm]	Ø int [mm]	Cost [€/m]
20	-	-	-	-	-	-	2	16	0.61	3	14	0.87
25	-	-	-	2	21	0.83	2.3	20.4	0.99	3.5	18	1.38
32	-	-	-	2.4	27.2	1.27	3	26	1.54	4.4	23.2	2.15
40	-	-	-	3	34	1.98	3.7	32.6	2.42	5.5	29	3.36
50	-	-	-	3.7	42.6	3.03	4.6	40.8	3.69	6.9	36.2	5.23
63	-	-	-	4.7	53.6	4.79	5.8	51.4	5.83	8.6	45.8	8.2
75	4.50	66.00	4.74	5.6	64.8	6.82	6.8	61.4	7.55	10.3	54.4	11.66
90	5.40	79.20	6.84	6.7	76.6	9.79	8.2	73.6	10.97	12.3	65.4	16.72
110	6.60	96.80	10.18	8.1	92.8	14.47	10	90	16.22	15.1	79.8	25.03
125	7.40	110.20	13.81	-	-	-	11.4	102.2	20.39	17.1	90.8	28.96
140	8.30	123.40	17.33	-	-	-	12.7	114.6	25.44	19.2	101.6	36.38
160	9.50	141.00	21.94	-	-	-	14.6	130.8	32.35	21.9	116.2	47.32
180	10.70	158.60	29.43	-	-	-	16.4	147.2	43.45	24.6	130.8	61.66
200	11.90	176.20	34.18	-	-	-	18.2	163.6	50.45	27.4	145.2	74
225	13.40	198.20	46.05	-	-	-	20.5	184	67.83	30.8	163.4	96.34
250	14.80	220.40	53.14	-	-	-	22.7	204.6	78.53	34.2	181.6	115.43
280	16.60	246.80	70.89	-	-	-	25.4	229.2	104.55	38.3	203.4	149.19
315	18.70	277.60	84.53	-	-	-	28.6	257.8	124.56	43.1	228.8	183.25
355	21.10	312.80	114.29	-	-	-	32.2	290.6	168.05	48.5	258	239.34
400	23.70	352.60	135.94	-	-	-	36.3	327.4	200.78	54.7	290.6	295.07
450	26.70	396.60	182.94	-	-	-	40.9	368.2	262.15	61.5	327	373.23
500	29.70	440.60	226.08	-	-	-	45.4	409.2	323.48	-	-	-
560	33.20	493.60	283.20	-	-	-	50.8	458.26	405.26	-	-	-
630	37.40	555.20	358.68	-	-	-	57.2	515.6	513.46	-	-	-
710	42.10	625.80	455.79	-	-	-	-	-	-	-	-	-
800	47.40	705.20	577.98	-	-	-	-	-	-	-	-	-

Figure 3.6: *Example of a commercial table in archive (Oppo)*

ELECTRICAL CONNECTION

The design of the electric connection was carried out through a simplified approach chosen due to a lack of more detailed information regarding technical characteristic of the cables. For these reasons, only the type of cables required (high, medium or low voltage) and the length of the network were taken into account for this analysis.

Two main components were considered in the electrical network:

- A transmission network, necessary to connect a village either to the plant or to another village
- A distribution network, that connect the various households inside the same village

The transmission network was designed with a tree structure, connecting on a case-by-case basis the closest not yet connected point to the already connected ones. The length of the cables was simply evaluated considering the as crow flies distance dist and the altitudinal difference between the starting and ending point:

$$dist = \sqrt{(x_{start} - x_{end})^2 + (y_{start} - y_{end})^2} \tag{24}$$

$$L = \sqrt{dist^2 + (z_{start} - z_{end})^2} \tag{25}$$

The cables for the transmission network were assumed to be realized in medium-voltage (33 kV) due to the relative low power and short distances, whereas, those dedicated to the distribution network, are supposed in low-voltage (0.2 kV),

3.2.3.1 ENERGY STORAGE

As discussed previously, it was decided to limit the energy storage by computing the energy balance only on a preselected number of days $n_{balance}$ during which there are the lowest discharge values. During those days, the energy produced (generally variable) is confronted with the constant energy demand, creating a daily vector of energy balance. The negative elements will compose the vector of not-satisfied daily energy NSDE [kWh] while the positive one the vector of daily energy surplus SDE [kWh]. The amount of energy to be stored in the batteries will then be equal to:

$$E_{batteries} = \frac{\sum_{i=1}^{n_{balance}} NSDE_i}{\eta_{batt}} = \frac{\sum_{i=1}^{n_{balance}} SDE_i}{\eta_{batt}} \tag{26}$$

where η_{batt} represents the percentage of energy that is conserved during the charge and discharge phases.

3.2.4 COST EVALUATION

The cost evaluation was carried focusing on the two main components of the mini-grids: the hydroelectric plant and the electrical network. The plants cost was estimated starting from the average distribution of investment on a generic small hydro-power plant (Figure 3.7). Among all the different components the only ones over which enough information are available are the penstocks (which accounts for a fraction of the civil works) and the turbines (namely turbo generator set in the pie-chart). For safety reasons, it was decided to assign to the penstocks half of the fraction of the civil work cost, even though in run-off-river plants the other components (diversion weir, headrace etc.) do not contribute significantly to the total expenditure. Therefore, the cost of the plant was calculated by multiplying by two the sum of the penstock's cost and the turbo-generator's one.

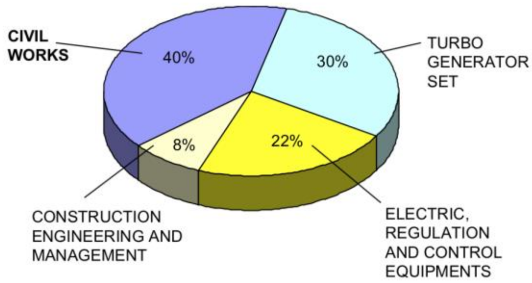

Figure 3.7: *Investment cost breakdown on a hydro-power plant*

The cost of the turbine coupled with the alternator was estimated for each kind of hydraulic machine, specifically the first correlation was validated for impulse turbine (Cross Flow in our case), the second for Francis turbine and the last one for Kaplan and Turgo turbine. These empirical equations were previously validated in the studies of Ogayar and Vidal (2009):

$$C_{turb} = 17.693\, P^{-0.3644725}\, H^{-0.281735} \tag{27}$$

$$C_{turb} = 25.698\, P^{-0.3644725}\, H^{-0.127243} \tag{28}$$

$$C_{turb} = 33.236\, P^{-0.58338}\, H^{-0.113901} \tag{29}$$

where:

C_{turb} = specific cost of the turbine + alternator [€/kW]

P = nominal power [kW]

H = net head [m]

The penstocks cost was determined directly from the same commercial table from which the internal diameter and the penstock' material were derived (Figure 3.6). For what regards the electrical connection, the inputs were derived from a similar study by Nerini et al., 2015 while the price of the batteries were obtained from a quote of SIRONI BATTERIE s.r.l, expert of storage systems for mini-grid applications (Vaccarone 2016).
Finally, the levelized cost of the electricity (LCOE) was evaluated as follows:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + O\&M_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{Et}{(1+r)^t}} \quad (30)$$

$$I_t = \begin{cases} (C_{turb} + C_{pipes}) * 2 + C_{net} + C_{batt} & if\ t = 1 \\ 0 & if\ t > 1 \end{cases} \quad (31)$$

3.3 SENSITIVITY ANALYSIS

The definition of the previous exogenous parameters was needed to define the technology status and economic context of the model. In this way the outcome of the hydrological section can be further developed by means of the hydroelectric module.
Among all these, the most important for the micro-grid design are: the maximum transmission length between two villages (L_{max}) and the maximum pipe length between the turbine site and the main diversion point (d_{max}).

In this study, it was privileged an approach centred on local people energy demand. This means that the sensitivity analysis was conducted to explore different potential solutions to guarantee the most effective combination of the following quantities: number of power plants, number of villages served and LCOE. The levelized cost of the electricity, define by the Formula 30, is an economical convenience index for the sustainability of any possible solution proposed as its value determines the economic affordability level of a technical implementation.
For seek of this purpose, the sensitivity analysis was developed through the simulation of different scenarios characterized by the same maximum pipe length (d_{max}) and variable maximum transmission length.

In this way it was possible to proceed at fix hydroelectric potential for a given pair of diversion and restitution points while varying the area of influence of the single power plant and widening the range of the micro-grid. This led to the isolation of the effects that an increase of villages served by the same system could have on the system itself. With regard to the different technological solutions investigated, a major importance was given to the LCOE, the number of power units and the coverage percentage.

Proven this, for each maximum pipe length several maximum transmission lengths were tested, ranging from 5000 m to 10000 m with a step of 1000 m, the same discretization was adopted for d_{max}.

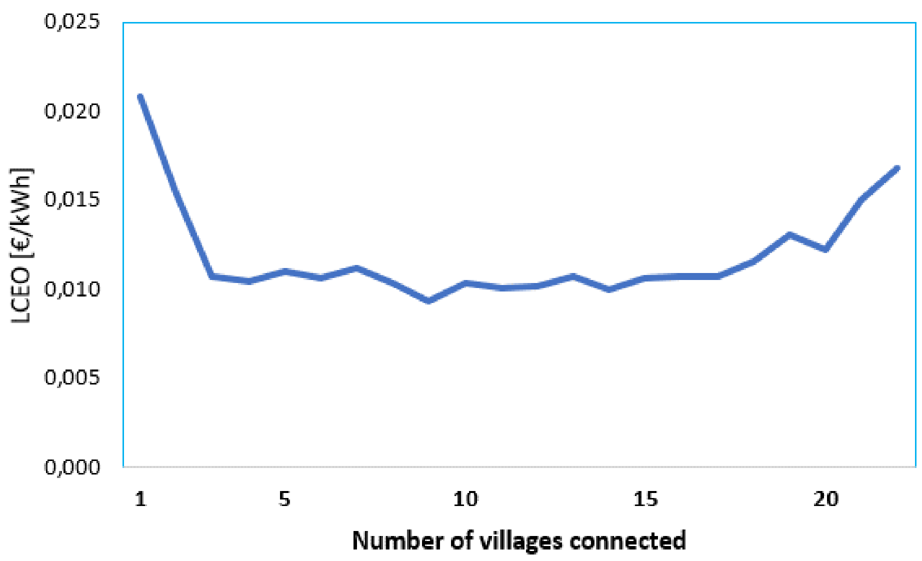

Figure 3.8: *LCEO as a function of the villages connected*

As it can be seen from Figure 3.8, in the first part of the graph the LCOE has a decreasing trend due to the economy of scale; after reaching a minimum value there is a plateau due to distribution of the villages, which is quite uniform in some areas, eventually the grid contribution becomes dominant ant the LCOE returns to increase. It should be also noted that this trend is not constant and various fluctuations are encountered which reflects the non linearity of the function.

CHAPTER 4

4. DATA AND METHODS

In this chapter all data necessary to run and calibrate the model are presented, including their sources and methods applied to them.

The hydrological model requires as input spatial data characterizing the basin (altitude and land use) and meteorological data (temperature and precipitation). In the first section the thematic maps used for the characterization of the catchment are illustrated. The next two sections are dedicated to the meteorological input data most which have already been used in previous studies (Buizza 2014 and Brunetti 2017). However, for what regards the spatializion of the precipitation, different methodologies and input data were chosen and therefore, a particular attention is dedicated to this aspect.

Subsequently the methodology used to estimate the demographic distribution of the inhabitants is shown; such an information is of crucial importance for evaluating the energy demand that in the catchment is prevalently due to self-consumption. In the final paragraph, a summary of the input parameters necessary to run the model is reported.

4.1 BASIN CHARACTERIZATION

In order to properly run the hydrological model, spatial input such as the fraction of vegetated soil f_v, the maximum soil water content S_{max} and the digital elevation model of the area (DEM) are required. These typologies of information were derived from a series of thematic maps of public domain, which are reported below. Some of them were originally at a finer spatial resolution with respect to the model's one and thus the data were aggregated in order to obtain regular square cells of 300 m side.

The CN map (Figure 4.2) was estimated by cross-referencing the land cover map provided by ICIMOD (Figure 4.3). The DEM map (Figure 4.1) was taken from the ASTER Global Digital Elevation Model (ASTGTM v002), a project developed jointly by the U.S. National Aeronautics and Space Administration (NASA) and Japan’s Ministry of Economy, Trade and Industry (METI).

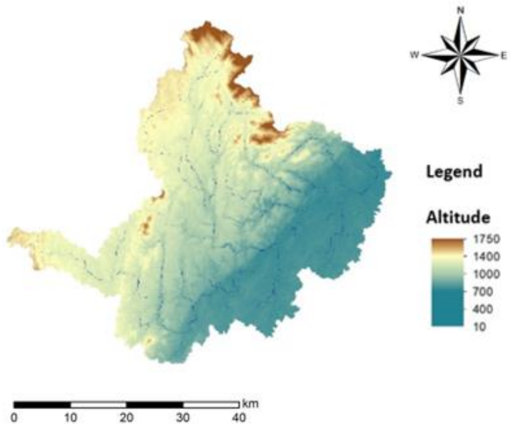

Figure 4.1: *Digital elevation model (DEM) resized at 300 m resolution (ASTGTM v002)*

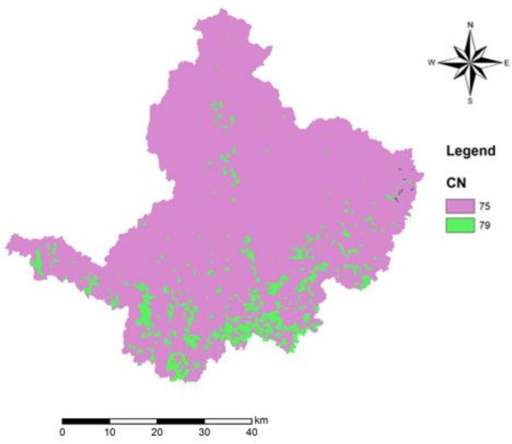

Figure 4.2: *Curve number (CN) map at 300 m resolution*

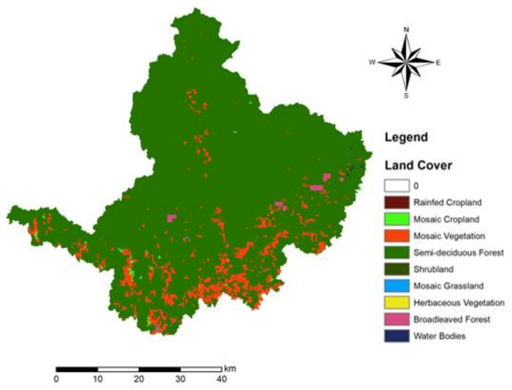

Figure 4.3*: Land cover map resized at 300 m resolution (Arino 2010)*

4.2 TEMPERATURE

Temperature plays a fundamental role in the lend use function. Since the basin object of study is located in the middle of Colombia, in a mostly flat region, the temperature trend during the whole year is nearly constant, with little oscillations around an average value equal to 29 °C.

This consideration unable us to consider also temperature stations not strictly inside the basin extension, but in the soon adjacent regions.

4.2.1 GROUND STATION DATA

In table 4.1 are reported the stations from which temperature data were retrieved. However, given its geographical position, the Cimitarra basin is characterized by almost constant temperature during the year, as shown in the Figure 2.16.

Each time series was reduced to the model temporal resolution by the extraction of the daily minima, maxima and average.

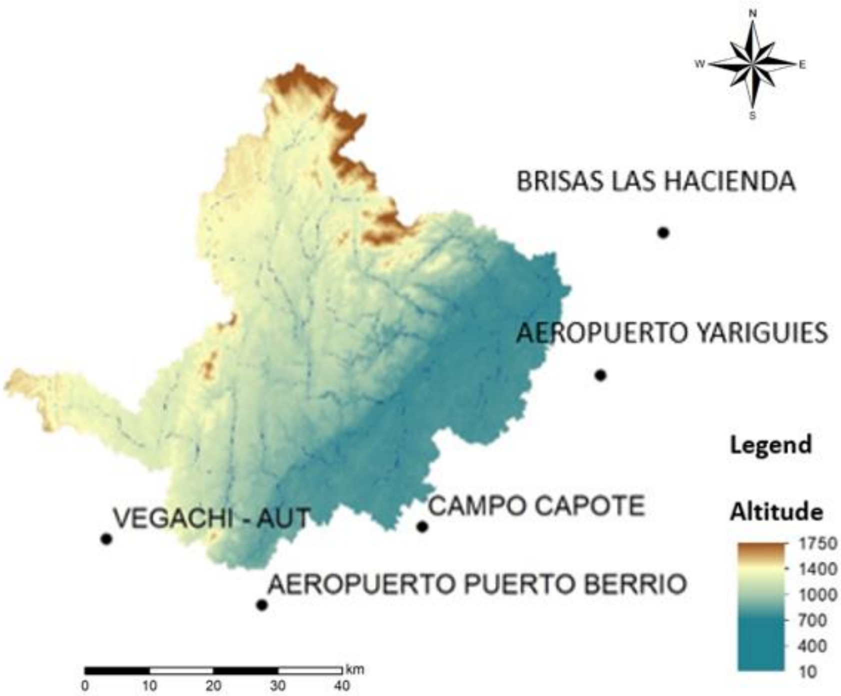

Figure 4.4: *Location of the temperature stations used in the study*

Station	Elevation [m a.s.l.]	Period	Frequency
Aeropuerto Puerto Berrio	150	1984-1990	daily
Aeouerto Yariguies	126	1984-1990	daily
Brisas Las Hacienda	138	1984-1990	daily
Campo Capote	180	1984-1990	daily
Vegachi	990	1984-1990	daily

Table 4.1: *Temperature stations considered*

4.3 PRECIPITATION

Precipitation is the most important quantity among the model's inputs as it determines the water mass balance of the system and thus it governs the availability of the hydropower plants resource.

It has been recalled many times that the orography of Colombia territory strongly influences the common idea of equatorial climate, which is associated with a two seasons weather, distinguished by the precipitation intensity. Colombia climate is far from this, as mountains induces significant variations of temperature, wind and precipitation profiles.

The precipitation stations considered were both inside the basin and outside, also in this case because of the uniformity of precipitation distribution in the basin and in the surrounding area.

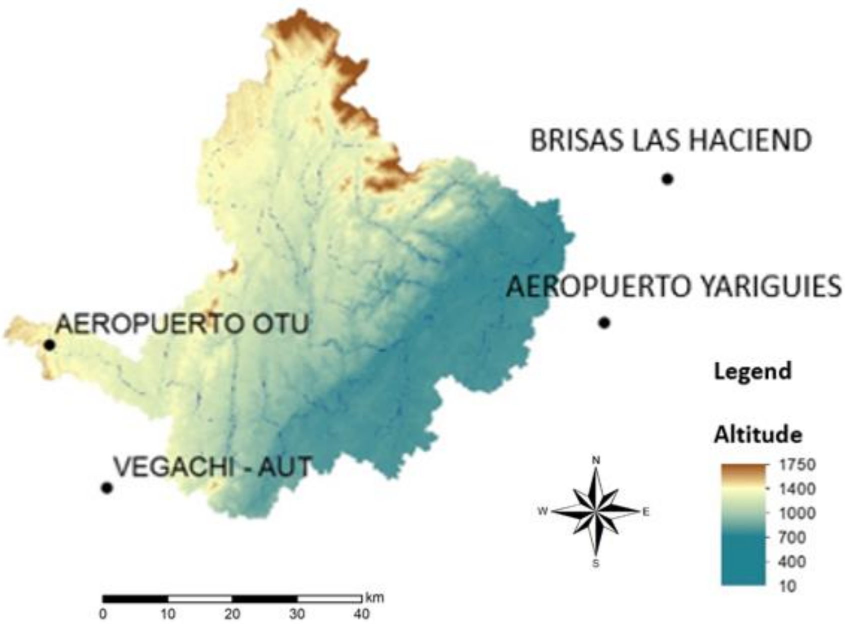

Figure 4.5: *Location of the precipitation stations used in the study*

Station	Elevation [m a.s.l.]	Period	Frequency
Aeropuerto OTU	643	1984-1990	daily
Aeouerto Yariguies	126	1984-1990	daily
Brisas Las Hacienda	138	1984-1990	daily
Vegachi	990	1984-1990	daily

Table 4.2: *Precipitation station considered*

4.4 DEMOGRAPHY

High resolution data regarding population amount and its distribution inside the study area are a fundamental information for the hydroelectric module. In fact, due to the substantial lack of significant productive activities, in the catchment energy is almost entirely required for subsistence needs.

For this study the spatialization of villages in the catchment was taken from the UPME database (Database UPME 2019), whose data were referred only to villages distribution on the territory, considering those with electric energy service and not. The population distribution was estimated by using census and DANE population forecast.

Data population derived from the census 2005 (DANE 2005) were projected on the basis of DANE official forecast, in this way combining the census information with the previous one it has been possible to define also a population distribution.

4.4.1 NATIONAL DATA

National data were taken from the DANE census (DANE 2005), in particular from those sections related to the municipalities included in the basin (Remedios, Segovia, Vegachi Yondo). From the census it was possible to extract the amount of population residing in each municipality, with a further detail about distribution between urban and rural distribution.

Since the census was dated back to 2005, it has been required to project the information in the future, taking as reference the DANE Projection (DANE 2010).

Eventually, it was possible to define the population both in urban and rural areas, in the desired historical period.

4.4.2 SPATIAL DISTRIBUTION

The Colombian government provides census data at maximum at a municipal level and such a resolution was not sufficient for the level of detail required by the model. Therefore, national data were integrated by using the UPME database (Database UPME), which provided a distribution of rural villages across the country and also reported information about the number of viviendas, classified on the basis of electricity energy access.

As previously mentioned, even if the spatialization provided was accurate, the information related to the number of viviendas and to the number of people was averaged on the whole municipality. The procedure follower to deal with this particular characteristic has been described in Chapter 4.4.1.

4.5 INPUT PARAMETERS

In the following paragraphs all the parameters necessary to run the model are reported. They are subdivided into hydrological and hydroelectric parameters and their values derive either from literature studies or calibration for the study area.

4.5.1 HYDROLOGICAL PARAMETERS

The values of the parameters described in section 3.1 are presented in Table 4.3.

Parameter	Description	Unit of measurement	Value
T_s	rain/snow threshold	[°C]	0
T_i	ice/snow threshold	[°C]	0
T_{ET}	evapotranspiration threshold	[°C]	0
DDF_s	degree day snow	[mm d^{-1} $°C^{-1}$]	3.5
K	hydraulic conductivity	[mm d^{-1}]	1
k_g	Scale factor	[-]	2
θ_w	water content at wilting point	[cm^3_{water}/cm^3_{soil}]	0.15
θ_l	water content at field capacity	[cm^3_{water}/cm^3_{soil}]	0.35
θ_s	water content at saturation	[cm^3_{water}/cm^3_{soil}]	0.45
$t_{lag,sup}$	surface lag time	[h]	3864
$t_{lag,inf}$	sub-surface lag time	[h]	3432

Table 4.3: *Hydrological input parameters*

4.5.2 HYDROELECTRIC PARAMETERS

Most of the parameters required to run the hydroelectric model were derived from previous literature studies (Table 4.4).

The maximum distance between two villages and the maximum length of the penstock are not reported in table 4.4 together with the others since they were not assigned unique values; instead a sensitivity analysis was performed on them the result of which will be illustrated in Chapter 5.

Parameter	Description	Unit of measurement	Value
$A_{thrshold}$	minimum subcatchment area	[km^2]	10
$P_{nom,max}$	maximum nominal power	[kW]	100
$ED_{vivienda}$	energy demand	[kWh viv^{-1} d^{-1}]	3
e%	maximum head loss	[%]	5
c_{transm}	transmission line cost	[€/m]	9
c_{distr}	distribution line cost	[€/m]	5
$c_{conn,HH}$	cost for connecting a household	[€/HH]	100
c_{transf}	transformers cost	[€/kVA]	100
c_{batt}	battery cost	[€/unit]	100
$capacity_{batt}$	battery capacity	[Ah/unit]	180
V_{batt}	battery voltage	[V/unit]	6
ele_{loss}	Transmission and distribution losses	[%]	5
r	discount rate	[%]	5

Table 4.4: *Hydroelectric input parameters*

CHAPTER 5

5. RESULTS

In this chapter, the results of the simulations carried out are reported and analyzed.

In the first section, the output of the hydrological model is compared with the observed discharge series at Cimitarra over the period 1984 – 1990 at daily scale.
As a second step, the results obtained by the sensitivity analysis are investigated.
Firstly, the cost of the various mini-grid components as function of the number of villages connected is analyzed. Secondly, the results of the sensitivity analysis are discussed and a possible configuration is selected, taking into account the main purpose of the study.

5.1 HYDROLOGICAL MODEL'S CALIBRATION AND VALIDATION

The hydrological model described in Chapter 3 requires the calibration of four input parameters. The tuning of these parameters was done against observed discharge at Cimitarra following such approach: on one hand, a first value of the parameters that govern the sub-superficial flow (i.e. the scale factor k_g and the hydraulic conductivity K) was obtained by comparing the model with the monthly average measured values, due to their greater importance in longer time spans. On the other hand, the surface $t_{lag,sup}$ and sub-surface lag times $t_{lag,sub}$ were tuned against the daily values.

The calibration was aimed at matching the cumulative observed values with the simulated ones (Figure 5.1). The model underestimates the monthly cumulative discharge of 10%, nevertheless on annual basis the error on cumulative volumes was around 5%.

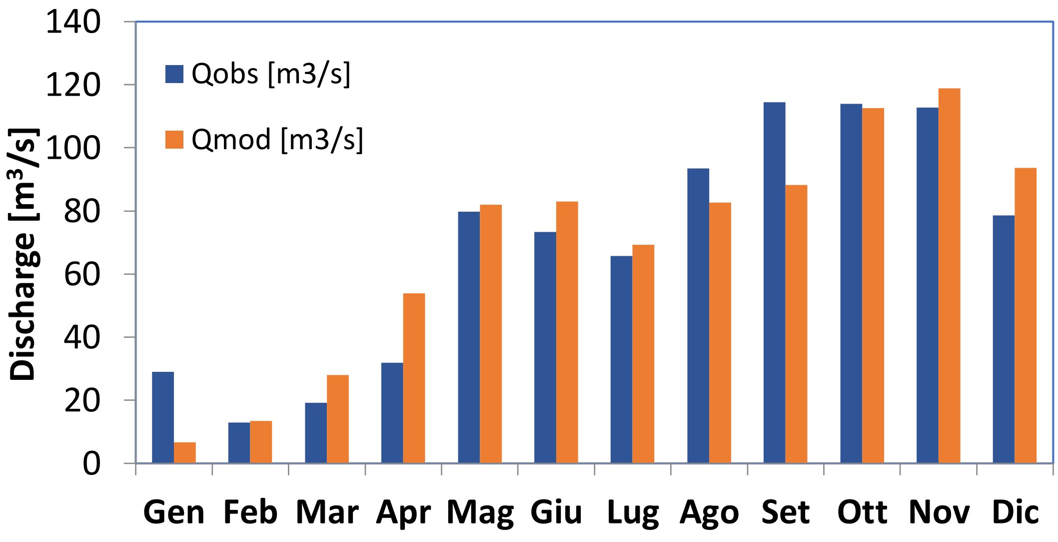

Figure 5.1: *Average monthly observed discharge at Cimitarra basin*

The daily values were tuned in order to maximize two efficiency indexes:

$$NSE = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O}_i)^2} \tag{33}$$

$$\ln_{NSE} = 1 - \frac{\sum_{i=1}^{n}(lnO_i - lnP_i)^2}{\sum_{i=1}^{n}(lnO_i - ln\bar{O}_i)^2} \quad (34)$$

Where P_i is the discharge prediction at step i and O_i the discharge observation.
By squaring the differences, the Nash-Sutcliffe Efficiency (NSE) weights more large values and therefore is used to describe the goodness of fit of high flow. Conversely, the logarithm of the NSE (Equation 33), gives more weight to low values and thus to low flows. The indicators range from 1 to -∞, with the unity being the optimum, negative values indicate that the mean of the observation is a better predictor than the model.

The results obtained (Figure 5.2) showed a quite good correlation even at a daily scale. Moreover, the particular condition of constant temperature trend and precipitation profile enabled to require less strict values on these parameters. Eventually, the calibration process revealed to be sensitive to the t_{back} parameter. This parameter is less connected to physics quantities of the model, it expresses for each year the period of time to be consider to begin the simulation in the following year. This is needed to reduce the computational burden. In this study it was set to 120, previously it was equal to 60 but it gave relevant problems to the calibration process, in particular at the beginning of the new year.

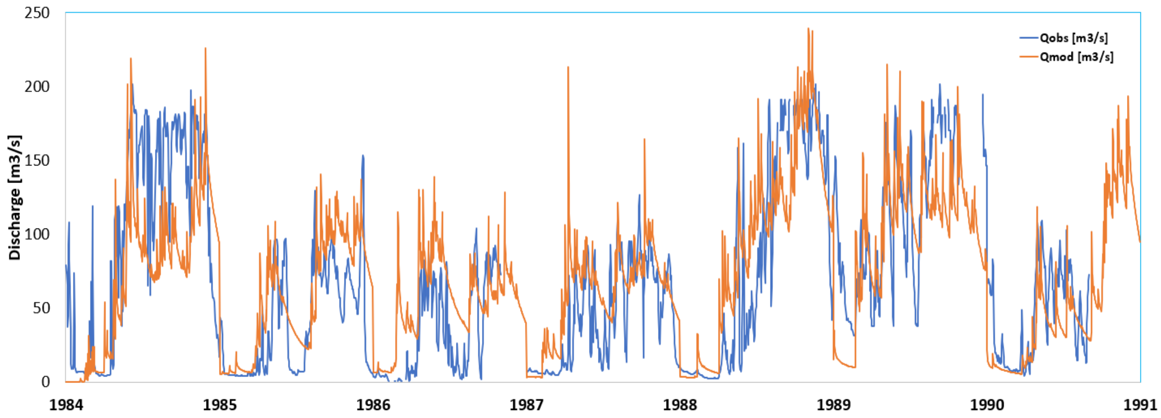

Figure 5.2: *Observed and simulated daily flow for the calibration model*

Indicator	Calibration period
NSE	-1.70
lnNSE	0.95

Table 5.1: *Model efficiency for the calibration and validations period*

Given the absence of ice and snow melt, rainfall played a major role. However, the flows measured did not follow precipitation trend as the high vegetation coverage induced a delay between the water and the evapotranspiration contributed to diminish the water available I the rivers.

5.2 HYDROELECTRIC MODEL SENSITIVITY ANALYSIS RESULTS

5.2.1 COST DISTRIBUTION

As a first step of the analysis, it was investigated the relationship between the cost of the various mini-grids' components and the number of villages served. Figure 5.3 illustrates the case of a specific mini-grid, even though similar results were obtained for all other plants.

In the hydroelectric module the electrical storage solution was not discarded, however the implementation of such technology drifted the overall cost of the related grid. Since this, in most cases it was preferred not to meet completely the energy demand of the inhabitants rather than ensuring a fully constant energy supply but at prohibitive costs for local people.

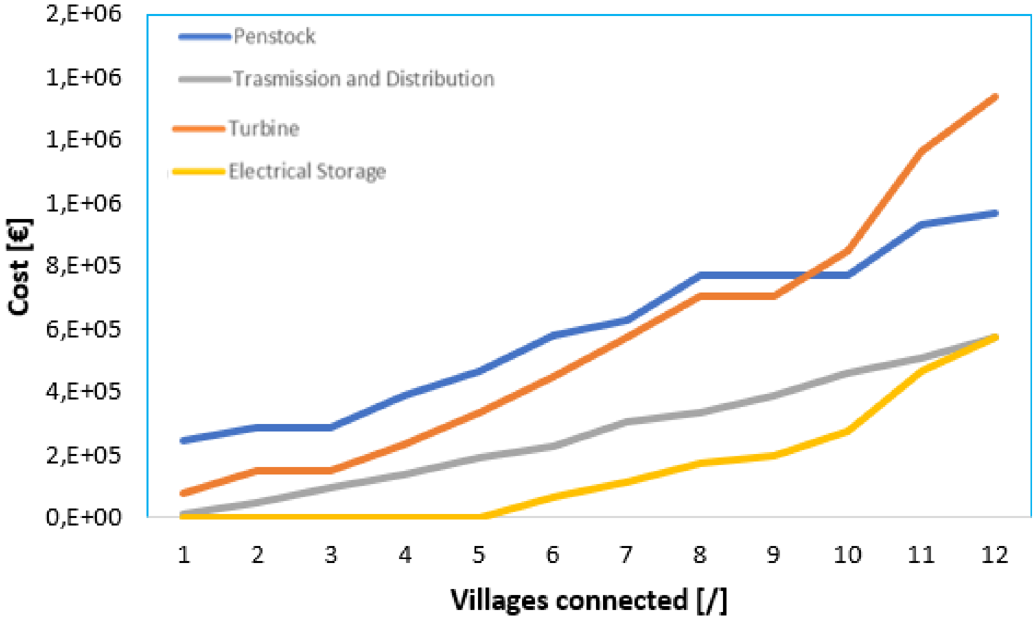

Figure 5.3: *Cost pattern of the mini-grid's components according to the number of villages connected*

The results obtained highlight trends absolutely coherent with those of literature. At the beginning, in many micro-grids the main expenditure is the penstock due to the low initial energy demand. As the system grows the turbine size increases becoming dominant, the importance of transmission and distribution costs depends on the input parameter L_{max}, which determines the maximum length of transmission. Indeed, in some configuration they can equal and overcome the turbine cost. Eventually, as mention before, the usage of electric storage is an uncommon technical solution which leads to a loss of competitiveness of the micro-grid, in fact even small storage modules involve significant costs.

5.2.2 SENSITIVITY ANALYSIS RESULT

The procedure and the main concerns about the sensitivity analysis were discussed in Chapter 3.3 and are here summarized.

The most important parameters of the analysis were the maximum transmission length between two villages (L_{max}) and the maximum penstock length between the turbine site and inlet of the supply line (d_{max}).
The variation of the last quantity is associated with a variation of the hydropower potential of each couple of diversion and restitution point, thus with the hydro resource potential of the turbine given a specific site. The analysis followed an approach more oriented to consider the energy demand of the villages, thus the scenarios were developed for d_{max} fixed coupled with a variation of the maximum transmission length. In this way, it was possible to highlight the effect of an enlargement of the micro-grid, therefore the impact of coverage percentage variations on grid design and cost was addressed.
Given this, for each maximum pipe length several maximum transmission lengths were tested, ranging from 5000 m to 10000 m with a step of 1000 m, the same discretization was adopted for d_{max}.

Figure 5.4 reports the average LCOE of the various micro-grids designed.
The difference among all these trends lies in the different d_{max}. By considering the first step with L_{max} equal to 5000 m, it is clear that when higher maximum values of distance between the diversion point and the turbine are given the LCOE already begins to increase. The reason

is that the model can design more complex micro-grids already in the initial stage, in fact there are more potentially available couples as a relatively low hydro resource is balanced by the possibility to have higher gross head.

In addition to this, the results show two clearly different trends.

For d_{max} equal to 5000 m and 6000 m the LCOE shows the most common trend. In the first case, the restrictive combination of both parameters forces the model to evaluate only three potential micro-grids, with low overall coverage percentage (Figure 5.6). These conditions lead to an increase of LCOE when considering to meet the energy need of further villages. The second trend is the most typical one, in this case the mini-grid reaches an optimal value of LCOE before starting to increase. The difference between these two case-study is the coverage percentage (Figure 5.6), which shows how with a similar infrastructure the second solution can reach more villages, thus being more competitive.

The other trends, apart from d_{max} to 10000 m which follow the trend just discussed, show the same behaviour with respect of L_{max}. The increase of mini-grid complexity justifies the increase of the average LCOE, whereas the significative degree of freedom to choose the best couples suitable to design the grids justifies the LCOE decrease when L_{max} increases. This means that given the loose constraints for the mini-grid development, the solving process is able to find couples better distributed with respect to villages position, however the high degree of complexity prevents these from being the best solution.

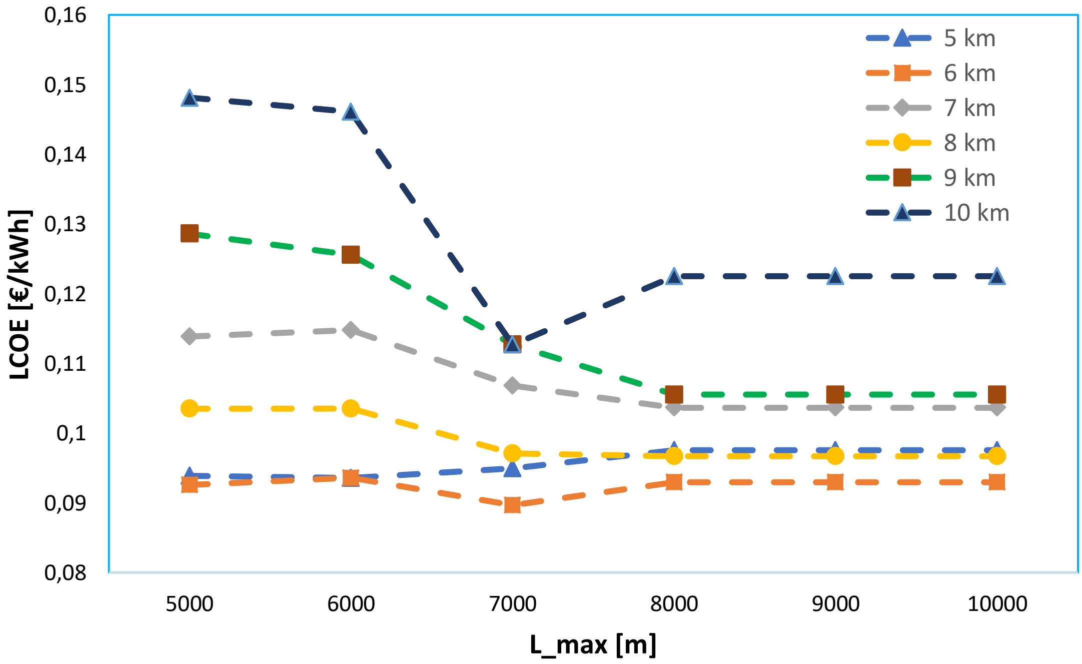

Figure 5.4: *Effect of the parameter L_{max} on the average LCOE of the design mini-grid*

Another crucial aspect that must be analysed to better understand the meaning of the LCOE trend can be introduced recalling the last statement about grid complexity.

The variation of d_{max} and L_{max} affects the hydroelectric model resolutions in terms of centralized micro-grid design or distributed. On one hand, the first parameter determines the maximum energy available for each possible couple, on the other hand the maximum transmission length determines the maximum number of villages that can be served by the mini-grid.

These considerations are in accordance with the results shown in Figure 5.6.

The increase of d_{max} gives the possibility to find more potential couple to build the mini-grid, as mentioned before these grids will be more complex thus the LCOE associated higher.

Strong of these, it is easier to understand the LCOE trend of Figure 5.4. It can be clearly seen how the mini-grid developed with the lowest d_{max} can not increase the number of power units, so the increase of L_{max} must be followed by an increase of LCOE, as the system will handle the energy demand of a new little but far village. For the same reason the grid associated to d_{max} equal to 6000 m has the lowest LCOE in correspondence of a power plant number decrease, meaning that those power units are optimized, thus a further centralization will not benefit to the grid itself, as shown in the LCOE trend.

There is no doubt that the LCOE is strongly influenced by the centralization process induced by the different intensity of mini-grid expansion constraints.

Eventually, all these considerations follow the trends of Figure 5.6 where the results of coverage percentage analysis are reported.

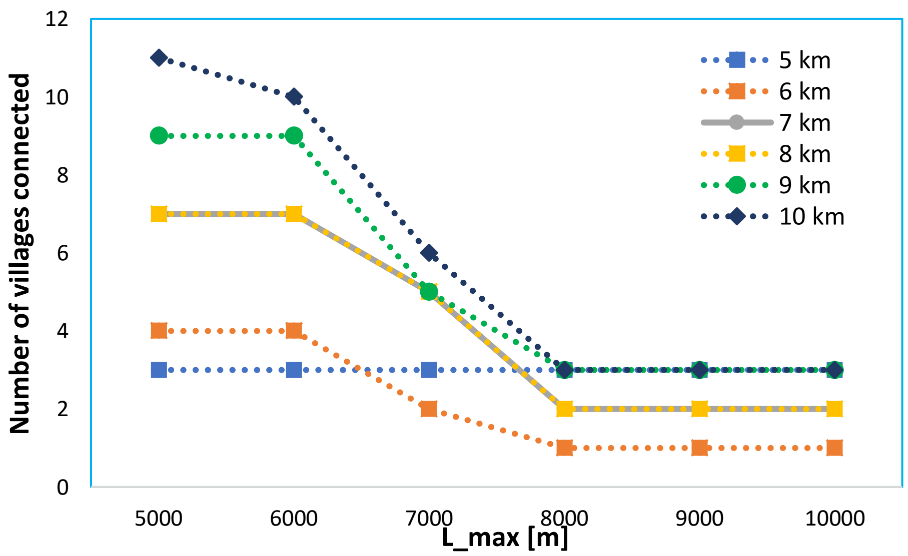

Figure 5.5: *Effect of the parameter L_{max} on the average LCOE of tje designed mini-grifs*

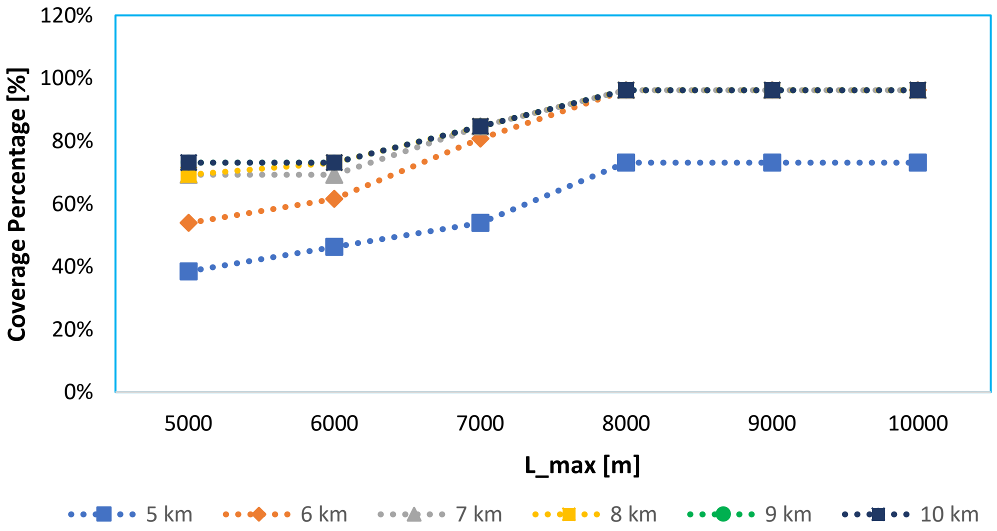

Figure 5.6: *Effect of parameter L_{max} on the average coverage percentage of a given couple*

In this last section the characterization of the chosen solution is reported.

Due to the availability of hydro resource in the basin, the solving process was able to design large and complex micro-grid characterized by a strong centralization. Such solutions are often not viable, despite their theoretical low LCOE, as they would require higher investment costs and a more complex transmission and distribution system. Moreover, the implementation of those systems would mean a minor degree of flexibility and availability of the electricity service.

The proposed micro-grid solution shows a competitive LCOE, often lower than the electricity cost in the National System, which is approximately equal to 0,11 €/kWh in the last years (UPME 2016).

The best configuration for the micro-grid was fund for d_{max} equal to 8000 m and L_{max} equal to 7000 m, conditions highlighted in Figure 5.4 and 5.5. This design was preferred to other with lower LCOE, as it granted an already important degree of coverage (Figure 5.6) with a limited centralized power production system. All these enable the solution to be competitive, spread enough and flexible.

Finally the LCOE and coverage percentage trend are reported.

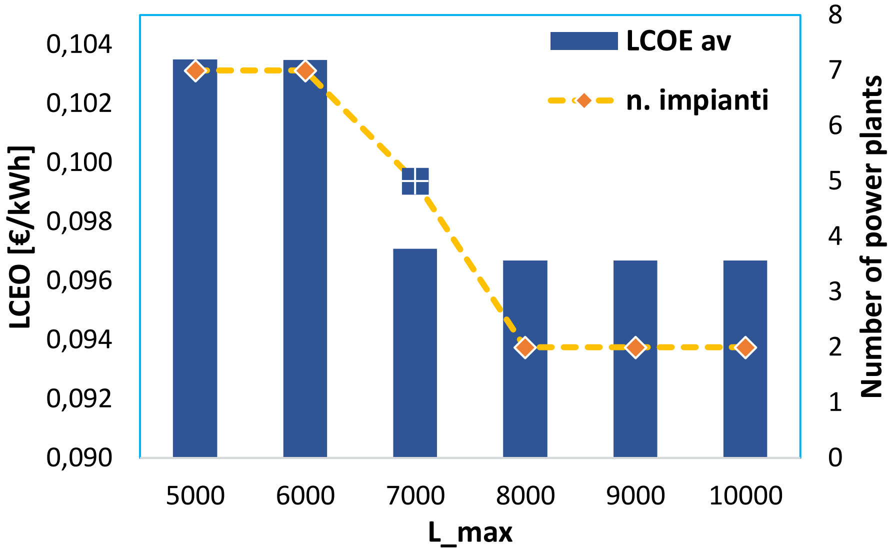

Figure 5.7: *Effect of the parameter L_{max} on the LCOE and number of power plants*

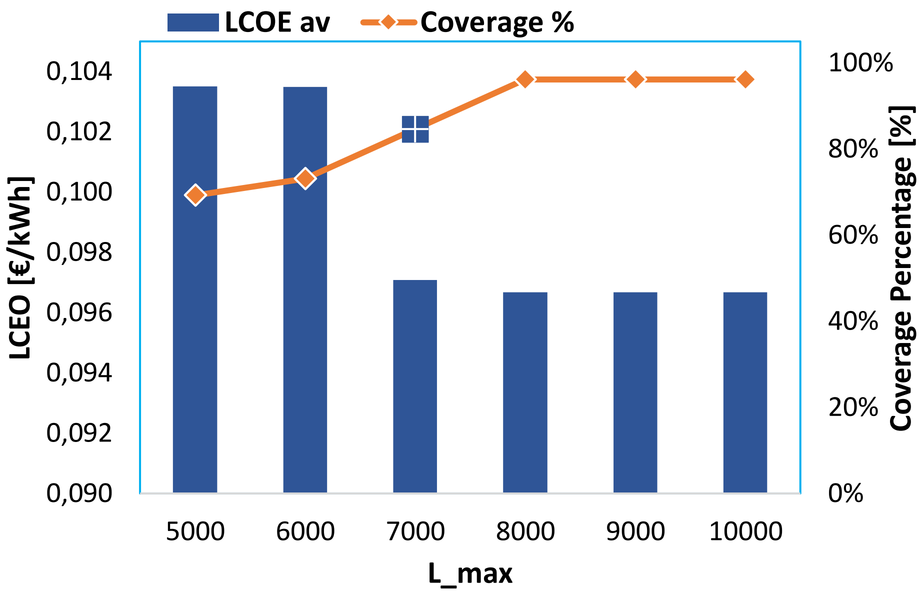

Figure 5.8: *Effect of L_{max} on the LCOE and coverage percentage*

CHAPTER 6

6. CONCLUSION

Colombia has the second hydroelectric potential in Latin America, exploited only in a minimal proportion. This represents an absolutely concrete opportunity to reach those villages, which are currently without electricity access due to their isolated position with respect to the national grid. Such a problem is common for rural communities, indeed the IEA reported that the urban access rate is approximately 95% in urban areas, but it falls down to 75% when rural areas are considered. This alarming inequality can be overcome by means of distributed generation, smart solutions with reduced environmental impact, initial investment costs and financial implication.

Micro-grid, in this case study based on run-off mini-hydro power plants, might be the most sustainable solution to reach the goals proposed in the SDG 7.

The thesis was carried out under this belief and the purpose was to develop an effective tool to support the planning of rural electrification for the Cimitarra river basin (Colombia).

A semi-distributed hydrological model was firstly implemented and calibrated against observed discharge data at Bagre el**.** This procedure was based on a limited set of discharge measurements, as the gauging station has been removed in the early 90'. However, the uniform conditions of temperature and precipitation enabled to proceed with the calibration and the results were in accordance with the measured quantities (average error on the annual cumulative volume of 5% and a value of NSE equal to -1.7) and with the current trends.

Afterwards, taking as inputs the flow duration curved of all the different sub-basins, a hydroelectric model was developed. The model was implemented to size run-off river hydro-power plants and their related micro-grid according to the energy demand of villages located near them. For each grid the cost of the major components (i.e. the penstocks, the electro-mechanical equipment (turbine + alternator) and the electrical connection) were estimated and subsequently the levelized cost of electricity (LCOE) was derived. As a final step, the potential of the model was investigated through a sensitivity analysis, whose aim was to identify the micro-grid design behavior in terms of LCOE, centralization of the grid proposed and coverage level. The results obtained showed that it was possible to provide electricity to 85% of the villages at an average cost of 0.10 €/kWh.

6.1 LIMITATIONS AND FUTURE DEVELOPMENT

When dealing with rural villages and isolated regions, it is common to have missing data in the available series. For the Cimitarra basin having only one station for the discharge measurement was definitely a restrictive condition. However it was placed in best position, the closure point of the hydrological system, therefore it was possible to deal with this.
Another significant limitation was due the insufficient information related to the population distribution and their energy demand. The database used provided accurate information about villages distribution, whereas the population information was averaged on the municipal influence area. In addition to this, it was not possible to have more specific data about the energy demand , such as the domestic and commercial activities carried out in each village.
Finally, the micro-grids were designed under the assumption of being completely powered by hydro-electric energy. This strongly influenced the planning procedure of these systems, nevertheless interesting and viable results were obtained. However, to make it more flexible and to maximize the competitiveness of these solutions, the integration with other local renewable resources is mandatory.

All these considerations serve as suggestions for future developments of the current study:

- Survey the current spetial distribution of the population and their consumption patterns; this is crucial to build the spatial and temporal profile of the load curve and afterwards to match it with the most suitable storage system.
- Since the electrical storage systems proved to be a non effective solution, it should be explored the possibility of couple the power block with a small water storage system or even a back up diesel generator.
- Given the limited availability of data, the discretization level used to design the micro-grid was equal to 2000 m. However, this aspect should be improved in order to have the best planning process of the grid.

- With the same purpose of the previous suggestion, the combination of different renewable sources should be investigated. In this way complementary trends could be discovered and implemented to improve the quality level of the electricity supply service. It is worthy to say that by means of the PVGIS tool, a project developed for more than 10 years at the European Commission Joint Research Centre, at the JRC site in Ispra, Italy, a preliminary investigation of off-grid photovoltaic systems has been already conducted. However, the effectiveness and the robustness of its results strongly relies on a deeper knowledge of the activities and energy consumption profiles of the rural communities involved.

Finally, some personal consideration about this analysis.

Climate change is one of the biggest global challenges of the XXI century and its impact on both human and natural system is becoming clearer year by year.
For this reason, when it comes to face the energy problem around the world systems based on renewable resources become fundamental. Mini-hydro has proven to be a cost-competitive solution for rural electrification, potentially able to increase the life quality level of local people and reduce the pressure on the surrounding environment.
For this reason, in rural areas the implementation of micro-grids based on mini-hydro or other RES should be encouraged by fund support programmes, because any important, permanent and true achievement, like the SDGs, is the sum of small steps.

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