KTH Industrial Engineering and Management

Polygeneration system model in rural areas of Colombia. Filipinas ETCR as a case of study

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Abstract

This project has addressed the design of a cost-effective Polygeneration system that guarantees a continuous, equitable and environmentally friendly energy supply for the rural settlement of Filipinas ETCR, (in Spanish, *Espacios Territoriales de Capacitación y Reincorporación*) Colombia, which is currently not achieved, due to a system that relies on the national electricity grid (with numerous outages) and on LPG (Liquefied Petroleum Gas) and wood to meet the thermal demand, mainly for cooking. For this purpose, in addition to the current energy supply situation, the energy demand according to type (electricity and heat) and sector (residential, commercial and agro-livestock) is characterized. Also, the availability of renewable energy sources is examined, resulting in the existence of a potential for solar and residual biomass resources. Then, the most suitable sub-systems and technologies for their exploitation have been analyzed. In this way, HOMER Pro software has been used to find the most competitive solution (the lowest LCOE, Levelized Cost of Energy), together with a technical, economic, environmental and social analysis to analyze its impact on the ETCR. Thus, the final solution results in a Polygeneration system based on a PV (Photovoltaic) subsystem, the electrical grid and a biogas production plant (48 m^3/day) by anaerobic digestion of agricultural, livestock and urban waste biomass coupled with an ICE (Internal Combustion Engine). The PV (250 kW) would be the major source of electricity generation, followed by the grid and, as a back-up, the biogas-fired ICE (25 kW), which is also used to replace LPG and wood for heating purposes. The solution presents a remarkable renewable fraction (73% instead of the current <0.5%) and a significant reduction of polluting emissions (60.5% of CO_2 emissions). Moreover, it is ensured an economic viability over time (a ROI of 9.7% and DPB (Discounted Pay-Back) lower than 18 years) and a potential positive impact in the socio-economic development of Filipinas ETCR. To conclude, these results are in line with the UN SDGs (Sustainable Development Goals) 7 and 13, being an example of the viability of such systems and the positive environmental, social and economic consequences they can have in rural locations with economic difficulties and non-renewable and weak energy supplies.

Sammanfattning

Detta projekt har behandlat utformningen av ett kostnadseffektivt polygenereringssystem som garanterar en kontinuerlig, rättvis och miljövänlig energiförsörjning för bosättningen på landsbygden i Filipinas ETCR (Espacios Territoriales de Capacitación y Reincorporación på spanska) i Colombia, vilket för närvarande inte är uppnått på grund av ett existerande energisystem som är beroende av det nationella elnätet (med många avbrott) och av gasol och ved för att tillgodose det termiska behovet, främst för matlagning. I detta syfte har man förutom den nuvarande energiförsörjningssituationen även karakteriserat efterfrågan på energi efter typ (el och värme) och sektor (bostäder, handel och jordbruk och boskapsskötsel). Dessutom undersöks tillgången på förnybara energikällor, vilket påvisar att det finns potential för både solenergi och biomassa. Därefter har man analyserat lämpliga delsystem och tekniker för att kunna nyttja energikällorna. För detta har programmet HOMER Pro använts till att hitta den mest konkurrenskraftiga lösningen (med lägst LCOE), tillsammans med en teknisk, ekonomisk, miljömässig och social analys för att analysera dess inverkan på ETCR. Således är den slutliga lösningen ett system för polygenerering som bygger på ett delsystem av solceller, elnätet och en biogasproduktionsanläggning (48 m^3/dag) som använder sig av anaerob nedbrytning av biomassa från både jordbruk, boskap och stadsavfall i kombination med en ICE. Solcellerna (250 kW) skulle då vara den främsta källan till elproduktion följt av elnätet, varav den biogaseldade ICE-anläggningen (25 kW) används som reserv och för att ersätta gasol och ved för uppvärmning. Lösningen innebär en anmärkningsvärd andel förnybara energikällor (73% jämfört med nuvarande <0,5%) och en signifikant minskning av förorenande utsläpp (60,5% av koldioxidutsläppen). Dessutom garanteras en ekonomisk lönsamhet med tiden (med en ROI på 9,7 % och en DPB på mindre än 18 år) och en potentiellt positiv inverkan på den socioekonomiska utvecklingen i Filipinas ETCR. Sammanfattningsvis ligger dessa resultat i linje med mål 7 och 13 av FN:s hållbarhetsmål, eftersom de är ett exempel på lönsamheten hos sådana system och de positiva miljömässiga, sociala och ekonomiska konsekvenser som de kan få på landsbygden där det förekommer ekonomiska svårigheter, och där eltillförseln är opålitlig och baserad på energikällor som inte är förnybara.

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Abbreviations

ETCR	Espacios Territoriales de Capacitación y Reincorporación
LPG	Liquefied Petroleum Gas
LCOE	Levelized Cost of Energy
HOMER	Hybrid Optimization of Multiple Energy Resources
PV	Photovoltaic
ICE	Internal Combustion Engine
DPB	Discounted Pay-back
CO_2	Carbon Dioxide
UN SDGs	United Nations Sustainable Development Goals
ROI	Return of Investment
IEA	International Energy Agency
FARC-EP	Fuerzas Armadas Revolucionarias de Colombia - Ejército del Pueblo
GDP	Gross Domestic Product
USD	United States Dollars
WETI	World Energy Trilemma Index
ZNI	Zonas No Interconectadas
GHG	Green House Gases
PROURE	Program for Rational and Efficient Energy Use and Non-Conventional Energy Sources
FAZNI	Financial Support Fund for the Electrification of Non-Interconnected Zones
DG	Distributed Generation
SIN	Sistema Internacional Nacional
UPME	Unidad de Planeación Minero Energética
PERS	Planes de Energización Rural Sostenible
RES	Renewable Energy Systems
NPC	Net Present Cost

Ni-Fe	Nickel-Iron
IPSE	Instituto de Planificación y Promoción de Soluciones Energéticas para las Zonas No Interconectadas
SHW	Sanitary Hot Water
FNCE	Fuentes No Convencionales de Energía/Non-Conventional Energy Sources
DANE	Departamento Administrativo Nacional de Estadística
ICA	Instituto Colombiano Agropecuario
EVA	Evaluaciones Agropecuarias Municipales
OUSR	Organic Urban Solid Residues
DWP	Drinking Water Plant
WWTP	Wastewater Treatment Plant
LHV	Low Heating Value
VS	Volatile Solids
IRENA	The International Renewable Energy Agency
O&M	Operation and Maintenance
DC	Direct Current
AC	Alternating Current
NPC	Net Present Cost
HR	Heat Recovery
NPV	Net Present Value
EPA	United States Environmental Protection Agency
FAO	Food and Agriculture Organization of the United Nations
NGO	Non-Governmental Organization
CEO	Chief Executive Officer
ACPM	Aceite Combustible Para Motores
STC	Standard Test Conditions
NOCT	Nominal Operating Cell Temperature
DoD	Depth of Discharge

1 Introduction

Rural electrification is a vital requirement for the development of remote rural areas to obtain economic growth, poverty elimination, employment generation and improvement of livelihood of the villages. According to estimates of the International Energy Agency, 90% of the population of many developing countries do not have access to sufficient and sustainable supplies of energy and over 84% of them live in rural areas [1]. Poor electricity distribution is mainly due to geographical inaccessibility, rugged terrains, lack of electrical infrastructure and high required economic investment for installing large grid connected power lines over long distances to provide electricity for regions with a low population density.

Therefore, there is an urgent need to find cost-effective solutions that meet the basic needs of these populations without further compromising the environment with the use of cheap, but polluting, fossil fuels. Bearing this in mind, grid-connected renewable energy generation systems are an economically viable option for the supply of electricity in already electrified villages where grid electricity is only available for a few hours and which are located in remote areas in underdeveloped or developing countries. Such systems allow excess electricity generated during peak renewable resource hours to be sold to the grid, improving access, quality and reliability of electricity supply, while the cost of power generation is reduced compared to off-grid hybrid power generation systems (stand-alone).

1.1 Objective and scope

The main objective of this thesis is based on the proposal of a Polygeneration system that satisfies the energy and drinking water demands of a rural village in Colombia through the use of renewable and local resources that reduce the environmental impact of this settlement and, at the same time, promote the creation of economic activities. The work carried out in this project is based on a preliminary study developed by a student group including the authors, which, due to lack of resources and time, did not obtain results with the precision and magnitude required for this type of project [2].

This project is focused on the Filipinas ETCR (in Spanish, *Espacios Territoriales de Capacitación y Reincorporación* or, in English, Territorial Spaces for Training and Reincorporation). It is located in the municipality of Arauquita (Department of Arauca, Colombia). This village belongs to a group of settlements spread throughout the Colombian territory, which were created by the government as a result of the peace agreements between this organism and the FARC-EP (in Spanish, *Fuerzas Armadas Revolucionarias de Colombia - Ejército del Pueblo* or, in English, Revolutionary Armed Forces of Colombia - People's Army). The former combatants of the former guerrilla group have organized themselves within these spaces to comply with a settlement phase so as to speed up what was agreed upon within the peace agreement. In the ETCRs, reintegration activities are carried out in order to facilitate the initial phases of adaptation of the members of the FARC-EP to civilian life. Currently, there are 24 ETCRs spread throughout the country, although each one of them has very different energy-related characteristics. In the case of Filipinas ETCR, it is equipped with a non-sustainable energy supply system which cannot guarantee security, continuity, and environmental friendliness. Hence, due to the importance of the educational and professional development of these settlements, it is essential to propose a solution that guarantees a continuous electricity supply to their inhabitants.

1.2 Colombian context

This study focuses on a village located in a rural area of northeastern Colombia. It is therefore helpful that, prior to a detailed analysis of the current citation of this locality is performed, an examination of the situation at the national level is carried out.

1.2.1 Colombia & energy

Colombia is a country whose population has grown steadily since the 1960s to more than 50 million inhabitants. For its part, GDP has experienced significant and continuous growth since the 2000s (99 billion USD), despite a slight drop in 2015, until the arrival of the SARS-CoV-2 pandemic, having reached 323 billion USD in 2019 [3]. However, its GDP per capita (6,432.4 USD/per) falls below the average for Latin America and the Caribbean region (8,847.4 USD/per).

In line with the increase in its population and wealth, Colombian energy consumption has been progressively increasing last decade up to 38,847 ktoe (2018). This consumption has been covered historically and currently mainly by fossil fuels (74% of the energy supply, in 2018). This dependence on fossil fuels does not translate into dependence on imports, since Colombia is a historic and major exporter, a role which has been accentuated since the 90s (-20 Mtoe net imports in 1990) until today (-90 Mtoe in 2018, 3.5 more times) [4].

The remaining 31% of supply is covered by renewable energies, mainly hydroelectric and biofuels and waste (around 50% each one). Wind, solar and geothermal energies are negligible in the Colombian energy mix. The sectors that concentrate energy consumption are transport (37%), industry (26%) and the residential sector (21%). With respect to electricity consumption, it represents 18.4% of total consumption (71.9 TWh) and it is mainly distributed among the residential (39.9%), industrial (32.3%) and commercial sectors (21.5%) [4].

In 2015, Colombia presented a national energy plan called (in Spanish) as *Plan energético nacional: Ideario Energético 2050*. Its aim is to secure energy supply and diversify the energy mix (for example, increasing the share of renewable energies) [5]. In fact, Colombia has decided to incorporate 2,200 MW of renewable energy into its system as part of this plan.

According to UN Sustainable Development Goals (SDGs), energy is a key aspect for the development of a territory. This importance is reflected mainly in SDGs 7 (Affordable and Clean Energy) and 13 (Climate Action). Colombia has improved in its achievement of these SDGs. For SDG 7, population with access to electricity is 99.6% (2017) and to access to clean fuel and technology for cooking 91.8% (2016). For SDG 13, the tonnes of CO_2 emissions per capita have been reduced [6].

For its part, the World Energy Council has developed an index, the World Energy Trilemma Index (WETI), which aims to provide information on a country's relative energy performance in relation to energy security, energy equity and environmental sustainability [7]. Colombia is 35th (72.3 of 100 points), having experienced an improvement due to higher scores in all three areas, but mainly in the environmental.

As a conclusion, Colombia has experienced during the last years an increase on population and wealth and it presents an energy system which strongly depends on non-renewable energy resources to cover its energy demand. Nevertheless, the recent improvement in the SDGs 7 and 13 indicators as defined by the WETI and its last energy policies reflect how Colombia is trying to take steps towards sustainability.

1.2.2 Rural areas

In rural areas, where Filipinas ETCR is located, the situation differs from the global image of Colombia. The rural population has been reduced from 53% (1960) to 19% (2019). In addition, the poverty rate in these areas stands at 40.3%, when the national average is 27.8%. At the same time, the growth rate of the agricultural sector, a key activity in these areas, has been half in comparison of the whole economy. One of the causes of this inequality is the 50-year conflict between the Colombian state and different guerrilla groups. An emerging aggravating factor is also the effects of climate change, due to the forecast of increasingly less intense rainfall due to higher average temperatures [8].

Major part of rural areas is located on the non-interconnected zones ZNI, by its acronym in Spanish) where there are no grid services. These areas correspond to 52% of the country, covering 17 regions, where 96%

of energy supply is generated by diesel generators [9]. It implies high levels of GHG emissions and economic costs.

As it is recollected by [1] the Law 697, issued in 2001, states that the rational and efficient energy use is a matter of social, public and national interest. Under this law, PROURE (Program for Rational and Efficient Energy Use and Non-Conventional Energy Sources) and FAZNI (Financial Support Fund for the Electrification of Non-Interconnected Zones) programs were established. In this way, Distributed Generation (DG) appeared as a technological alternative which allows electricity to be generated as close as possible to the place of consumption. Thus, the use of the hybrid microgrids has been seen as a reliable solution for these areas.

The ETCR is not located on a ZNI. However, areas that are indeed connected to the national grid (National Interconnected System, SIN) present recurrent outages due to grid problems or lack of power capacity (18.6 times per year in Filipinas ETCR with a mean repair time of 0.95 h). Colombia's grid reliability is much lower than the average for the Latin American countries. A study in 2005 showed that the average number of interruptions per subscriber in Colombia was 185.7 and the mean duration of those interruptions was around 66 hours.

Furthermore, the Mining and Energy Planning Unit (UPME, by its abbreviation in Spanish) is promoting the Sustainable Rural Energisation Plans (PERS), whose purpose is to collect and analyse socio-economic and energy information to promote projects that help solve problems in these areas [10]. This mechanism is part of the *Plan energético nacional: Ideario Energético 2050* previously mentioned.

To sum up, although the rural areas of Colombia do not currently have sufficient, secure, equitable and environmentally sustainable energy systems, the government has recently launched a set of strategic plans whose aim is to solve or mitigate this problematic.

2 Literature review

Polygeneration systems consist of the provision of multiple energy services through the combination of several renewable energy sources, such as solar, biomass or wind. This represents a promising new area for the next generation of renewable-based energy systems (RES) [11].

Most of the studies reported in the literature are primarily focused on the various combinations of available renewable energy base systems to provide electricity access to off-grid villages in developing countries. Some examples are given hereafter. Mamaghani et al studied seven off-grid configurations in three small rural communities in Colombia, based on various capacity combinations for diesel generators, solar panels and wind turbine units. Results exposed that, although the entirely renewable and hybrid configurations are the most preferred designs from the environmental perspective, they require a significantly higher investment and operation and maintenance costs. The combination of diesel, solar PVs, and wind turbines was revealed as the most profitable option from an economic perspective for the three considered areas [11].

Similar to the previous article, Islam et al analyzed a set of different energy technologies configurations for electricity generation in the rural unelectrified areas of Bangladesh. The outcomes of the study showed that the per-unit cost of electricity from the optimum off-grid supply configuration is much lower than the diesel-only supply option or the cost of owning a solar home system. As a result, the proposed Polygeneration system would cut CO_2 emissions by 75% compared to the existing methods [12].

Mandal et al investigated the PV/Diesel/Battery system both technically and economically to meet the power demand of a remote village in Bangladesh and reported that the decentralized hybrid energy system is an economically viable option for rural electrification where grid extension is not feasible and reduced CO_2 emission by around 62% in comparison with the kerosene used in a current situation and 67% with the grid-connected system [13]. As a result of the primary analysis from the previous articles, it is concluded that the generation of energy for a rural village with a conventional source through a hybrid system of resources is a promising area with a high probability of generating economic savings and, of course, reducing the environmental impact.

Moreover, the previous two articles made a comparison between the grid and off-grid hybrid energy systems for better understanding. In both cases, the proposed systems were costly than national grid connection, although the operational CO_2 emissions were lower than for the grid-connected electricity (13,720 kg/year and 41,085 kg/year for off-grid and grid-connected systems, respectively).

In contrast to the conventional energy sources, most renewable sources hold high uncertainty due to their intermittent properties under different atmospheric conditions, which, in turn, has a significant impact on the resulting energy production. Therefore, in an effort to overcome the variability of the output of renewable energy systems and to provide a reliable energy supply, which sufficiently meets the demand, Polygeneration systems can be combined with the national electricity grid, non-renewable energy systems, such as diesel generators, or energy storage technologies, like batteries [14].

There are just a few articles reported in the literature where the possibility of connecting renewable energy systems with the grid is studied and none of them takes Colombia as a case study. Prodromidis and Coutelieris compared the techno-economic aspects of an off-grid system and grid-connected hybrid system for different Islands of Greece and observed that grid-connected hybrid systems are economically more competitive, due to the sale of excess electricity generated from renewable energy systems [15]. Rajbongshi et al. also discovered that the cost of energy for a grid-connected hybrid system is lower compared to an off-grid hybrid system. This study also determined the economic distance limit for choosing between off-grid hybrid system and conventional grid extension and concludes that grid extension is preferable to those villages that are within the breakeven distance and, beyond that distance, an off-grid hybrid system is the optimum economic alternative [16].

Various authors have studied the environmental and economic impacts of using different types of batteries and diesel generators in stand-alone and grid-connected RES in remote villages. Eteiba et al. conducted an optimal sizing design of a stand-alone hybrid system consisting of a solar array, biomass genset and battery storage. The authors compared various optimization techniques which selected the capacity of the three types of generators based on minimizing the NPC of the system. Furthermore, several battery technologies were considered for this study. The simulation results indicated that Nickel Iron (Ni-Fe) batteries have the best performance for this type of application. [14].

Nevertheless, there are several barriers against the market uptake of decentralized renewable energy applications in developing countries. One of the main challenges is the lack of access to quality data on the available renewable resource in the areas where its implementation is being studied. Several papers have been found that investigate the biomass energy potential in Colombia. Gonzalez-Salazar et al. applied a bottom-up approach which estimates a theoretical energy potential of 0.744 EJ (Exajoule) and technical potential of 0.059 EJ in 2010 [17]. The great difference between both values is that the latter one is calculated by considering various constraints and excluding the fraction that is already used for energy production. In a different project, the same authors studied the prospective of the theoretical bioenergy potential in Colombia for 2030, which resulted in a 56%-69% larger in 2030 than the one calculated for 2010 [18].

In light of the above, there is not enough work investigating the techno-economic viability of renewable-based energy systems in rural areas of Colombia where the electricity supply is not guaranteed. As a consequence, the main purpose of the present study is to demonstrate the technical feasibility of this type of projects in rural areas of Colombia, as well as investigating the different means of financing the project in order to achieve the best economic profitability.

3 Methodology

The modelling of a hybrid power generation system is not an easy task, and the literature review shows different methodologies that can be applied for this procedure. R. Luna-Rubio et al carried out a literature review on the different methods used during the last decade in the design of this type of systems [19]. This study found that there are four main approaches: probabilistic, analytical, iterative and hybrid. In the case under study, the second one has been selected because, although it cannot deal with the non-linear behavior of system components or the random variability of solar or wind power, it is an effective and simple tool that allows the designer to simulate the performance of several hybrid system configurations. Recently, the analytical method has become the most recurrent, as Polygeneration energy systems are designed using computational models that make it relatively easy to evaluate possible system architectures and component sizes and to choose the optimal model based on multiple performance indicators. Specifically, the indicators that have determined the selection of the final model are economic, the LCOE (USD), and environmental, the renewable fraction (%).

The chosen methodology starts by gathering all the data necessary to, later on, carry out a techno-economic analysis with the aim of finally obtaining an optimized system which meets the constraints, available resources and hypotheses previously stated. This procedure can be divided in five main categories: data gathering, data analysis, model set-up, results analysis and conclusions and future work.

The first phase consists of the gathering of basic information through a bibliographic review of existing energy systems, specifically in rural areas of Colombia and, in general, in other developing countries of the world. Information was taken from scientific reports, authorities, news articles and other various Internet sources. In addition, in order to obtain more detailed information about the location where the project is to be carried out, contact was made through e-mails and meetings with those responsible for the administration of the ETCR. However, it is considered that a better way might be to establish communication with local people and measuring firsthand data in the ETCR itself. This could be a way to describe more effectively the availability of resources or the energy demand. Still, taking into account the existing constraints (distance, economic costs or the SARS-CoV-2 pandemic), the described method is considered the most feasible. All the information gathered is presented in sections 1 and 2.

The second phase of the project is exposed in Section 4 and is based on the analysis and understanding of the information collected in the previous stage. Firstly, the thermal and electrical energy demand of the different consumers of the Filipinas ETCR was estimated and the average daily load curve of the site for a typical day of the year was carried out. Secondly, the current energy supply system was explained, and the problems associated with it were identified. Then, an estimation of the energy resource potential in the area was undertaken.

The third phase focuses on building the model of the Polygeneration energy system using the HOMER Pro software. This work can be found in Section 5. Energy resources, equipment, constraints and other parameters are introduced based on the previous analysis. Then, the program generates different solutions to cover the energy supply that must be assessed. For this purpose, different sensitivity analyses are carried out to show which are the most susceptible factors to modify the original configuration of the system if deviations in the entered data occurred.

Once the final Polygeneration system has been chosen, in Section 6 it is examined from a financial, environmental and social perspective in order to develop a comprehensive sustainability analysis. This aspect is very relevant, taking into account the social importance of such a project for the village. In this way, the strengths and weaknesses of the final configuration are identified.

Finally, the main findings and conclusions are presented, and the future work requiring further development is outlined.

This methodology has two significant aspects that must be remarked. On the one hand, the data gathering process. As mentioned above, this step is meant to be developed through a hybrid way, by a literature review and by contacting ETCR staff. However, it should be noted that this last communication channel, although ideal, did not bear the expected results, as the contact with the ETCR was unexpectedly interrupted and the information provided so far was rather vague. Therefore, most of the information used in the modelling of the system has been extracted from scientific articles.

On the other hand, the justification for the use of HOMER Pro as a simulator. There are a lot of hybrid renewable energy modelling tools to design a small-scale Polygeneration systems as HOMER Pro, H2RES or EnergyPLAN [20]. These tools can have different characteristics and features. HOMER Pro is the most popular software and it presents two important features: an optimization module and the possibility to make sensitivity analysis [21]. This is a key aspect in order to compare different solutions on the basis of technical (e.g., renewable fraction), economic (e.g., LCOE) and environmental (e.g., GHG emissions) criteria or assess several scenarios (e.g. improvement in energy efficiency, increasement of population, a change in a resource cost). Thus, it allows to select a more suitable option in an easier and clearer way [21]. For example, EnergyPLAN and H2RES are not as useful in simulating microgrid energy systems because EnergyPLAN is a deterministic model and does not optimize investment costs, and H2RES does not simulate grid-connection [20]. Furthermore, HOMER Pro has been used in many projects which are included in the literature review, such as in [11] and [14].

Attending to their features, HOMER Pro and the rest of modelling tools do not include social factors as job creation or health [22]. Therefore, it could be difficult to consider the social perspective while the model is being built. This tends to consider them once an optimization process (in the case of HOMER Pro) or a design has been selected based on technical, economic and environmental criteria. For the project, this is not considered a problem, since it is intended to incorporate the social and, in a deeper way, the environmental one, after a technical-economic optimization.

3.1 Limitations

A Polygeneration energy system focuses on electricity and gas supply. Therefore, it does not take into account the energy needed for transport (cars, motorbikes or agricultural machinery) which usually work by diesel or gasoline.

At the same time, not being able to collect information on site is a limitation for different aspects such as the estimation of energy demand (section 4.4), the energy resource (residual biomass, subsection 4.3.3) or the application of different technologies as PV (available space in the ETCR), which is minimized through interviews with the project coordinators in Colombia and information from similar case studies.

As for the HOMER Pro software, there are two main limitations. First of all, there are technologies that cannot be modelled, such as an anaerobic digester, which has been replaced by a ratio of kg of biogas per kg of biomass consumed (section 5). Moreover, only it is possible to introduce one type of biomass (in this project there are residual biomass from agriculture, livestock and household waste). Secondly, the entire gas demand has to be modelled as a boiler with the same efficiency and fuel.

Finally, the cost of equipment and components is an estimation based on different sources as other projects and data sheets (sections 5 and 6).

4 Data analysis

In this section, the information collected through the different methods described in the methodology is presented and analyzed. The daily energy consumption is identified, and the necessary load curves are built. Apart from assessing the demand, it is equally important to assess the resource potential available in the area of the village to choose the best possible combination of technologies that suffices the local energy demand. Therefore, this process was conceived and executed in three stages:

- Village site identification and characterization
- Resource assessment
- Energy demand assessment

4.1 Location description

Filipinas ETCR (Latitude: 6.66, Longitude: -71.22) is located in the municipality of Arauquita, inside the region of Arauca and in the northeast of the Orinoco region of Colombia, which borders with Venezuela. There is an estimated population of 370 people, of which 179 are ex-combatants. The number of dwellings is 87, resulting in around 4 people living per household. Currently, although the ETCR has an allocated area of 153 ha, about 7 ha are built on.

Figure 1. Filipinas ETCR geographical location (source: Google maps)

Although this region does not fall within the IPSE's definition of a ZNI, the electricity supply from the grid is not constant in the village, with multiple network outages occurring on a daily basis.

Climate is characterized by being warm all year round, with a short dry season followed by a wet one with heavy rainfall from April until December (Am - Köppen classification). The average annual temperature in the area is around 25 ºC and total annual rainfall between 2,000 and 2,500 mm [23].

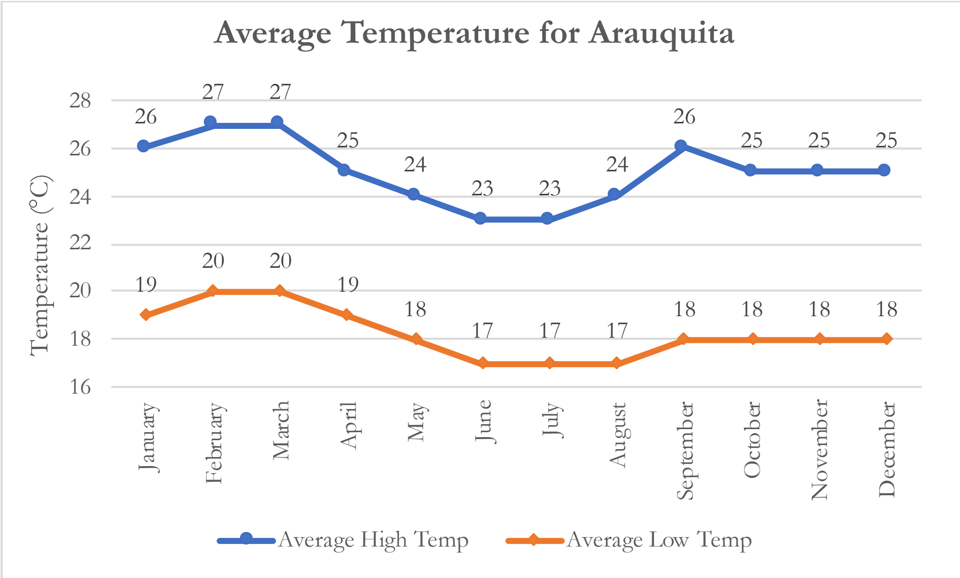


Figure 2. Yearly average high and low temperature

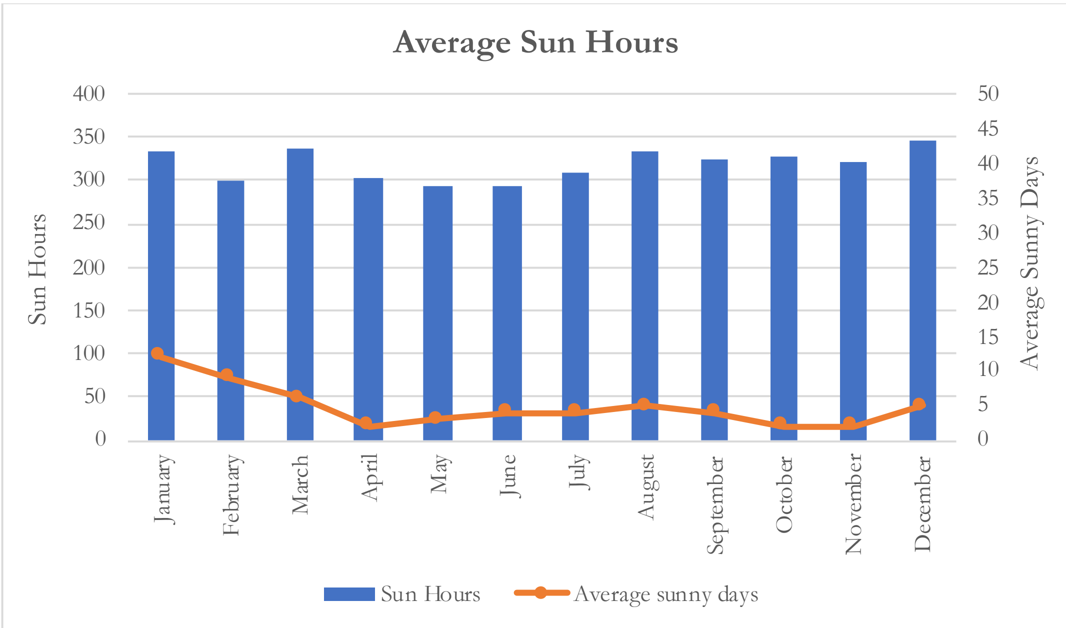


Figure 3. Yearly average sun hours and sunny days

The number of hours of sunshine each month is fairly stable, although a clear decrease is observed during the rainy season, when the percentage of cloudy skies is expected to increase.

The regions' main economic activities are based on agriculture, livestock and hydrocarbon extraction. The community is surrounded mainly by farmland, with plantain, cocoa and various types of cereals being the most widely cultivated crops in the area. Furthermore, there are 19 productive initiatives [24] in order to increase labor market integration in agro-livestock and other sectors.

4.2 Current system description

Currently, Filipinas ETCR's energy supply is unreliable and is mainly based on the consumption of fossil fuels. The ETCR is connected to the national electricity grid in four different nodes and the supply of this energy is carried out by the company ENELAR. This company has 35 years of experience in the energy sector and has the largest market share in the Arauca region. Furthermore, there is no gas supply by grid. Gas is supplied by means of small cylinders of LPG.

It is worth explaining that in Colombia the tariff scheme relies on a socio-economic stratification system through which the charging of public services is regulated, going from levels 1 to 6, being 1 the lowest and 6 the highest. The stratum is assigned by residential unit, which means that it does not depend on the income of those who live in the dwelling but rather on the environment in which it is located, so that the stratum of a dwelling is generally determined by the quality of the neighbourhood or locality where it is located. This system of strata allows that subsidies can be applied to the less favoured social classes and, in contrast, to charge contributions to users in higher strata, so that they can subsidise users in the lower strata. Specifically, Filipinas ETCR belongs to stratum 4 and 'official' type of tariff. Thus, according to Law 142 [25], costumers that belong to this stratum do not benefit from subsidies but neither do they pay excessively to subsidise the energy supply to the lower strata. Consequently, the citizens of this village only pay for the energy they consume.

Despite this, as in most rural areas of Colombia and other South American countries, the continuous supply of electricity through the grid is not guaranteed, and interruptions are frequent all around the year. This situation is intensified during the periods of the year when the fish farm located within the village is at full load and, as a consequence, it has a peak demand for electricity. In order to be able to supply electricity during the hours when this supply is cut off, the ETCR is equipped with various electricity generation back up technologies.

On the one hand, it has a diesel (called as ACPM in Colombia) generator that just supplies electricity to the fishing farm industry and the commercial when blackouts happen. This alternative is frequently used in areas with little or no electricity service mainly due to the low cost and high availability of both fuel and the required technology [9]. However, it has certain drawbacks, since the combustion of petro-diesel is associated with large emissions of polluting gases into the atmosphere and, if working in low load operating mode, the operating efficiency and lifespan of the installation are reduced, and the maintenance costs are increased.

Furthermore, it must be noted that, according to reliable sources, the power of this generator would be sufficient to supply electricity to the entire ETCR during the hours of the blackout. However, at the moment, there is no physical connection between the power supply and all the family units that make up the village and this solution is at the very least environmentally friendly.

On the other hand, the ETCR multipurpose room has a pv system that also starts up when the electricity supply is cut. Unlike the previous one, this can only be used during sunny hours since, for the moment, no energy storage system has been installed. This decision was taken on the basis that, as specified in the following section, this room is only used during the day. Moreover, it is worth mentioning that this installation has not been built directly on the roof of the building, but on a pipe structure placed over it, since the tiles with which the roof surface has been covered are not suitable for the weather conditions of Arauquita and, when strong storms occur, part of the structure breaks.

According to thermal energy production, the ETCR does not have Sanitary Hot Water (SHW) nor heating demand, since the temperature during the whole year is rather constant and close to 25.5°C.

Nevertheless, as far as energy consumption for cooking is concerned, LPG cylinders are currently used in order to supply this residential thermal demand, as well as wood.

4.3 Available energy resources

Colombia stands out for its great potential for renewable energy sources as stated in the document *Integración de las energías renovables no convencionales en Colombia* [26]. Their use is essential to the sustainable development of rural areas where the connection to the grid is very weak or simply non-existent. The new energy plan expects, as reflected in the *Plan de Expansión de Referencia 2014-2028* [10], an increasement of FNCE (Non-Conventional Energy Sources) in rural areas. It refers to solar, wind, biomass (cogeneration, production of electricity and heat) and geothermal energies. These together with hydropower (given its importance and tradition in the Colombian energy mix) are discussed in this section.

4.3.1 Solar

Colombia is a country crossed by the equator. This gives it a privileged location in terms of sunshine hours and solar irradiation. In Arauquita the direct normal irradiation (DNI) is 1,344 kWh/m^2. It means heaving a specific PV output value above the world average, 1,490 kWh/kWp (for a panel with 11% efficiency and tracking with one axis) [27].

For electric generation, solar PV is one of the most mature renewable energy sources worldwide and the second most implemented [28]. In Colombia is not a significant source of energy generation (<1%) [4]. Nevertheless, as set out in [29], since 2017 it has been undergone a constant increasement of its installed capacity due to the auctions carried out by the Colombian government. Moreover, it is expected to increase a 34% in the period 2021-2024. Therefore, PV costs (CapEx), which are decreasing since 2017, are expected to continue falling, from more than 2.00 USD/W (2017) to less than 0.8 USD/W (2028)[29]. Now, it is the cheapest renewable energy technology in Colombia [30].

4.3.2 Wind

Wind power is the most renewable energy implemented worldwide and it is promising in Latin America region [26]. Nevertheless, average surface wind speed in Arauquita area is 1.5 – 2.0 m/s [31]. Therefore, the use of wind turbines is not technically feasible because it is needed values higher than 3 – 4 m/s.

4.3.3 Biomass

In Colombian rural areas, there is plentiful livestock and agricultural residues that can be used for energy generation purposes. According to [17], in Colombia biomass is the second largest renewable energy resource after large hydroelectric energy. However, estimating current biomass energetic potential is one of the critical challenges, especially in developing ones where availability and quality of data is limited.

The UPME developed the *Atlas del Potencial Energético de la Biomasa Residual en Colombia* [32], using information from 2006-2008 to estimate the existing energy potential of residual biomass from the most representative products of the agricultural and livestock sectors. Four other studies on biomass can be found, with different methodologies and scopes: AENE [33], Escalante et al. [34], Arias et al. [35] and Kline et al. [36]. Except for AENE, from 2003, the rest deal with data from 2007-2010. A later study by Miguel Angel Gonzalez-Salazar et al. [17] developed a methodology for estimating the energy potential of biomass and applied it to the case of Colombia, resulting in similar data to UPME's atlas, despite being evaluated 6 years later (in 2014). Therefore, biomass potential is carried out following the atlas developed by UPME. In addition, it recollects departmental and not national data, so it is expected to provide a more detailed information.

The following subsections focus on taking advantage of the information collected by the UPME about agricultural, livestock and urban organic solid residues (household waste) in order to estimate the biomass potential in Filipinas ETCR. Nevertheless, some data regarding agro-livestock production or land use are recollected from more recent and accurate sources as DENA (in Spanish, *Departamento Administrativo*

Nacional de Estadística) and ICA (in Spanish, *Instituto Colombiano Agropecuario*). In Annex I (see 10) are a detailed recollection of gathered data and a more detailed calculation procedure for agriculture and livestock residues.

Currently, wood waste is supposed to be used directly as fuel for cooking purposes in the rural areas of Arauquita [37]. For Filipinas ETCR, it is estimated that wood waste covers the 33% of heat demand. Despite it, wood is not considered in this work due to two main reasons. Firstly, it is preferred to use agricultural and livestock residues because they could generate incomes to the farmers and breeders of the region. Secondly, the UPME has not considered wood at its atlas and it is complex to correctly estimate the potential of the wood waste.

The analysis is carried out for the whole territory of Arauquita. Then, the results were narrowed down considering the size of the Filipinas ETCR. It is supposed to be 153 ha, which includes both, the 7 ha of the current built area and the farming land surrounding it.

In Table 1 the estimated biomass by each source (agricultural, livestock and household waste) and its total amount for the ETCR are summarised. The total value is almost 1.90 ton/day.

Table 1. Estimated biomass potential for the Filipinas ETCR total and by source.

	Biomass potential (ton/day)	Biomass potential (%)
Agricultural	0.60	31.7
Livestock	1.25	66.2
Household waste	0.04	2.1
TOTAL	1.89	100

4.3.3.1 Agricultural residues

In the UPME's atlas [32] several crops are considered. Maize and rice as transitional crops and bananas, coffee, sugar cane, panela cane, oil palm and plantain as permanent crops. According to the most recent EVA [13] (in English, Municipal Agricultural Assessments of 2019), rice, maize and plantain are the most commonly sown in Arauquita. Therefore, it is possible to estimate the residual agricultural biomass of these three crops, which account for the 85.7% of the production and 49.7% of the sown area of the municipality. It is essential to highlight the importance of plantain, which alone accounts for 81.3% of the total production and 39.3% of the area sown in Arauquita.

Moreover, according to the data gathered in [32], it is possible to obtain the quantity of residues per production or sown area for the Department of Arauca. Thus, Table 2 shows plantain, maize and rice sown area, production, residues (UPME's atlas) and resulting ratios.

Table 2. Data about Arauca's crops recollected in residual biomass atlas from UPME and ratios of quantity of residues per production and sown area

Crop	Plantain	Rice	Maize
Sown area (ha)	9,399.00	3,636.00	16,765.00
Production (ton)	73,653.00	14,190.00	28,634.00
Residues (ton)	452,966.00	36,185.00	40,517.00
Residues/production (ton/ton)	6.15	2.55	1.41
Residues/sown area (ton/ha)	48.19	9.95	2.42

Since it is not expected any changes in the relation between sown area and residues (the resulting ratios), it is possible to calculate for a more recent period (2014-2017) [16] the annual average quantity of residues for Arauquita (Table 3).

Table 3. Average area sown, production and residues of plantain, maize and rice in Arauquita for period 2014 to 2017

	Plantain	Maize	Rice	Total
Average A. sown (ha)	4,855.50	3,311.50	2,650.75	10.817,75
Average Production (ton)	63,881.00	4,922.25	11,276.50	80.079,75
Average Q. residues (ton)	233,986.55	8,013.83	26,374.96	268.375,34

Consequently, considering only Arauquita's rice, maize and plantain the quantity of biomass is estimated as 268,375 ton/year or 735 ton/day.

For Filipinas ETCR, considering only its own area and the same crop distribution as the rest of Arauquita, it is possible to estimate the agricultural residues of biomass. The total sown area in Arauquita is 17,645 ha [38], but 10,817.75 ha are selected if only UPME crops are considered. Thus, if average production of plantain, maize and rice is 80,080 ton/year (Table 3), the ratio *production/sown area* is 15.21 ton/ha. Then, considering an agricultural area of 3.6% (dividing Arauquita sown area of rice, maize and plantain by its total area) for ETCR (in total 153 ha), the estimated agricultural biomass potential is 602 kg/day (0.60 ton/day).

4.3.3.2 Livestock residues

The UPME's atlas includes the potential of livestock residues: porcine, bovine and poultry manure. As in the previous case, the atlas information is used to know the residues production rate. The information recollected by the ICA [39] is used to know the most recent data about livestock in Arauquita.

In this case, the significant ratio given by the atlas is the manure production rate. The ratio used for each animal results from the data for the whole Colombia because at the time of the atlas creation no poultry population was considered in the Department of Arauca. In Table 4 is shown the main information recollected and the results obtained.

Table 4. Head of livestock per year, manure production rate and estimated quantity of manure per year for poultry, pig and bovine livestock in Arauquita.

	Category	Livestock (heads/year)	Manure production rate (kg/head of livestock)	Manure (kg/year)
Poultry	Fattening	9,670	25.55	247,069
	Laying	14,237	38.33	545,704
Porcine	Suckling piglets	222	102.20	22,688
	Pre-feeding	501	445.30	223,095
	Breeder	226	2,051.30	463,594
	Rising	841	799.35	672,253
	Lactating and pregnant female	947	2,551.98	2,416,724
Bovine	< 1 year	49,690	1,460.00	72,547,400
	1 - 2 years	47,000	3,285.00	154,395,000
	2 - 3 years	42,452	5,110.00	216,929,720
	> 3 years	71,637	6,570.00	470,655,090

Therefore, the quantity of manure which could be used as biomass in the municipality of Arauquita is estimated as 919,118 ton/year or 2,518 ton/day.

Considering the same percentage of livestock area as in Arauquita [40], 50.5%, it is assigned to the ETCR a manure production (livestock residues) of 1,252 kg/day (1.25 ton/day).

4.3.3.3 Household waste

UPME's atlas does not recollect household waste or organic urban solid residues (OUSR) values from rural areas. However, it is known the quantity of solid urban residues produced in the municipality of Arauquita and the ratio of OUSR in other municipalities of Arauca's department, 50 – 58% [35]. Taking a conservative value of 50%, the quantity of OUSR in Arauquita can be estimated to 1,382 ton/year or 3.78 ton/day.

In the specific case of the ETCR, considering the same production of OUSR per capita, the value results in 35 kg/day (0.035 ton/day).

4.3.4 Hydropower

Hydropower is one of the most developed renewable energies in Colombia (around 15% of energy supply [4]), but mainly on a large scale (projects with a capacity of more than 10 MW) [30]. The municipality of Arauquita has a river bordering with Venezuela. However, the ETCR is located further inland. This, together with higher installation costs of hydropower plants than other technologies as PV or biomass [30], leads to the rejection of this option.

4.3.5 Geothermal

Colombia is not noted for its geothermal potential, estimated at between 1 and 2 GW [41]. The technology is not well established, with only two potential projects under development and still at the stage of analyzing deeply the country's potential [42]. Moreover, Arauca's region does not seems promising [43]. Hence, geothermal is not considered as a feasible option.

4.4 Energy demand composition

In this section, a calculation of the energy demand from both thermal and electrical sources is carried out. This step is necessary to prepare the format of the collected data prior to its introduction into the simulator program.

4.4.1 Electricity demand

The electricity demand of the Filipinas ETCR has been calculated on the basis of data obtained through several interviews with administrative staff of the site, as well as estimates of values taken from scientific articles which investigate related projects. For this purpose, a bottom-up approach has been used, as the total demand of the ETCR has been obtained once the demand of each of the sectors identified within the ETCR was calculated. In the following subsections a detailed explanation of the calculation of the electricity demand for each of the sectors is given.

Figure 4 shows the average daily load curve of the whole village for a typical day during the weekdays and weekends. This graph has been obtained as a result of entering all the electricity demand data from each of the sectors into HOMER Pro. Likewise, the average daily demand is 670 kWh/day, the average load 28 kW and the peak load is reached on weekdays and in the evening hours with 46 kW, resulting in a load factor of 0.61. This factor shows the efficiency of energy use, as it is calculated as the ratio between the average daily power required in the system and the peak power reached during the same period. The closer this value is to 1, the smoother the peaks reached throughout the day and, hence, the better the efficiency of electricity consumption.

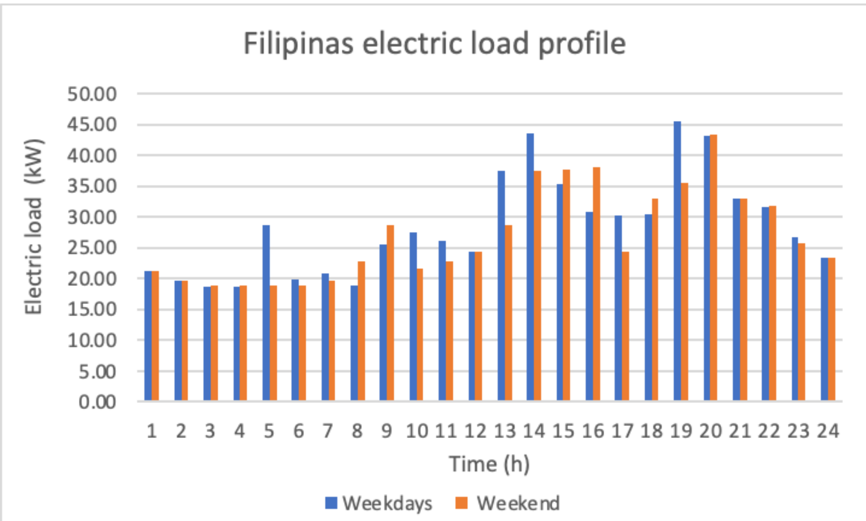


Figure 4. Total Filipinas ETCR daily electricity demand curve for weekdays and weekends

4.4.1.1 Residential sector

The residential demand has been built based on specific data obtained from two scientific reports selected after a literature review was developed. Once the load curves were plotted, a verification of the results obtained was carried out with the scarce, but first-hand, information extracted from the interviews with the ETCR management agents during the first step of the project.

On the one hand, the per-unit power values of the basic equipment that can be found in a typical rural Colombian house, as well as the electricity consumption habits of their inhabitants, was extracted from an article based on the proposal of a hybrid energy generation solution for an isolated community in the Colombian Caribbean department [44]. The previously mentioned project makes a distinction between typical weekday and weekend consumption habits, which has been used to build the daily load profile graph of the ETCR displayed in Figure 5. However, due to the great stability of the temperature in the region of study of Colombia throughout the year, it has not been considered necessary to include differences in energy consumption between each month, beyond those derived from the difference in the number of days between each of them.

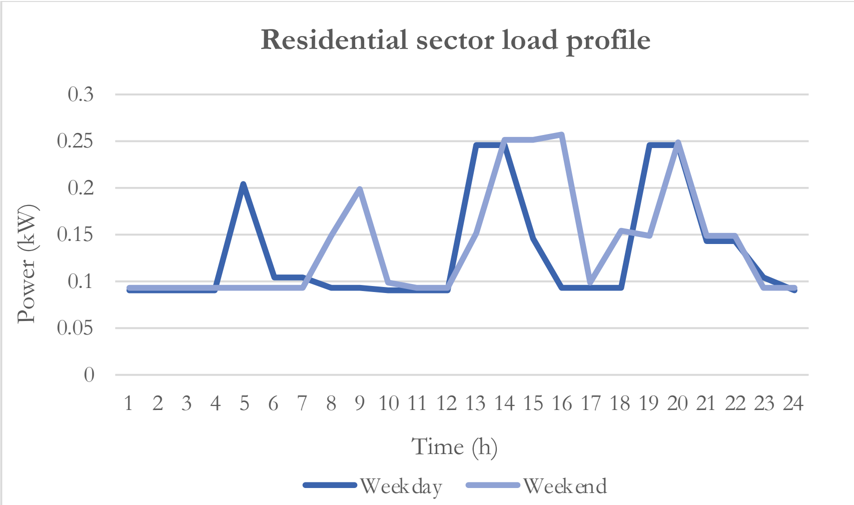


Figure 5. Weekday and weekend residential daily electricity demand curve

On the other hand, a study carried out in 2017 was used to determine specific energy consumption values in rural areas of the municipalities of Arauca, including Arauquita [37]. This information collection process was carried out first-hand through surveys, providing reliability to the data collected. Thus, this article has values of the average annual electricity consumption of a rural residence in the municipality of Arauquita, as well as of the consumption percentages of the four main types of energy end-use in the residences, which are lighting, refrigeration, environment adaptation and electronic equipment (Shown in Figure 6).

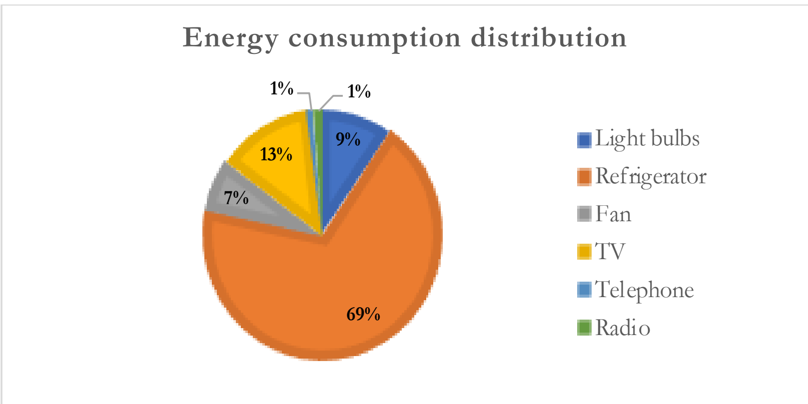


Figure 6. Energy uses in rural households in Arauquita

Compiling the information extracted from the two aforementioned articles, the typical load curves for a weekday and weekend for the residential sector has been elaborated, as well as the average monthly consumption of this sector within the ETCR.

4.4.1.2 Common areas

Filipinas ETCR has several common rooms which have different uses and help the professional and educational development of the villagers. The following services are identified: a nursery room, a kindergarten room, an internet room, a library, six adult classrooms and a multipurpose room. In this case, the energy consumption values of the equipment available in each of the areas mentioned above have also been extracted from the same reference as before [44]. Nevertheless, the information on the opening hours, as well as the existing equipment in these spaces has been obtained from the interviews carried out in the previous stage.

All of these rooms are used only during weekdays, except one of the adults' classrooms which is sporadically used on Saturdays as a conference room. However, for the sake of simplicity of the model, this weekend consumption has been neglected.

Moreover, the monthly electricity consumption for the common areas has been calculated taking into consideration the national bank holidays for the year 2020 in Colombia [45]. The adult's classroom and the kindergarten will be closed during the following days.

- From 6th-19th of January
- From 6th-12th of April
- From 15th of June to 5th of July
- From 5th-11th of October
- From 30th of November to 3rd of January

After summing up each load profile for each type of room, it can be concluded that the daily energy consumption for the common rooms has one peak during the morning and one during the afternoon and that this demand is nearly zero during the nights and during the lunch time, except for the consumption due to the standby power.

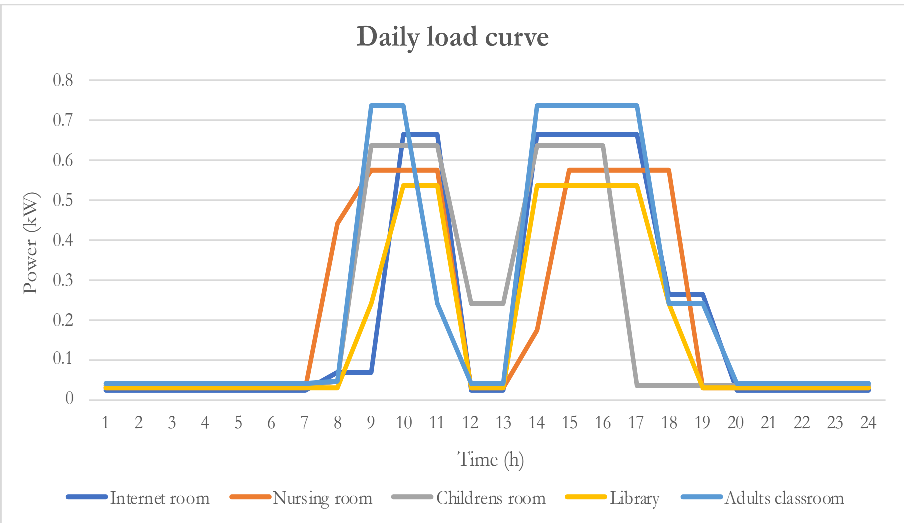


Figure 7. Common rooms daily electricity demand curve

4.4.1.3 Water treatment plants

In the ETCR Filipinas there are two water treatment plants, one for wastewater and the other for drinking water generation. Both are energy-intensive industries, and, in most cases, are the largest consumers of energy within local city and community government loads. Energy requirements in water treatment are mainly for pumping, treatments, space heating, and sludge heating and disposal [46].

On the one hand, the WWTP is based on collecting the grey and black residential water, treating it to achieve acceptable permit standards, and discharging this wastewater into the natural environment. Due to the lack of specific data for the plant located in the site of study, the electric demand was calculated following an estimation process which started from the information extracted after a literature review was carried out. First of all, it is considered that one person generates 4 m3/month of wastewater. Moreover, since the WWTP is only used by the ETCR, the specific energy consumption value used in the calculations is the one characteristic for small plants, around 2.1 kWh/m3. Knowing the number of inhabitants in the ETCR, the estimated monthly electricity demand of the wastewater treatment plant is 3,152 kWh. Furthermore, the typical daily load profile has been obtained from a scientific paper in which a WWTP in Romania is optimized [47]. The technical data of this plant has been used since the capacity of both plants and the processes to which the water flow is subjected are relatively similar. When looking at Figure 8 it is observed that the highest consumption peaks occur during the afternoon and at night.

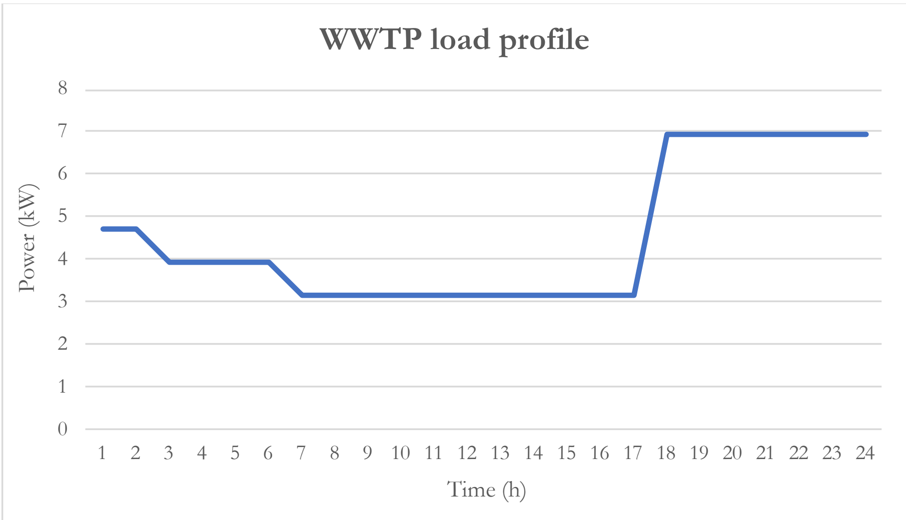


Figure 8. WWTP daily electricity demand curve

On the other hand, a drinking water plant has been recently built in the ETCR vicinities to supply this resource to the inhabitants of the area. In the same way as the plant described above, its energy consumption is also important, although slightly lower, due to its greater efficiency. Furthermore, in this case we also do not have access to the basic sizing data of the plant. For this reason, a process of estimating the demand for electricity identical to the previous one has been carried out. Starting with an estimate of the demand for drinking water per subscriber and per month (15.4 m3) and considering that the number of subscribers in the ETCR is equal to the number of houses, the monthly demand for drinking water is obtained. Finally, with this data and the specific electricity consumption of a typical DWP (0.14 kWh/m3), the monthly electricity consumption can be calculated, resulting in 188 kWh.

While residential electricity demand follows an electrical distribution, which oscillates between day and night, using more electricity during the day and less at night, the electricity power profile for a DWP on a day and a week is relatively flat and stable [47], with an average hourly load of 260 W. In order to simulate de daily power demand of the plant, the random variability tool from HOMER Pro was used. Realistically, the size and shape of the load profile varies from day to day. On the one hand, adding the day-to-day variability to the input data changes each day's load profile by a random amount, so the load retains the same shape for each day, but is scaled upward or downward. On the other hand, introducing a time-step-to-time-step variability changes the shape of the load profile without affecting its size. If combined, a realistic-looking load data can be created. In our case of study, a 16.6% of day-to-day and 8.21% of time-step-to-time-step random variabilities are considered.

4.4.1.4 Public lighting

The electric demand for public lighting was calculated based on an estimation of the number of streetlights in the ETCR (31 units) and their unit power (150 W). This estimation was done based on the previously mentioned project [44]. It is considered that they will be on from 7:00 pm to 8:00 am. Since the number of sun hours throughout the year is quite stable, the electric demand per month is considered to be equal. The daily load profile for public lighting is shown in Figure 9.

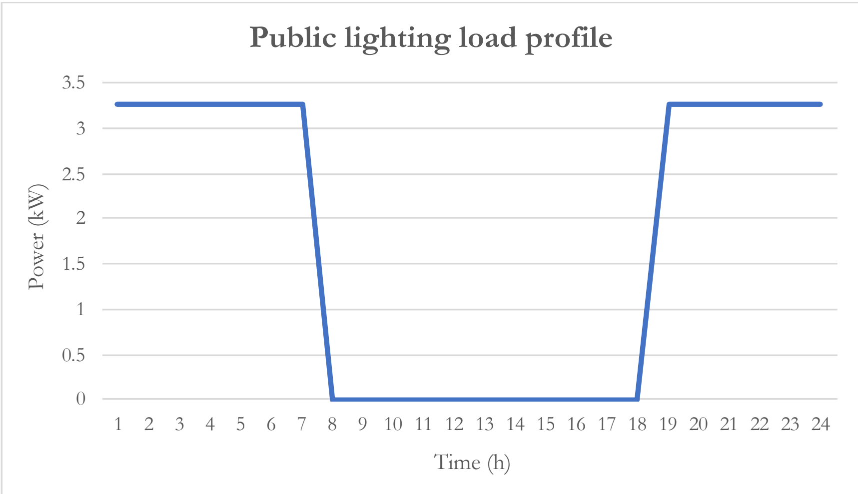


Figure 9. Public lighting daily electricity demand curve

4.4.1.5 Commercial sector

Filipinas ETCR has a commercial area were four supermarkets, a hairdresser, two restaurants, two clothing stores and two stationery shops can be found. Information could not be obtained on the type of equipment used in each of the businesses mentioned above. Although these establishments are not characterised as electro-intensive, the possible presence of large refrigerators for the supermarkets or multiple hairdryers in the hairdressing salon has led to the decision not to dismiss the demand for this sector.

It is worth mentioning that the opening hours of the establishments have been obtained first-hand from the meetings held with the ETCR representatives. Nevertheless, the monthly electricity demand for each of the businesses has been calculated with the help of Annex 1 of Reference [48] in which many businesses in Colombia belonging to the tertiary sector are inventoried. For this purpose, this data has only been collected from those establishments located in the north-eastern part of the country (where Arauquita is also located) and with a surface area similar to those of the ETCR, in all cases of micro size.

In Figure 10, the electric load profile of the commercial sector is determined. The daily distribution of the electricity consumption previously calculated was carried out based on the typical distribution of the Colombian commercial sector extracted from Reference [49]. As shown in the graph, the peak consumption hours occur from 10:00 am to 7:00 pm, when the establishments are opened.

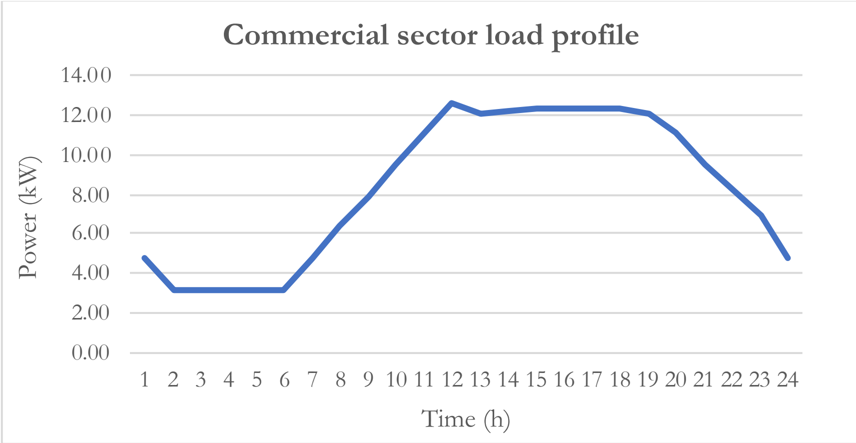


Figure 10. Commercial sector daily electricity demand curve

4.4.1.6 Agriculture and livestock sector

Agro-livestock is a key sector in Arauquita's economy. The specific electrical consumption is estimated as 0.50 kWh/ton for agriculture and 20 kWh/ton for livestock sector [50]. This consumption is considered to come from lightning and electronic equipment.

According to the recollected data from Filipinas ETCR about the agro-livestock sector (land use, quantity and type of production) and from Reference [50], daily electricity consumption is estimated as 34 kWh/day in agriculture and 19 kWh/day in livestock. In Annex III (see section 12) the calculations which lead to the heat and electricity demand calculated for the agro-livestock sector are developed.

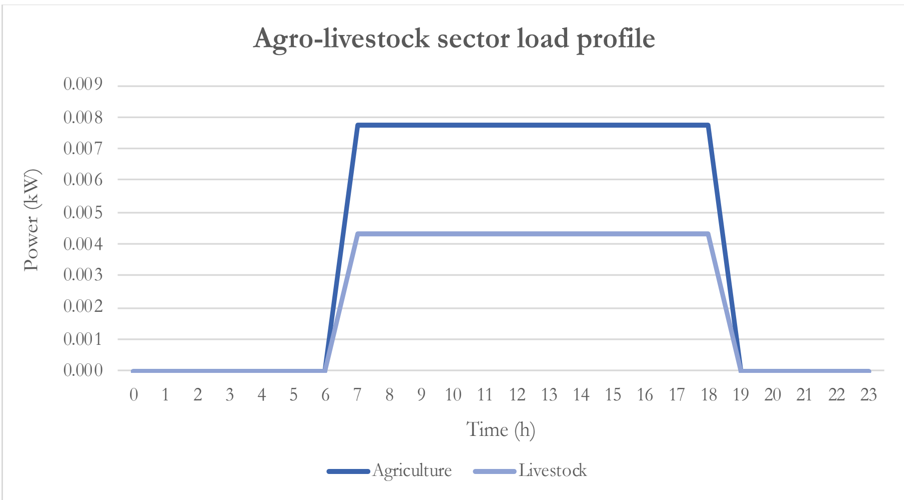


Figure 11. Agriculture and livestock daily electricity demand curve

4.4.2 Heat demand

In Arauquita, heat demand is mainly focused on cooking. As it is mentioned in section 4.2, this ETCR does not have a gas supply grid system [37]. The consumption of LPG in small cylinders of 40 lb or less [51] is a common solution. Consequently, the heat demand for the village can be calculated by knowing the fuel consumption per capita which is shown in the bills. According to Reference [37], it is estimated that 67% of users in rural areas of Arauquita use LPG. The rest of the heat demand is supplied by wood (28%) or directly do not have supply (5%). Since no information has been reported about thermal demand shortages, it was assumed that 67% of ETCR inhabitants use LPG and 33% wood waste. This is the starting point for, by estimating LPG consumption and its sectorial distribution (residential, commercial and agro-livestock) based on UPME's statistics [46], estimating the heat demand in the ETCR. Then, it is estimated the fuelwood consumption.

It has been argued that cooking is the main heat demander. However, other smaller demands are expected for some agro-livestock purposes as direct heating on poultry farms or drying crops. Considering UPME statistics [44], it is estimated a specific consumption of 5.4 kWh/ton for agriculture and 53.2 kWh/ton for livestock. According to ETCR data, these values imply 340 kWh/year and 1,850 kWh/year, respectively. In Annex III (see section 12) the calculations that lead to the heat and electricity demand in agro-livestock sector are developed.

It is essential to remark that LPG is not the only fossil fuel which is expected to be used in the ETCR. For example, ACPM or kerosene are fossil fuels whose presence in Arauquita is rather common [37]. Nevertheless, it is supposed to be used for transport and other agro-livestock purposes (prime mover and vehicles) which are not going to be studied because there are not integrated into the Polygeneration system, which it is focused on stationary purposes.

About the LPG daily consumption, the Department of Arauca consumed around 200 (b/d) (barrels per day) in one year. It is estimated as 17% was consumed in rural areas (34 b/d) [46]. Considering a 37.7% [52] of rural population and the same consumption per capita in these areas, the estimated consumption of the ETCR would be 14 l/day. It means 107 kWh/day (considering LHV = 13.99 kWh/kg and density = 0.54 kg/l [46]). Taking an efficiency of 45% [47], it is 48.3 kWh/day.

Therefore, if agriculture is 0.4 kWh/day and livestock 5.1 kWh/day, residential consumption is 42.8 kWh/day. These results are similar to the statistics recollected by the UPME in [53] which indicates a more than 80% of gas consumption in residential and commercial (the ETCR has bar and restaurant with cooking demand) purposes.

In addition, the quantity of LPG consumption per user and month is estimated as 4.1 kg. Comparing to the livelihood consumption (limit for subsidies) calculated by the UPME [46], which is 14.6 kg, Filipinas ETCR gas consumption per user and month represents a 28% of it. There could be different reasons for this large difference, although the most likely is that there is no demand for DHW or space heating in the ETCR at this site.

It is said that LPG covers 67% of heat demand (48.3 kWh/day). It supposed an average LPG consumption of 7.7 kg/day and a global heat demand of 72.1 kWh/day. Thus, fuelwood consumption could be estimated as 15.8 kg/day, considering a ratio of 400 kg wood/43 kg LPG [54].

Table 5. Heat demand and fuel consumption by type of fuel

Fuel	Covered heat demand (%)	Covered heat demand (kWh/day)	Consumption (kg/day)
LPG	67	48.3	7.7
Wood	33	23.8	15.8

To conclude, according to the received data from the contact of the ETCR, the following demand time periods were considered: 11 – 13 h and 18 – 20h for residential demand (cooking) and 7 – 20h for agriculture and livestock. Therefore, the daily heat demand curve can be built.

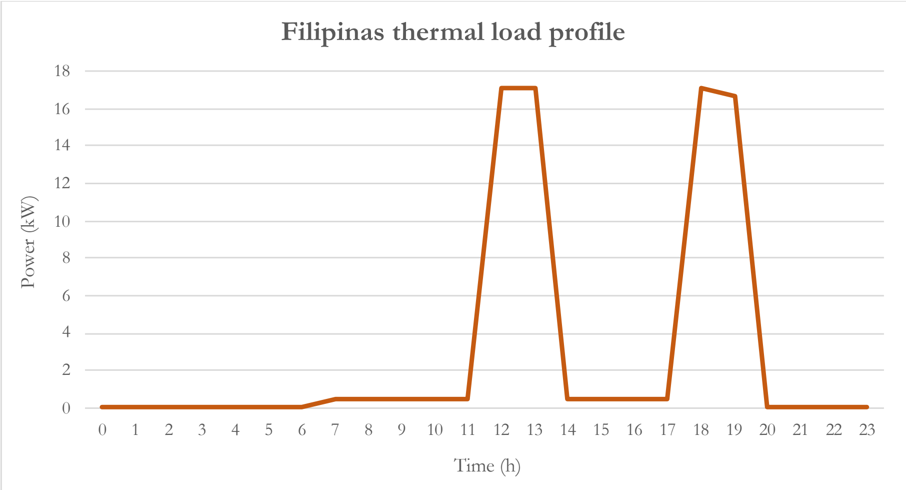


Figure 12. Filipinas ETCR daily thermal demand curve

5 Modeling in HOMER Pro

Once all the necessary data have been collected and formatted, they are entered into their corresponding sections of the HOMER Pro program. This section also explains the selection process of the equipment that can potentially make up the Polygeneration system.

5.1 Current energy system

To model the power generation system currently running in the Filipinas ETCR, the components mentioned in section 4.2 were introduced in the software HOMER Pro.

On the one hand, Colombia's national grid operates at 110 V and 60 Hz. The current electricity price is about 0.167 USD/kWh, without a cost difference depending on the period in which it is consumed (price obtained from Filipinas ETCR electricity bills). No electricity sales are produced for the moment. The power grid in Colombia still experiences frequent interruptions and this village is not an exception to this problem. According to the project's local correspondents, the area experiences roughly around 20 outages per year, with a mean repair time duration of 1 h.

On the other hand, due to the lack of information regarding the capacity and technical characteristics of the solar system installed at the ETCR, it has been estimated based on the electricity demand data it supplies. The peak power of the internet room on a typical day can reach up to 670 W. Therefore, three monocrystalline solar panels from the company CanadianSolar with a nominal capacity of 285 W each and an efficiency of 17.41% were chosen. They are considered to be connected in series and lack a solar tracking system. In addition, a Schneider converter with a rated output of 3 kW and an efficiency of 90% has been chosen to cover the needs of the solar system. Finally, a ACPM power plant (25 kW) has been modelled to represent the outages.

According to the heat demand, since HOMER Pro only allows to simulate one boiler per system, only the 67% of the heat demand, the part which is covered by LPG, was considered, being this the main fuel (the other fuel is wood waste and its cost is supposed to be zero). LPG is characterized by a LHV of 46.3 MJ/kg and a density of 510 kg/m^3. Wood will be estimated as the same proportion than in section 0. Then, it is modelled an LPG-fired boiler, with an efficiency of 45% and a fuel price of 4.87 USD/l (ETCR staffs' information).

As a result of the model, the grid system supplies 99.55% (299,896 kWh/year) of the village's electric demand. Only when power outages occur during the hours when there is solar resource, the photovoltaic system comes into operation (0.37%, 1,105 kWh/year), which only supplies for the internet room in the communal areas. As a consequence, about 0.1% (472 kWh/year) of the total annual demand of the ETCR remains unmet by the current electricity supply system.

Heat demand is covered by 5,980 l/year (3,050 kg/year) of LPG and wood 6,250 kg/year.

The operating costs simulated by HOMER Pro are around 79,000 USD/year, with 63.1% of this value coming from the grid electricity consumption costs, 36.7% from the LPG purchase cost and the remaining 0.2% from the O&M cost of the solar system.

Finally, the renewable fraction is around 0.37%. Therefore, the annual emissions of CO_2 for the electricity generation are 114.3 tons CO_2/year (0.367 tons CO_2/MWh [55]). For the thermal demand, LPG produces 8.5 tons CO_2/year and wood 5.8 tons CO_2/year (which are not considered to contribute to global warming since these carbon emissions were carbon previously captured, so it is a neutral carbon cycle). As a result, the annual emissions produced by both types of energy are 128.6 tones CO_2/year.

5.2 Polygeneration energy system

Once all the information presented in section 4 was gathered, the data was entered in HOMER Pro. According to the available resources and the demand for both types of energy, the next step is based on selecting the equipment and its dimensions that will potentially compose the Polygeneration system. Preliminarily, this system will be formed by a PV system with a converter/inverter and a battery bank, a biogas plant (with a bio-genset) and the power grid (see Figure 13).

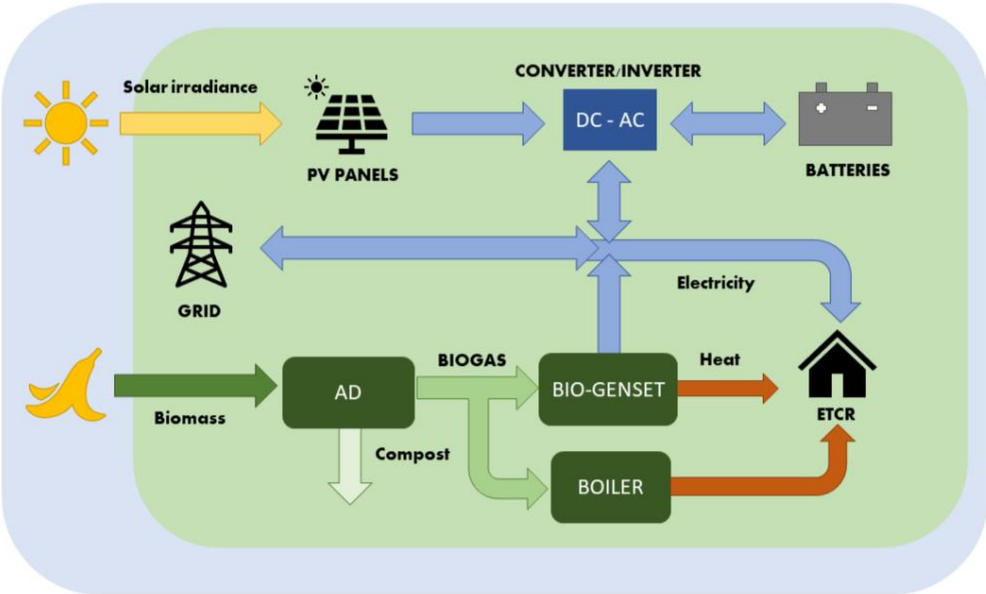


Figure 13. Diagram of the preliminary Polygeneration system

The aim is to take advantage of the large existing solar resource and residual biomass. PV system is composed by the modules which converts the solar irradiance into DC current. Then, the converter/inverter adapts it to AC current. Finally, the battery bank could give flexibility to the system. The proposed biomass system, a biogas plant, is divided into two sub-systems: one to convert residues (biomass) into biogas, which can be used directly for cooking (anaerobic co-digester) and one which turns biogas into electricity and heat (bio-genset). For the grid, it is expected to purchase and sell electricity when it is convenient.

For modelling in HOMER Pro, there are some constraints introduced. First of all, a minimum renewable fraction of the 60%, although the software does not consider the energy produced by the bio-genset for this calculation. Secondly, a project life of 25 years. Thirdly, a discount rate of 8% and an inflation rate of 2%.

5.2.1 Polygeneration system components

5.2.1.1 Power grid

The data entered in HOMER Pro for this component are the same as those explained in the previous section. The only new addition is the possibility to sell surplus electricity from the system at a price of 0.07 USD/kWh. This price has been obtained taking into account a new regulation recently approved in Colombia and based on Law 1715 of 2014 for which self-generators with installed capacity greater than 100 kW and using renewable energy sources are reimbursed approximately 40% of the price of the cost of the energy service for each kilowatt delivered to the grid [56].

5.2.1.2 Biomass-to-biogas system

Two main processes can be followed for the production of biogas from biomass resources: thermal and biochemical processes. Biomass obtained from household organic waste, livestock and plantain residues are more suitable for biochemical processes (fermentation and anaerobic digestion), due to the high level of humidity (> 50%) they present, instead of thermal processes, such as pyrolysis, gasification and direct combustion [32].

Anaerobic digestion allows to generate a gas called biogas. It is mostly composed by methane, CH_4, (50 - 70%) and carbon dioxide, CO_2. It can be used to generate electricity, heat and compost, three significant outcomes for the Filipinas ETCR. Furthermore, there are other multiple general advantages such as the reduction of GHG emissions and resources depletion, increase of job opportunities, valorization of waste and improvement of air quality [57][58].

According to IRENA [21], there are different technologies of small-scale biogas plants. IRENA focuses on three: balloon or bag digester, floating drum plant and fixed dome plant. For this project, it is selected the balloon digester technology due to its widespread presence in Latin America and its reduced cost. Reference has been found on its good performance in other locations in Colombia [59]. This technology is characterized by its digester.

The digester is the place where the feedstock, a mix of waste (biomass) and water are introduced. It has a total volume divided into two parts, biogas and slurry (a mixed of feedstock of different days). A balloon digester (Figure 14) [60] is a large strong plastic bag which is connected to two drainpipes at each extreme where the slurry remains at the bottom and the biogas at the top. The pipes allow to introduce feedstocks (inlet pipe) and remove slurry (slurry outlet). The bag is situated on a trench to protect itself. Also, it is slightly deeper at the slurry to avoid it to get out. There is a third pipe at the top to obtain the biogas (gas outlet pipe).

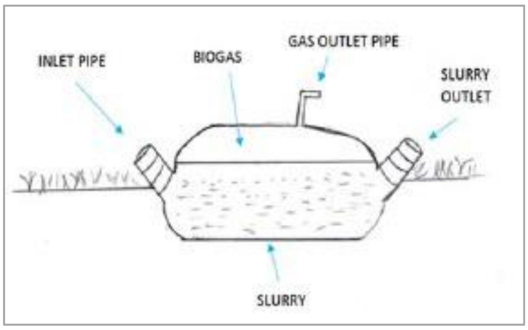


Figure 14. Diagram of a balloon or bag digester (source: IRENA)

Biogas production depends on several parameters: plant capacity, total feedstock volume, feedstock properties (total solid content and volatile solid content), feedstock retention time and temperature [60]. IRENA has developed a formula to obtain the plant capacity by the other parameters.

The formula is:

$$G = \frac{Y \times V_d \times S}{1000}$$

Where:

- G: biogas production (m^3/day).
- Y: yield factor, parameter which relates temperature and feedstock retention time (-).

- V_d: digester volume (m^3).
- S: initial solid concentration (kg/m^3).

According to the results obtained in section 4.3.3, the maximum biogas production can be estimated considering only the ETCR potential (153 ha) and following the formula of IRENA.

As in the ETCR there are different residues, it is essential to talk about co-digestion. This process consists of the mix of different types of feedstocks. Different researchers have achieved additional advantages through this process. Nevertheless, further research efforts are necessary to enhance its knowledge by kinetic models and microbiota studies [49]. According to Reference [50], the co-digestion of banana waste and livestock residues like porcine or bovine manure could turn into an increase of biogas production and higher volatiles solids proportion. Also, in Reference [51] it is reached a similar conclusion for co-digestion in general, a higher digester performance (so that, higher biogas production rate) and stability. In addition to these two possible advantages, a higher nutrient value of the generated co-digestate and an improved digestibility are highlighted in Reference [49].

In consequence, considering the different residues, the feedstock volume is estimated as the sum of daily waste (it is assumed a density of 1 kg/l), 1,890 l/day, and water (it is estimated as the same proportion of waste). Hence, it is 3.78 m^3/day. Multiplying it per a retention time of 22 days (as average value between the suitable range of 11 – 40 days for mesophilic temperatures, 20 – 40 ºC [61]) and considering a security factor (10%), it is obtained a digester volume (V_d) of 91.80 m^3.

The yield factor, Y, is 6.7. This is consequence of following the relations developed by IRENA [60] between retention time (22 days) and countries' average temperature (24 ºC in Colombia). It is not the only possible value (several retention times are feasible). In fact, longer retention times could lead to a slightly higher biogas production due to an increasement of the volatile solids (VS) rate. Nevertheless, it turns into higher costs since it is needed higher digesters [61].

The initial solid content, S, is 77.77 kg/m^3. It is the result of dividing the daily weight of added VS and the daily added feedstock. For each type of biomass, the VS as weight of biomass per percentage of VS is calculated (Table 6). For agricultural biomass, it is considered a quantity of 36% of crop residues (rice and maize) and 84% for waste fruit (plantain).

Table 6. Volatile solids content and proportion of each type of biomass

Type of biomass	Proportion of VS (%)	Quantity of VS (kg/day)
Household waste	15	5.25
Agricultural residue (crop)	20	43.39
Agricultural residue (fruit)	14	67.49
Cow	14	177.84

The final biogas potential production, G, is approximately 47.7 m^3/day. This is the maximum potential of biogas that could be used to produce heat or electricity within Filipinas ECTR.

As heat demand is supposed to be supplied only by biogas, it is necessary to calculate the required quantity in order to know the fraction of heat demand which would be covered.

Depending on the fuel type that wants to be replaced, LPG and wood in our case of study, the biogas that must be supplied changes due to fuel properties and equipment efficiency, although the heat demand would remain unchanged. Hence, it is essential to ensure a suitable substitution relation between biogas and the previous fuels. For LPG and wood is considered a substitution relation of 2.10 m^3 biogas/kg and 0.25

m^3/kg, respectively [60]. Since LPG and wood consumption in Filipinas ETCR are 7.7 kg/day and 15.8 kg/day, respectively (sub-section 4.4.2), the biogas demand is calculated as 20 m^3/day (following the same equation of IRENA).

Nevertheless, it is not known with total certainty that currently part of the thermal demand of the village is supplied by burning wood, as this estimate comes from a document that covers the entire Arauquita region. Thus, it has also been calculated the amount of biogas that would be necessary to produce to cover the thermal demand if it were 100% supplied by LPG stoves (11.9 kg/day). In this case, the required biogas production would be of 24 m^3.

Consequently, the worst-case scenario (24.0 m^3/day with 100% of the thermal demand supplied by LPG) would imply that only 50% of the potential production of biogas would be demanded for thermal energy generation.

Following the same procedure as for obtaining the biogas generation, but backwards, it is obtained a digester volume of 47 m^3. Biomass resource is estimated as the 50% available, 0.96 ton/day (directly proportional to the biogas production).

As it is said before, a small-scale biogas plant has two parts. The maximum volume of each part is called gas storage volume (biogas place) and digester volume (slurry place). The sum of both results in the total plant volume. In the case of a balloon digester plant, the gas storage volume is the 25% of this total plant volume and the digester volume is the 75%. Ideally, if 24 m^3 would be required, the digester volume of 47 m^3 implies a gas storage volume of 16 m^3 and a total plant volume of 63 m^3. According to IRENA, there are different feasible configurations to supply it [47]. For instance, by 5 digesters with 3 m of diameter and 2 m of length.

As a consequence, since only 50% of biogas potential production is used for heating demand, there is another 50% which can be allocated to feed a bio-genset to produce electricity and maybe heat too.

In Table 7, the biogas plant main results are summarized.

Table 7. Main results of the biogas plant

Concept (unit)	Value
Potential biogas production (m^3/day)	48.0
Biogas to cover heat demand (m^3/day)	20 - 24.0
Biogas to cover electric demand (m^3/day)	24.0

Regarding the model of the biogas plant in HOMER Pro, this software does not offer this option. The calculations about biogas production from biomass resource were developed outside the software and then directly introduced.

Biogas has different properties depending on its composition and application. For anaerobic digestion, it can be introduced with a LHV = 20 MJ/kg and a density of 1.1 kg/m^3 [62] to feed the boiler and the bio-genset.

5.2.1.3 Boiler

For modelling heat supply in HOMER Pro, a boiler representing a stove will be used since cooking is the most significant heat demand. Thus, the biogas-heat efficiency is defined as 45% and the cost of biomass is set at 0.03 USD/kg. This price has been extracted from a government document which suggests a range of costs for the purchase of biomass in Colombia. The value chosen is the average of this range.

In HOMER Pro, the fuel of the boiler cannot be limited, but it is not expected to be a problem since there is enough biomass resource (0.96 ton/day) to supply the thermal demand.

5.2.1.4 Bio-genset

Biogas can also be used to produce electricity (and optionally heat) by means of a genset. There are different genset technologies as an ICE, a Stirling engine or a gas microturbine. It is decided to select an ICE due to its maturity, cost and deeper roots in Latin America countries [54] [55].

An ICE can be used for small-scale applications (< 1 MW), it is modular and flexible, it has a short starting time and it is not too sensitive to the environmental conditions. Moreover, it has a lower economic cost than gas microturbines, and the Stirling engines technology costs are still too high to be competitive, given their lack of maturity [54] [55].

An ICE of 25 kW with an electrical efficiency of 31.5% and a minimum load factor of 25% was selected in HOMER Pro. It is fed by biogas produced by biomass resource. This way, the biogas production for electricity can be limited, since only a 50% of the available biogas in the ETCR can be used for electricity production purposes, as explained in the previous section. If this limit were not to be enforced, HOMER Pro could take more than the available biomass for this purpose (biomass is prioritized to supply the heat demand, as it is the only source to be considered).

Consequently, the available 24 m^3/day for electricity implies 0.96 biomass ton/day, with a gasification factor of 0.018 kg biogas/kg biomass and a carbon content of 50%. The gasification ratio is the result of dividing 24.0 m^3/day of biogas (17.3 kg/day) and 0.96 ton/day of biomass (960 kg/day). The carbon content is an estimated value from the atlas of residual biomass of UPME [32].

Capital costs are set at 33,700 USD [63] for the ICE and O&M costs are 0.75 USD/op. hour. The estimated investment cost of the anaerobic digester/s is also included in the capital costs.

Finally, a heat recovery ratio was not preliminarily considered for the ICE since the role of the bio-genset in the Polygeneration system was yet to be identified. As heat demand is characterized by two high peak powers, it is difficult to couple heat generation (recovery) to heat demand if bio-genset is not the main source of energy.

5.2.1.5 PV system

In addition to the previous system, it is proposed to install a photovoltaic solar field as an electricity generation system to take advantage of the high solar resource that this area of Colombia receives throughout the year.

For the purposes of this project a literature review among the different types of PV technologies has been carried out. In reference [64] is concluded that the technology that has the best performance among those sold in the market is the wafer-based monocrystalline silicone solar cell. This cell is made from a very pure form of silicon, making it the most efficient material when it comes to the conversion of sunlight into energy, reaching up to 15-20%. Additionally, monocrystalline solar cells are also the most space-efficient form of silicon solar cell due to their high efficiency. In fact, they take up the least space of any solar panel technology that is currently on the market. Another great advantage is their life expectancy, which is currently set at around 20 years. Nevertheless, monocrystalline solar cells are one of the most expensive options out of all the market, because each of the four sides is cut, which results in quite a large amount of prime material waste.

Specifically, the PV model chosen for this project is the monocrystalline silicon cell MaxPower CSU-340M from CanadianSolar, which has proven to be a cost-effective technology. The efficiency of a single module is 17.49% and the nominal maximum power is 340 W at standard testing conditions (STC) [T = 25° C, 1000 W/m^2]. However, these values are slightly lower when tested at nominal operating cell temperature (NOCT)

[T= 20° C, 800 W/m²], which is modeled by taking into account the NOCT cell temperature, the temperature coefficient of power in its calculations of power output, and a derating factor. On the one hand, the temperature coefficient of power, which is -0.41%/°C for the chosen PV module, indicates how strongly the PV array power output depends on the cell temperature [65]. On the other hand, the derating factor is a scaling factor that is applied in HOMER Pro to the PV array power output to account for reduced output in real-world operating conditions compared to the conditions under which the PV panel was rated. Since a solar panel model from the HOMER Pro library has been chosen for this project, this program gives a default derating factor value of 88%. This factor takes into account both external elements, such as dirt, snow cover or shading from surrounding trees or buildings, and internal elements, such as wiring losses and aging PV cells, that negatively affect the optimal performance of the solar panel.

Furthermore, the power output of the PV modules also depends on the location and design of the PV array. The slope of the PV module is a key factor to optimize the energy production in the yield since the panels are most efficient when they are perpendicular to the sun's rays [66]. In order to maximize electricity production, the default tilted angle is equal to the location's latitude +15° in winter, or -15° in summer. Arauquitas' latitude is 7.25°. Tracking systems also help to maximize electricity production, by rotating the PV panels in accordance with the changes in the sun's orientation to maintain maximum optimum angles over time. However, these systems require more maintenance, so their installation will not be considered for this project.

Regarding the economic data entered in HOMER Pro, for each 340 W solar cell, the capital cost is 710 USD, the replacement cost is 660 USD, and the O&M cost is 7.10 USD. This data was extracted from Reference [11], which analysis a Polygeneration project based in Colombia that uses the same panel technology, but different power.

5.2.1.6 Power converter/charger

Since PV technology produces DC electricity, inverters are required to convert the DC power to AC power so as to be used by the Polygeneration system and/or injected into the grid, if necessary. It should be noted that HOMER Pro uses the term 'converter' to refer to an 'inverter' so these terms are used interchangeably in the report.

The power inverter size has been selected based on the peak load demand obtained in the previous stage. A Schneider converter has been chosen from the HOMER Pro library, model Conext SW4024. The inverter efficiency is 92% at full load and the charger efficiency is 90%. The maximum output power of the inverter can reach 7000 W, which is close to the village peak load, estimated around 5700 W. The lifetime of this equipment is set to 10 years.

The capital cost, replacement cost and O&M cost considered for this component are USD 1500, USD 2000 and USD 10 per kW of installed converter, respectively.

5.2.1.7 Batteries

The integration of storage equipment within a hybrid power generation system can significantly help to bolster renewable capacity so that renewable resources, which are often intermittent, can provide a near-constant and reliable supply of electricity. As an added value, they allow excess energy generated during times of high renewable resource to be stored for later dispatch when the resource is not available, or to be sold when it is more valuable.

As mentioned in the literature review section of this report, in Reference [14] it was concluded that the Nickel Iron (Ni-Fe) batteries have the best performance out of the ones offered in the market. These types of batteries are made of nickel (III) oxide-hydroxide positive plates and iron-based negative plates, with an electrolyte of potassium hydroxide. They can withstand harsh work conditions and, consequently, they have a very long life. The year life expectancy is more than 20 years, also due to the fact that if a Nickel Iron battery is discharged by 80% or more will not negatively impact its life expectancy. These characteristics make them perfectly suitable for backing up renewable energy applications.

The selected battery model is the Edison 400 Ah with a nominal voltage of 1.2Vdc per cell, nominal capacity of 0.48 kWh per cell and 1% of self-discharge each day. The efficiency is relatively high, reaching 85% values, and the cycle life of the system is meant to reach 11,000 cycles at 80% DoD. Moreover, this battery model is normally sold in sets of 10 cells connected in series to create 12V, 24V or 48V nominal battery banks.

Finally, the capital and replacement costs are taken as USD 388, and the O&M costs are USD 1.5 per battery cell [14].

5.2.2 Control strategy

It is essential to devise an operating strategy for the hybrid generation system that determines the energy flow within the system and the interaction between the various components. The use of solar energy, which has an intermittent nature, together with battery storage and a backup engine, emphasizes the importance of determining an operating strategy, which main objective is to guarantee the continuous supply of demand while ensuring good environmental performance and minimize economic expenditure. Lack of a proper operating strategy leads to premature component failure, resulting in negative technical, economic and environmental impacts. Normally, there are different types of strategy depending on the type of demand to be covered: FEL (Follow Electricity Load), FTL (Follow Thermal Load) and CC (Cycle Charging).

In this case of study, due to the higher demand of electricity throughout the year in comparison with the heating demand, a FEL strategy is normally followed in the optimization scenarios calculated by HOMER Pro. This way, the hybrid system is forced to fulfill the total electricity demand of the village.

The following orders show the steps when a FEL strategy is adopted. Firstly, electricity and heat demand are initially supplied by the renewable energy sources available at the given time (biomass and PV). In case of excess of electricity, it will be initially charged in the battery and subsequently exported into the grid. On the contrary, in the event of deficit of electricity, the batteries will be firstly discharged and, later, electricity will be imported from the grid into the system.

Nevertheless, in those scenarios where energy storage is included in the proposed model, HOMER Pro suggests that a CC strategy should be followed in order to charge the storage bank when surplus energy is generated. The steps followed by HOMER Pro when this strategy is selected are three. First, selecting the optimal combination of power sources to serve the primary load and the thermal load at the least total cost. Next, increasing the output of each generator from the optimal combination to its rated capacity. Lastly, the storage starts charging without any interruption until the set-point state of charge is reached.

5.2.3 Base Polygeneration system results

Based on the technical data and assumptions mentioned in the previous section 5.2.1 for each component, HOMER Pro proposes various combinations and sizes of equipment as technically feasible. Table 8 and Table 9 show a summary of the size of each equipment and the economic results proposed by HOMER Pro for each optimized case, respectively. The analysis of these tables provides several insights on how the modelled system behaves.

Firstly, it is observed that those cases that are more economically profitable, i.e., have a lower LCOE value, are those that combine the power generation system together with the national electricity grid to supply the electricity to the ETCR. This enables the installed power of each of the equipment to be reduced and, therefore, installation costs can be shortened.

Secondly, the first three cases, those with the lower LCOE values, do not consider the installation of the bio-genset or simply use it as a back-up technology when grid outages occur during hours without solar resource or during peak demand hours with all equipment running at maximum power (10 operating hours per year).

Moreover, it is interesting to note that the scenario with the lowest LCOE (case 3) does not correspond to the scenario with the lowest NPC (case 1). The main reason for this is because case 3 considers a higher installed capacity of the PV and converter technologies compared to case 1. Thus, it is logical that the NPC reaches a higher value. However, with this configuration, more surplus electricity will be produced during the peak sun hours, which can be sold to the national grid in Colombia. Therefore, the LCOE for this scenario is reduced. A difference in more than 125,000 kWh/year of sold electricity between both scenarios is registered, which means, an additional income of around 8,500 USD for case 3.

Table 8. Proposed Polygeneration system capacities

Cases	PV array (kW)	Bio-genset (kW)	Battery bank (strings)	Grid	Converter (kW)	Boiler (kg/year)
Case 1	189.45	-	1,122.00	Yes	24.35	10,533.90
Case 2	189.45	25.00	1,122.00	Yes	24.35	10,533.90
Case 3	281.25	25.00	-	Yes	88.41	10,533.90
Case 4	198.36	25.00	1,799.00	-	39.11	10,533.90
Case 5	749.38	-	2,150.00	-	50.78	10,533.90

Table 9. Economic results for each proposed Polygeneration system

Cases	NPC (USD)	LCOE (USD)	Operating cost (USD/yr)	Initial capital (USD)
Case 1	1,125,602.00	0.345	20,284.00	867,464.90
Case 2	1,151,726.00	0.353	19,698.98	901,164.90
Case 3	1,221,896.00	0.249	36,539.80	753,625.60
Case 4	1,480,808.00	0.467	21,681.41	1,204,607.00
Case 5	2,839,358.00	0.895	28,482.55	2,475,247.00

In order to perform an economic and sustainable analysis in the following sections, case 3 has been chosen as the base case, since the LCOE has been prioritized. In this scenario, the bulk of electricity demand is covered by solar technology (72%, 363,364 kWh/year), followed by the grid system (27%, 135,849 kWh/year), which covers the base demand, and the bio-genset, which is used a back-up (213 kWh/year). Batteries are not included in the most cost-effective system because their cost is still relatively high compared to other storage or backup technologies. In addition, due to the large amount of biomass available in the ETCR environment, the lack of batteries does not compromise the reliability of the system, since the biogas generator is guaranteed to start whenever necessary. Figure 15 shows the monthly electricity production for each technology.

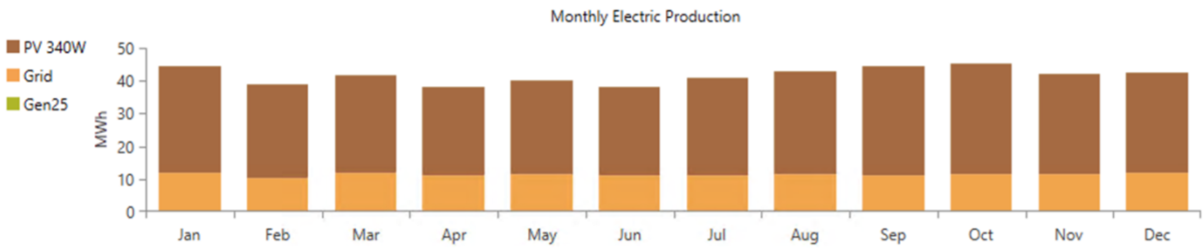


Figure 15. Monthly average electricity production per technology

The LCOE generated in this system is calculated to be 0.249 USD/kWh. The initial investment is the lowest among the proposed cases, limited at 753,626 USD. This indicator is highly dependent on the size of the PV plant and the battery bank since these technologies have the highest initial investment cost per kW. The fact that this scenario does not consider the inclusion of a storage system has lowered the initial installation costs.

In contrast, the operating costs for this system are around 36,540 USD, being the highest among all the analyzed scenarios. This economic factor is more influenced by the grid purchases and the PV facility, which are the main contributing systems to the electricity production in the selected case. As a consequence, it is expected that this configuration requires larger annual operating costs.

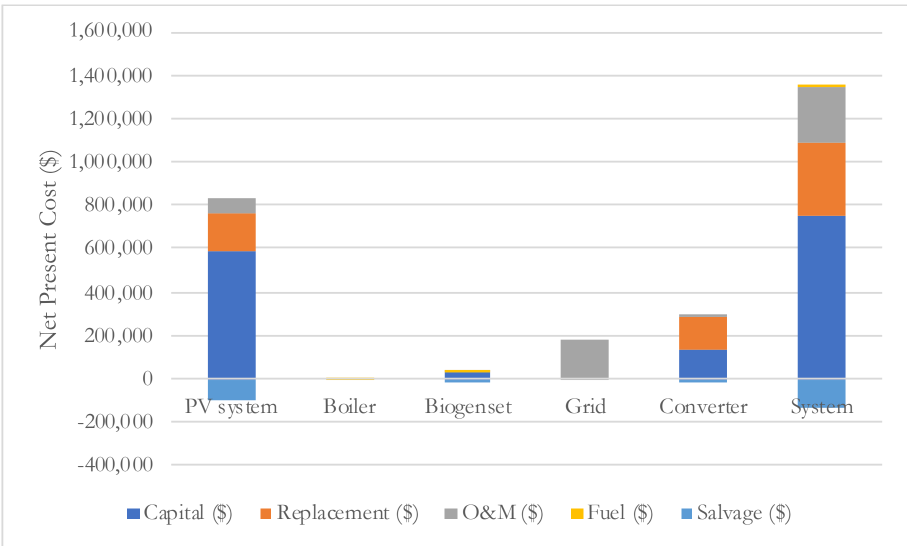


Figure 16. Summary of the NPC values for the Base system

In Figure 16 a breakdown of Net Present Cost (NPC) of the final system by cost type and component is shown. While it is true that the current thermal supply system has not been modified in any of the simulated cases, the resource from which the thermal energy is generated has been changed from LPG and wood (current system) to biogas. Therefore, the thermal economic analysis simply takes into account the cost of purchasing such fuel, since no investments are planned for the boiler. Moreover, in both cases, electricity and thermal production, the annual operating cost of the fuel is very low and almost negligible, as can be seen in the graph above, due to the low purchase price of biomass and, in case of the bio-genset, its few hours of use.

In addition, the costs of the biomass-to-biogas conversion facility were included in the capital cost of the bio-genset system. It is expected an around 11,000 kg/year of biogas. Following the procedure in 6.2.1.2, it would suppose 27.5 m^3/day, so a plant volume of 70 m^3 (53 m^3 of digester and 18 m^3 of storage).

Regarding generation of CO_2 emissions, the 135.8 MWh/year of the grid implies 51.8 tons CO_2/year, a 59.8% less than in the current system. Biogas combustion produces 18.1 tons CO_2/year, but they are biogenic. They are related to the natural carbon cycle and they are not considered, so they are not considered to contribute to the increase of the greenhouse effect.

5.2.4 Sensitivity analysis

After the preliminary system was designed, a sensitivity analysis was carried out to assess the effects of the input data uncertainty in the system configuration. The thermal demand, electric demand, biomass resource cost, the price of PV technology, components' life and bio-genset heat recovery level were taken as variables for the sensitivity analysis.

5.2.4.1 Increase in electric demand

The National Administrative Department of Statistics of Colombia (DANE) has estimated an increase of about 34% in the rural population of the country between 2020 and 2045 [67]. In addition to this forecast, the UPME has published a document in which a study of the national demand for electricity for the coming years is carried out. The results forecast a sustained growth of around 3% per year of this energy until 2023 [5]. Therefore, there is a clear need to analyze the capability of the proposed hybrid energy system to cover this possible growth in electricity demand and, if necessary, the need to oversize the capacity of certain equipment to guarantee a continuous supply in the near future.

These future scenarios were evaluated by selecting the scaled average electrical demand as sensitive variables, which were varied by an increase of 10%, 20%, 30% and 40%. The outcomes of this sensitivity analysis show that as electricity demand increases, the LCOE of the proposed optimized system decreases, emphasizing the need for higher load factors for RE projects to be economically viable. This trend can be seen in Figure 17. The optimal configuration resulting from each scenario shows a slight increase in the PV equipment capacity and the electricity purchased from the grid system. Similar to the base case, the bio-genset is still used as a backup equipment (13 hours of use per year) and the batteries are not included in any of the cost-optimal cases that HOMER Pro suggests.

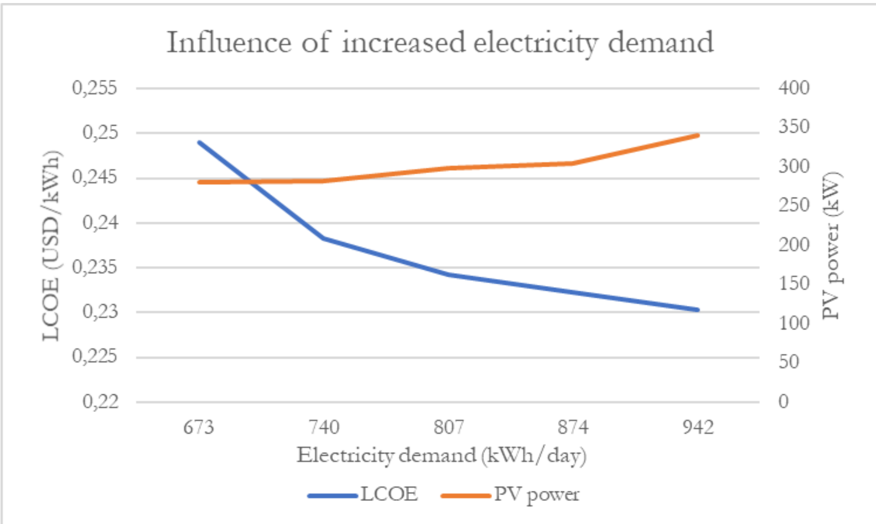


Figure 17. Influence of electricity demand increase on the Polygeneration system

As a consequence, it becomes clear that the proposed system is enough flexible to adapt to the expected increase in electricity demand over the coming decades. Thus, the number of solar panels and the associated converters, as well as the purchase of energy from the grid, will simply have to be accordingly increased.

5.2.4.2 Increase in thermal demand

Similar to the electric demand, a sensitivity analysis to estimate the future trends of thermal demand was developed, based on the same population projections calculated by DANE between 2020-2045 [67] (an increasement of the 34%.

In Table 10 is recollected the rural population projected for the Department of Arauca in five years steps, their relative increase (in %) and their expected daily heat demand.

Table 10. Evolution of LPG by UPME, its average annual increase and the estimated thermal demand for Filipinas ETCR

	2020	2025	2030	2035	2040	2045
Population	101,620	110,810	117,669	124,124	130,160	135,811
Increase of population (%)	0	9%	16%	22%	28%	34%
Heat demand (kWh/day)	72.1	78.67	83.53	88.12	92.40	96.41

The sensitivity analysis considers the heat demand values of Table 10. The results show that for the most competitive options, there is not a significant improvement of the LCOE. Logically, there is an increase of the boiler biogas consumption until 14,075 kg/year, whereas the bio-genset biogas remains as a constant value of 450 kg/year (bio-genset is used as a back-up, only 10 h/year). It means an average value of 36 m^3/day, so comparing to the maximum potential production of 48 m^3/day, it is clear that it is enough.

Table 11. Projected evolution of biogas for heating (boiler) and electric (bio-genset) production (2020-2045)

	2020	2025	2030	2035	2040	2045
Biogas boiler (kg/year)	10,533.90	11,485.82	12,195.38	12,865.52	13,490.40	14,075.86
Biogas genset (kg/year)	450.52	450.52	450.52	450.52	450.52	450.52

In section 5.2.1.2, it is concluded that around 50% of the potential production (24 m^3/day) could be used for electric purposes. This sensitivity analysis shows that for heat purposes it will be necessary more than the remaining 50% in the future. However, if the role of the bio-genset is still as a back-up (lower hours) there is not a problem and it is possible to increase the fraction of biogas production which can be used to supply heat. Supposing an annual average production of 19,270 kg/year of biogas (48 m^3/day), it is enough potential production to cover the heat demand if the bio-genset is a back-up.

Following the procedure in 5.2.1.2, a current potential demand of 11,000 kg/year of biogas would suppose 27.5 m^3/day, so a plant volume of 70 m^3 (53 m^3 of digester and 18 m^3 of storage). 14,500 kg/year (36.0 m^3/day), a plant volume of 92 m^3 (69 m^3 of digester and 23 m^3 of storage).

5.2.4.3 Decrease in PV technology prices

The increasingly widespread use of solar technology as a source of electricity has led to a reduction in the costs associated with this type of systems. IRENA concluded in its latest report on the global energy transformation that the total costs of installing solar systems would be reduced by almost 60% between 2019 and 2040 [68].

In order to analyze the effect of this phenomenon on the economic performance of our model, the investment, maintenance and replacement cost of this technology has been varied by multiplying it by a decreasing factor. The results obtained from this analysis lead to two conclusions.

On the one hand, as expected, as the cost of solar PV systems decreases, so does the total cost of the installation of the Polygeneration system and, with it, the NPC and LCOE of the project, reaching even values below 0.2 for the best cost reduction forecasts.

On the other hand, surprisingly, the most economically profitable options proposed by HOMER Pro keep the installed solar capacity unchanged. Before the analysis was performed, it was expected that as the price of solar technology decreases, its installed capacity in the system should increase. However, this correlation does not occur. The cause lies in the balance between the production and sale of energy to the grid. If the number of installed solar panels is greatly increased, so is the electricity production at peak solar resource hours and thus the surplus electricity. The selling price of such energy to the grid is 0.07 USD/kW, much lower than its production cost (the solar system LCOE is 0.11 USD/kW). Therefore, the increase in surplus electricity would generate more economic losses. As a result, after many simulations HOMER Pro has found at 281 kW the balance point at which the renewable fraction and the economic benefit of the solar installation is maximized. This tendency can be perfectly perceived in Figure 18.

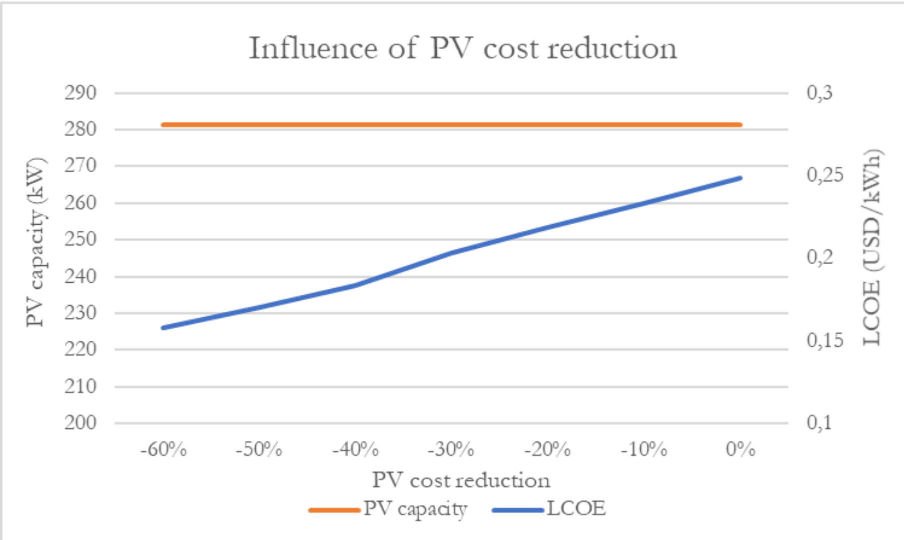


Figure 18. Influence of PV technology costs on the Polygeneration system

5.2.4.4 Biomass cost variation

The previous simulations have considered a biomass price set at 0.030 USD/kg. However, there is some uncertainty as to the reliability of this value because there is no registered biomass market in the region. One of the goals set in the document *Plan Energético Nacional 2050* is to promote the use of cogeneration (production of electricity and heat) through the use of local biomass resource [5]. However, the biomass cost is not specified since there is no precedent for this type of economic system in the area. In [69], it is estimated the operational and maintenance cost of biomass for Colombia as the same as IRENA recollected worldwide to bagasse cane. Therefore, in this project it has been estimated in the same way.

According to IRENA [70], biomass cost could be estimated between 0.020 – 0.050 USD/kg. Therefore, it is firstly developed a sensitivity analysis for the following biomass price values: 0.020, 0.025, 0.030, 0.035 and 0.040 USD/kg. As a result of this analysis, the most competitive cases show that between 0.020 and

0.025 there are a critical value. There is a biomass cost below which the bio-genset operates more than 2000 h and above which it acts as a back-up. Thus, it is added two more values, 0.022 and 0.023 USD/kg, to have a more accurate range (Table 12).

Table 12. Main economic and technical results for different biomass cost

Biomass cost (USD/kg)	LCOE (USD/kWh)	NPC (USD)	Bio-genset time (h/year)	Bio-genset consumption (kg/year)
0.020	0.230	1,169,017	2,394	125,573
0.022	0.246	1,214,423	2,320	121,725
0.023	0.249	1,224,988	10	450
0.025	0.249	1,225,272	10	450
0.030	0.249	1,225,982	10	450
0.035	0.249	1,226,692	10	450
0.040	0.249	1,227,402	10	450

The results obtained show two possible scenarios. On the one hand, when the biomass cost is higher than 0.023 USD/kg, it is irrelevant and bio-genset is used as a back-up (10 h). On the other hand, when it is lower than 0.023 USD/kg, the bio-genset is a significant generator, with a load factor of 27%. However, there is a key aspect. Both cases in which the bio-genset is not used as a back-up, the biogas consumption that is estimated for the ETCR is exceeded (an average daily value of 313 m^3/day, 6.5 more times than the maximum potential production, even without considering biogas for the boiler).

In conclusion, biomass cost is a key parameter which totally affects the bio-genset role in the Polygeneration system design. Nevertheless, it is not a well-defined factor due to there is not a biomass market yet.

5.2.4.5 Heat recovery

The Heat Recovery ratio (HR) is the portion of the fuel energy which is not converted into electricity and can be used for thermal purposes. This option was not considered for the bio-genset due to an expected unsuitable coupling between this component (maybe as back-up) and the boiler (with two daily remarkable peaks power). It has been developed a sensitivity analysis with 0, 25%, 50% and 75% of HR in order to check if this assumption was correct or if it is suitable to also produce heat by means of the bio-genset.

Table 13 summarizes the results for each level of HR simulated by HOMER Pro. The most competitive case uses the bio-genset as back up and no batteries are included in the system, the second one includes batteries but not the bio-genset and the least competitive proposes a high usage of the bio-genset.

Table 13. LCOE depending on HR level and role of bio-genset

	0%	25%	50%	75%
Bio-genset (back-up, <10 h/year)	0.249	0.250	0.255	0.259
No bio-genset	0.345	0.345	0.345	0.345
Bio-genset (>400 h/year)	0.467	0.565	0.599	0.651

Two main conclusions can be extracted from this analysis. On the one hand, for the two configurations with bio-genset, the best option is when HR is set to 0%, since the higher the HR is, the higher the LCOE results. On the other hand, the case in which the bio-genset runs as a major generator is less competitive than those cases where it is not included on the system or its function is as a backup. Therefore, it seems that the best solution is always to model the bio-genset without HR.

5.2.4.6 Solar system lifetime variation

A thorough search of the different models of solar panels and converters currently available on the market was developed and it was concluded that, depending on the manufacturer and nominal capacity, the technical data can vary greatly between equipment. Therefore, the selection of such equipment must sometimes be made with great care as it can turn out to be a decisive factor for the economic viability of the project.

On this occasion, the effect of modifying the lifetime of the components that make up the solar system proposed in the Polygeneration system was analyzed. The solar system has been chosen as the focus of the analysis, as it is the most cost intensive system in the proposed energy system and therefore the modification of its data can have the most noticeable effect on the overall system values. After a literature review was carried out, it has been reported that the lifetime range of the converters can vary between 10 and 15 years. Similarly, for the solar panels, a service life range of 15 to 25 years was found among different manufacturers. Hence, a sensitivity analysis between this range of values has been carried out in HOMER Pro and the results obtained are shown in Figure 19.

As expected, the change in the lifetime of such equipment affects only the economic values of the project. The optimal capacities proposed by HOMER Pro remain the same as in the base case, as well as the cost of installation. However, it is the replacement cost that is mostly affected. Due to the increased service life for each component, fewer replacements are required during the project lifetime and thus the replacement cost is drastically reduced. In the replacement cost graph, two different trends can be observed. This is because in the first section only the replacement cost of the inverter is reduced. However, in the second section, the converter replacement costs keep decreasing and the solar panels go from being replaced once (case 1 and 2) to not requiring any replacement during the 25 years of the project analysis (case 3). Therefore, a very severe cost reduction is observed in this section.

Furthermore, this cost reduction also leads to a reduction of the LCOE. Both analyzed factors are not directly proportional as the LCOE is also affected by other economic data such as the Net Present Cost of the project. As a conclusion, it can be deduced that the longer the useful life of the equipment incorporated into the installation, the lower the annual costs and, therefore, the better the economic results obtained for the project.

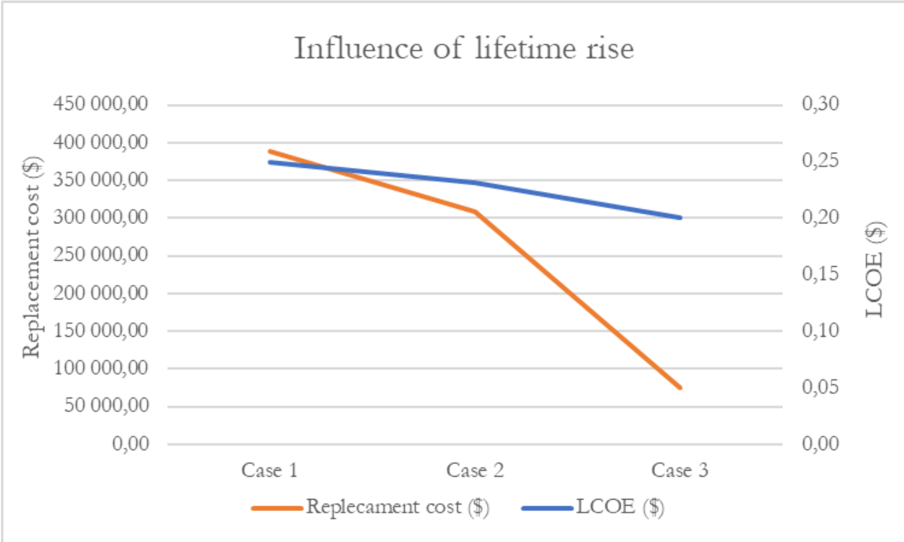


Figure 19. Influence of lifetime rise on the Polygeneration system. Case 1: Converter-10 years, Solar panels-15 years. Case 2: Converter-12 years, Solar panels-20 years. Case 3: Converter-15 years, Solar panels-25 years.

5.3 Optimized case

The sensitivity analysis carried out in the previous section has shown which are the variables to be closely controlled within the energy system, since a slight change in these can greatly affect the results calculated by HOMER Pro for each case. Furthermore, as a result of the conclusions drawn, it has been decided to upgrade the base case and adapt those variables that have proved to be more sensitive in order to obtain a model that offers a more technically and economically optimal operation. The change of these variables is possible, given that in the first instance their value was chosen as the average of a range found in the literature review and, on this occasion, the value chosen will be the one that offers the best performance of the installation within this same range.

- According to the *Biomass cost variation* sensitivity analysis, it is decided to change the biomass cost from 0.03 to 0.02 USD/kg for maximizing the use of residual biomass. This measure has been taken for purely social reasons. It is interesting to promote the use of biomass within the system, given that it is purchased locally and its benefits are transmitted directly to the community. Although the purchase price is reduced, this is compensated by the increase in the quantity that it is consumed, distributing the benefit among more people. However, a limit of 0.96 tones/day of biomass for electricity generation was set to ensure that the amount available calculated within the vicinity of the ETCR is not exceeded.
- According to the *Solar system lifetime variation* sensitivity analysis, the lifetime of the PV panels is extended to 25 years and of the inverter to 15 years. There are models on the market that offer these lifetimes and thus make the system economically competitive, which increases the likelihood of attracting capital and the viability of the project.

This new model yields new optimal cases which are suggested by HOMER Pro, but, for the same reason as in the base model, the case with the lowest LCOE is selected. According to the results, the installed PV capacity for the new system is slightly reduced since it is now covered by the biogas generator. In addition, the same trend line as in the previous models is followed where the grid is present in the three most economically competitive configurations and the battery bank is not used in the best one. The fuel consumption in the boiler is the same as in the base model.

According to the economic performance, compared to the base case model, the new optimized system is more competitive in terms of LCOE (0.209 USD/kWh, instead of 0.249 USD/kWh). This LCOE value is slightly below the average of the values obtained in similar projects both in Colombia and in the rest of the world found in the literature review. The NPC is reduced by 17%, due to the cut in investment capital and operating costs.

Table 14. Comparison of architecture between base and optimized cases

Cases	PV array (kW)	Bio-genset (kW)	Battery bank (strings)	Grid	Converter (kW)	Boiler (kg/year)
Opt. case	250.00	25.00	-	Yes	91.57	10,533.90
Base case	281.25	25.00	-	Yes	88.41	10,533.90

Table 15. Comparison of economic results between base and optimized cases

Cases	NPC (USD)	LCOE (USD)	Operating cost (USD/year)	Initial capital (USD)
Opt. case	1,012,823.00	0.209	24,731.02	693,111.90
Base case	1,221,896.00	0.249	36,539.80	753,625.60

Another reason for the selection of this new optimized system is that it reduces the installed capacity of the solar technology, slightly smoothing peak electricity production at times of high solar resource, which, subsequently, generates a large amount of excess energy. Figure 20 shows how the electricity production from the solar farm reaches a maximum of around 225 kW during the third day of the year, lower than the one recorded in the base model for the same day, which was around 260 kW.

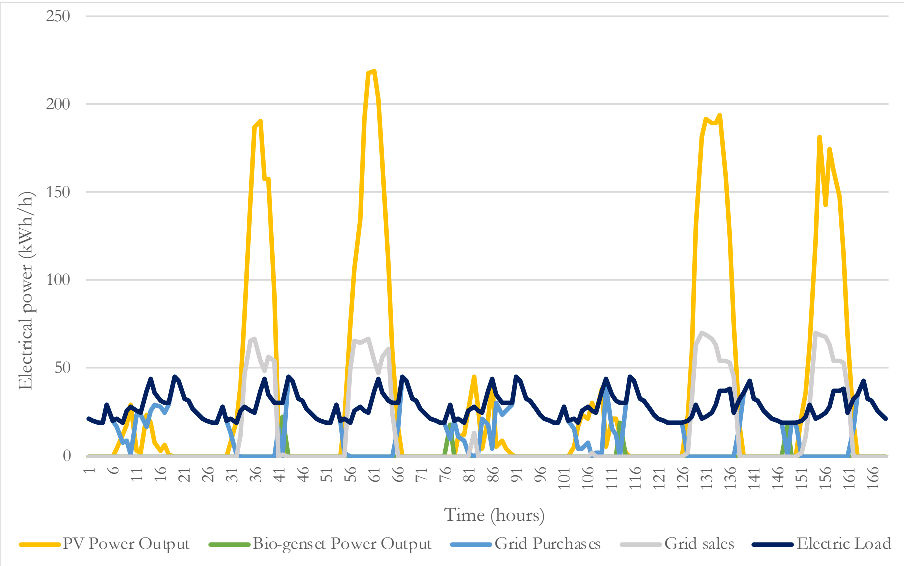


Figure 20. Electric power load and generation for first week in January

From an environmental perspective, the renewable fraction calculated by the software is around 60%. Nevertheless, when viewed from the electricity and thermal production, renewables account 71.1% (PV and bio-genset) and 100% (biogas boiler), respectively. Considering both, heat and electricity, it implies a 72.7% of energy generated from renewable sources within Filipinas ETCR. The CO_2 emissions assigned to the electric production (grid) are 50.8 tons/year (60.5% less than current system and 1.9% less than the base case). As in the base case, biogas CO_2 emissions are biogenic and are not considered as harmful for the environment. They are 10.3 ton/year.

In conclusion, this optimized case is technically feasible and, more economically competitive (LCOE of 0.209 USD/kWh and -17% of NPC) and environmentally friendly (almost 73% of renewable fraction) than the base case. Therefore, a deeper financial, environmental and social analysis was developed in the next section focused on this Polygeneration system.

Figure 21 shows a summary of the optimized Polygeneration system and its main parameters: power capacity, energy demand and production.

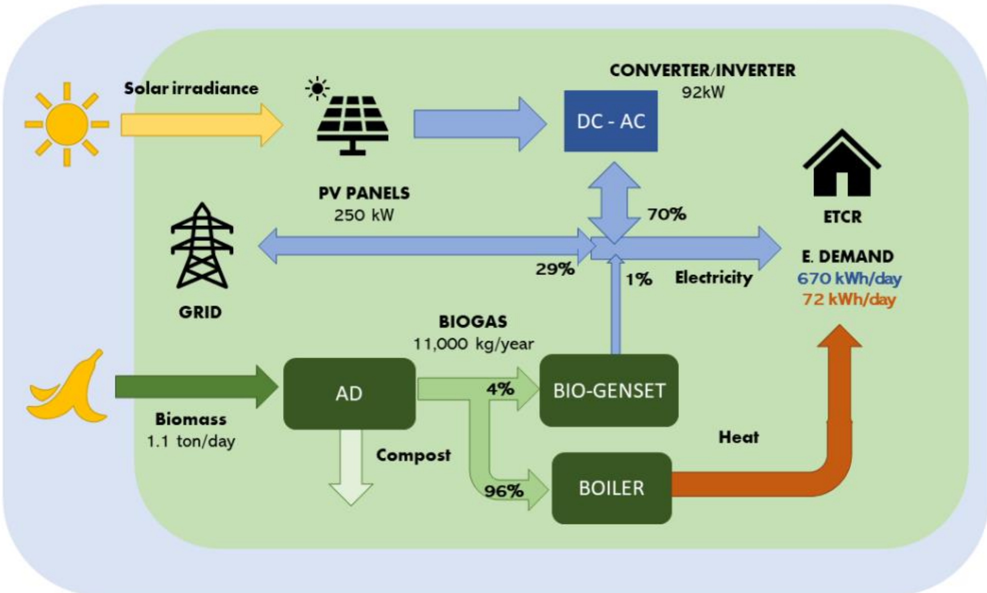


Figure 21. Diagram of the Optimized Polygeneration system

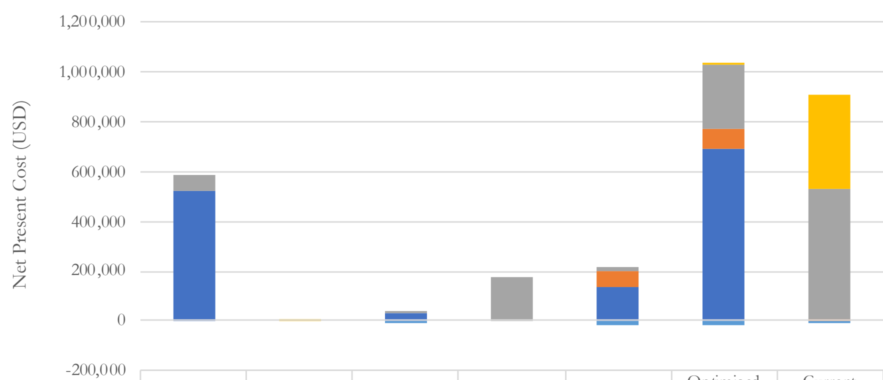
6 Discussion of results

In this section, a much more detailed analysis of the environmental, social and financial impacts of the Polygeneration energy system proposed in the previous section has been carried out. In addition, for each aspect a comparison is made with the current energy supply system of the ETCR. Finally, the possible investors and owners of the system to be installed are discussed and an implementation plan is proposed.

6.1 Financial analysis

One of the most important aspects, and often the main motivation, in the decision to install a renewable energy system is the expected economic outcome. For this reason, a detailed financial analysis is required to justify the capital investment and demonstrate the economic viability of such projects. The locality under study does not have the necessary biomass resources to meet the entire electricity demand, so it is necessary to scale up the energy system with solar technology in order to achieve considerably high renewable fraction values. Consequently, HOMER Pro calculated that large capacities of photovoltaic panels and their respective converters would be necessary in order to meet this objective. On the one hand, this leads to a flexible energy system, which relies on two different energy sources and is, therefore, more resilient to possible unexpected setbacks. On the other hand, this type of configuration largely increases the capital investment costs, which could complicate the financing process when looking for public and private investors. Nevertheless, despite the high initial investment costs, Polygeneration systems often have significantly lower project operating costs than systems based on conventional fossil sources or simply connected to the grid [71].

Figure 22 shows a detailed analysis of the costs per component and type of the proposed optimal system, as well as a comparison with the costs of the energy system currently running in the Filipinas ETCR. The NPC of the new system is slightly higher than that of the reference system, the difference being almost 100,000 USD. As mentioned earlier, this can be attributed to the higher investment and equipment replacement costs of the Polygeneration system. As shown in the figure, solar panels are responsible for almost 70% of the initial outlay required. In contrast, the operation and maintenance cost of the proposed system are half that of the current system. There are two main reasons for this. First, fuel costs are much lower due to the local availability of biomass. Second, the cost of buying electricity from the grid is higher than the LCOE of the solar system and the biogas generator, resulting in lower operating and maintenance costs in the new system. Finally, the salvage value of the optimized system is approximately 20,000 USD, indicating that several of the equipment could still operate for several years after the end of the project. In the thermal demand supply system, there is also a significant monetary saving after the fuel switch from LPG to biogas, which has lower purchase prices.



	PV system	Boiler	Biogenset	Grid	Converter	Optimised system	Current system
Salvage ($)	0	0	-4,790	0	-14,624	-19,414	-70
Fuel ($)	0	2,724	0	0	0	2,724	376,342
O&M ($)	68,155	0	2,366	176,343	11,838	258,701	528,134
Replacement ($)	0	0	0	0	65,723	77,700	514
Capital ($)	522,058	0	33,700	0	137,353	693,111	2,550

Figure 22. Summary of the NPC values for the Optimized Polygeneration system and the Current system

It has to be taken into consideration that the suggested change of fuel for the thermal energy production system entails an additional cost that cannot be introduced in HOMER Pro. As previously mentioned, approximately one third of the rural households in the ETCR have cookers that use wood as fuel. Therefore, the cost of changing these cookers to biogas cookers must be added to the initial investment cost calculated by the program. It has been estimated that each gas cookstove could cost around USD 70, including installation costs, leading to a final outlay of USD 2,030 for the entire ETCR. The replacement of cookers that currently use LPG as fuel is not considered as they are theoretically also suitable for biogas.

Once the economic results calculated by HOMER Pro for the proposed Polygeneration system have been presented, an analysis of the economic viability of the project is carried out. To this end, a discounted method will be followed by calculating three economic indicators recurrent in this type of study: the Net Present Value (NPV), the discounted payback period and the Return of Investment (ROI). In all of them, the economic values of the proposed configuration have been compared with those of the current system.

The NPV (USD) is a measure of profitability, and it represents the present value of the entire project benefits including the design, installation and execution phases, therefore, it shows the total money that potential investor could earn today if they decide to finance the project. As a minimum requirement, this indicator should be greater than zero during the service life of the installation, although the higher it is, the better economic profitability will be achieved. The NPV calculated for this project is positive and over 110,000 USD.

The discounted payback period is a risk measure and is defined as the time required to recover the investment costs. Likewise, this period must be greater than zero and within the lifetime planned for the project. However, unlike the previous factor, the shorter this indicator is, the more attractive the project is to investors. As can be seen in Figure 23, the NPV is equal to zero 18 years after the start of the investment, which means that from that point the project has been amortized and during the last years of the project lifetime all revenues are translated into real profits.

Finally, the ROI (%) is also a measure of profitability and it corresponds to the market discount rate which results in zero life-cycle savings, that is, the discount rate that makes the present worth equal to zero. A profitable investment requires a ROI higher than the market discount rate, which in this project was set to 8%. In this case, the ROI has turned out to be 9.70%, which offers a fairly wide margin with the minimum required.

As a consequence, the results obtained for the three indicators above demonstrate the economic viability of the project. However, these good results are often not enough to attract the investors interest. When it comes to renewable energy projects, there is always some uncertainty about how the markets will evolve, which directly affects the credibility of the economic results. Thus, public subsidies or incentives are used to encourage capital investment in these types of projects. Colombia recently passed Law 1715 [56], which aims to promote the development and use of non-conventional energy sources, mainly those of a renewable nature, in the national energy system. Among the different remuneration mechanisms proposed in this law, there are two that can directly reduce the capital cost of the installation.

On the one hand, the exclusion of goods and services from VAT on the purchase of domestic or imported goods and services, equipment, machinery, items and/or services is included in the law. If this financial support is applied, it would result in a 19% cut of the initial capital, corresponding to the value of VAT currently applied in Colombia. As shown in Figure 23, this would directly beneficiate the economic indicators previously calculated, by lowering the payback period to less than 11 years and increasing the NPV up to 200,000 USD.

On the other hand, an exemption from import duties on machinery, equipment, materials and inputs can also be applied to RE projects. The economic savings after applying this subsidy are more difficult to calculate than the previous one since, depending on the imported product, there are different tariff rates. However, the investment cost of the Polygeneration system would also benefit from this given that some of the equipment used in it is not produced within the country and, hence, must be imported.

Finally, the aforementioned law also states that income taxpayers who make new investment expenditures for the production and use of energy from non-conventional sources will be entitled to deduct up to 50% of the value of the investments. Although this is not a direct financial support to the cost of the installation, it does help to attract potential investors.

Table 16. Financial indicators results summary before and after VAT reduction

Economic indicators	Before VAT reduction	After VAT reduction
NPV (USD)	110,000	200,000
ROI (%)	9.70	12.00
DPB (years)	18	11

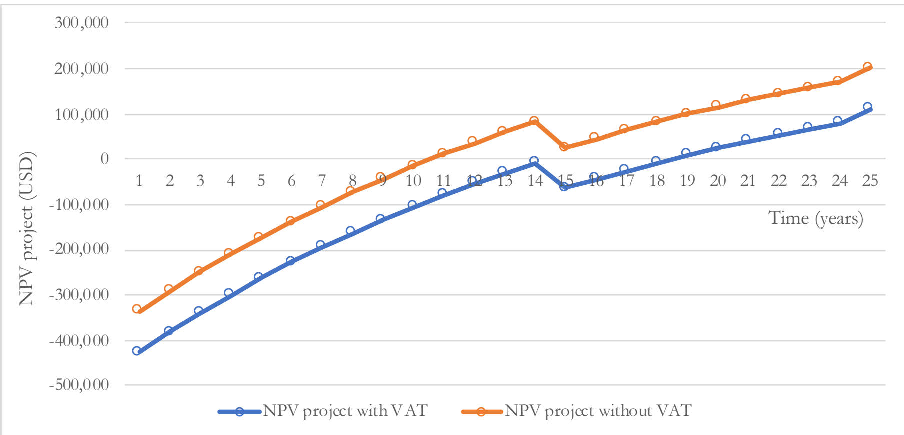


Figure 23. NPV with VAT and without VAT for the Optimized Polygeneration system design

6.2 Environmental analysis

One of the main motivations for proposing the replacement of the current energy system is for environmental reasons, as the current system is based on fossil fuels and the new one is based on the use of renewable and local resources. However, there are also a number of disadvantages associated with the new Polygeneration system, hence the following section analyses both perspectives.

6.2.1 GHG emissions

The combustion of fossil fuels results in the generation of pollutant emissions. Most of these are GHGs (greenhouse gases), the release of which into the atmosphere contributes to global warming. The best known and most widely used to measure this problem is the CO_2, which us normally measured by its ton or kg per year. However, there are other pollutants which also have a significant impact on the environment and biodiversity, such as N_2O and CH_4. For comparing the different types of pollutants, an equivalence of each one to CO_2 tons was developed, ton CO_2, eq. These equivalences (ton CO, eq/ton of pollutant) are known as GWP (Global Warming Potential).

According to the EPA [72], GWP is a measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time, relative to the emissions of 1 ton of CO_2 (a larger GWP implies more greenhouse effect contribution compared to CO_2). A time period usually used is 100 years. Hence, GWP-100 years for CO_2 is 1 as be the reference, whereas for N_2O is 298 and for CH_4 is 25 [73] emissions. These values are multiplied by each annual quantity (in ton) of pollutants emitted in order to obtain the ton $CO_{2,\ eq}$.

In Table 17 the most significant GHG emissions for the current and the proposed Polygeneration system are displayed. For the sake of comparing the contribution to the generation of the greenhouse effect of each pollutant, they are expressed in both values, their own emissions (kg pollutant/year [73]) and in GWP (ton CO_2, eq) too.

Table 17. Comparison of GHG emissions between the current and the proposal Polygeneration system

		N_2O	CO_2	CH_4	Total
Current system	**(kg pollutant/year)**	19.57	128.567.58	0.88	-
	(ton $CO_{2,\ eq}$)	5.83	128.57	21.89	156.29
Proposed Pol. System	**(kg pollutant/year)**	0.1	50,757.58	0.07	-
	(ton $CO_{2,\ eq}$)	0.23	50.76	0.002	50.98
Emissions reduction		96.10%	60.50%	100%	67.30%

Therefore, the table concludes that the total GHG emission savings from the change of energy system in the village would be 67.3%. Basically, this improvement is a logical consequence of the proposed energy supply, mainly composed of renewable energy resources and technologies (a 72% of renewable fraction).

Finally, one noteworthy aspect regarding GHG emissions is that indirect emissions are expected to occur in biomass management activities such as transport or harvesting, although they are expected to be negligible in the overall balance.

6.2.2 Land use

The proposed Polygeneration system needs a surface area to implement its subsystems. This is the main drawback for the photovoltaic subsystem (154 kW), as the PV modules require a surface area that can be estimated at 6-8 ha/MW [74]. It implies around 0.9 and 1.2 ha. This is an area that could be used for other purposes such as agriculture, livestock or housing and could also reduce the available biomass resource. However, the available area of 146 ha (153 ha without the 7 ha already used for buildings) makes this a minor problem. It represents less than 1% of the ETCR area. In addition, it should be noted that rooftop PV has not been considered due to the weakness of the roofs previously explained in section 4.2.

The biomass subsystem requires a much smaller footprint than the PV, so no major difficulties are expected in finding a site other than possible issues related to visual or noise impact.

6.2.3 Soil contamination

The proposed Polygeneration system promote the valorization of biomass residues in order to generate energy and compost. The use of this compost leads to a reduction in chemical fertilizers used by farmers. According to FAO [75], there are successful experiences in Latin America for this type of projects which promote the circular economy within the region. An estimation of the compost that can be obtained after subjecting agricultural, livestock and solid urban waste to the anaerobic digestion process has been made. This value has been estimated at 280 ton/year after being treated. This value was estimated using an online calculator for biogas and compost production from various types of waste biomass.

6.3 Social analysis

Due to the great importance of the social development of the inhabitants of the ETCR, a detailed study of the possible social impacts of the proposal in the village is made in this sub-section.

6.3.1 Job creation

Firstly, there are many examples from around the world of the success of Polygeneration systems in creating employment in the region where they are to be installed, for example in terms of the labour required for the construction and the operation and maintenance of the sub-systems [59][60]. However, it is difficult to specify clearly what proportion will be direct or indirect, full-time or part-time, formal or informal.

According to IRENA [76], microgrids (Polygeneration systems) are a potential source of employment in the whole value chain of renewable energy technology. However, local and permanent jobs are focused on the stages of distributing, selling, installing, O&M and servicing. Design and construction phases create a peak of employment, but they are temporal (1 - 2 years) and requires a percentage of skilled employment which maybe can be hard to find in the ETCR.

Furthermore, there are indirect jobs associated with the entire energy supply value chain, such as the extraction of raw materials, the manufacture of equipment or the biogas stoves maintenance. There are also incentives for the creation of productive jobs due to the reinforcement of new companies as a consequence of the improvement of energy supply.

For the proposed Polygeneration system, there are activities which undoubtedly are going to require a permanent employment for the Filipinas ETCR:

- O&M of the PV sub-system.
- O&M of the biomass sub-system (including biomass resource management).

Attending to the available literature about job creation in energy renewable systems and micro-grids such as [76] and [77], for the PV and biomass sub-systems could be made an estimation about the needed direct jobs.

For PV, depending on the source, direct job is not specified. It is not included indirect jobs associated to the whole supply value chain as the extraction of raw materials or the manufacturing of equipment.

In [77], it is considered direct as permanent (O&M) and short-time contractual jobs (design and construction). In [76], IRENA does not defined exactly which is a direct job. Considering the different job factors of each source, it is a range between 3 and 43 direct jobs created.

It can be supposed a local and permanent job are around 8-10 jobs, due to Rockefeller Foundation [77] considers only direct and permanent jobs and IRENA not specified.

Table 18. Different job per solar PV capacity (MW) ratios

Sub-system	Jobs/MW	kW	Jobs
IRENA [76]	30	250	8
Rockefeller [77]	40	250	10
Mlinda [77]	277	250	69
SA [77]	253	250	63

For the biomass sub-system, the literature focuses on the biomass power plant (solid fuel) and not biogas. However, the same estimations will be considered for the biogas plant. Using job factors and considering when it is possible, indirect job associated to biomass resource (recollection and transportation). This is the case of IRENA [76].

Therefore, for the biomass system (ICE, bio-genset and digesters) is going to be supposed as 2 – 4 direct full-time job. Some examples of anaerobic digestion solution recollected by the Global Methane Initiative (GMI) a maximum of 2 jobs direct and full-time created [78]. Thus, local and permanent direct jobs could be estimated as a minimum of 2 people for the O&M of the sub-system.

Table 19. Different job estimations for per biomass and biogas system

Sub-system	Jobs/MW	kW	Jobs
IRENA [76]	43	42	2
GMI [78]	-	-	2

It is essential to remark that the job creation estimation for both sub-systems are based on rough and conservative values. It is expected a higher job creation due to indirect jobs (temporal and related to design and construction phases), productive jobs (local and permanent) and more direct jobs.

A major challenge in terms of employment is the training of local people for skilled jobs and thus contributing to the development of the community.

6.3.2 Health

According to WHO, ambient and household air pollution affects to a greater extent to low- and middle-income countries. In fact, it is estimated that 9/10 people are exposure to higher limits than recommended [79] .

Exposure to indoor pollutants as PM, VOC, CH_4, CO, SO_x, NO_x leads to a several health impacts as respiratory illnesses, cancer or eyes problems. 3.8 million of deaths per year are estimated to be direct or indirect consequence of air pollution from cooking with fuels, as wood or coal, inefficient stoves or open spaces. Moreover, working with these types of fuel and stoves tend to produce accidents, burns or poisonings.

Different studies [62][63][64] show that changing cooking fuels (wood and LPG) to biogas for cooking reduces indoor air pollution and improves respiratory health, which is a direct benefit for women (see 6.3.3). In Table 20 is gathered the most significant pollutants (emissions factors of [80], [81]) which affect human health at the current and proposed system heat supply.

Table 20. Comparison of the main health impact pollutants' emissions between the current and the proposal Polygeneration system

Emissions	Current system (Kg pollutant/year)	Proposed Pol. System (Kg pollutant/year)	Emissions reduction
PM	0.76	17.65	95.7%
VOC	8.16	20.09	59.4%
CH_4	0.07	0.88	92.0%
CO	0.87	1.20	27.7%
NOx	0.10	19.57	99.5%
SO_2	0.16	0.75	78.3%

Although there is a large reduction in emissions in general, the most notable is PM, -95.7%, which is directly related to negative health impacts. Also, NO_x (-99.5%) and CH_4 (-92.0%) have a high rate of decrease.

6.3.3 Gender equality

Different studies [82] [54] [83] and organisations as IRENA [76] remark the gender aspect as a positive impact of Polygeneration systems. As in other rural societies, the use of wood as a cooking fuel is common in the ETCR (it is assumed to cover 33% of the heat demand). Collecting firewood is an arduous task that is usually carried out by women. In addition, the use of wood cookers results in a longer cooking time than biogas. For example, a study focusing on a rural society in India quantified 40 minutes for cooking and 70 minutes for collecting firewood [84]. Without these two tasks, women can better manage their time for other purposes such as adult education, social participation or work.

Moreover, another crucial positive health impact of replacing wood and LPG with biogas is based in the fact that it directly affects to women, as they are the ones who usually cook in these societies and spend more time in the cooking space, i.e., exposed to the absorption of these pollutants (see 6.3.2).

6.3.4 Socio-economic development

Security of energy supply enables the socio-economic development of the ETCR. As it is conveyed by [76], [77], [85], it reinforces and promotes current and new local businesses. In addition, it allows a better comfort and welfare of the inhabitants and the well-functioning of education and health facilities.

Furthermore, the Polygeneration system contributes to boost agro-livestock businesses due to the generation of new economic incomes by selling their residues as biomass.

Finally, the produced compost is a by-product that can be used by farmers and livestock breeders for a much lower price than those currently in use.

6.4 Stake holders analysis

The lack of effective management in some community microgrid projects, as well as the insufficient integration of adequate compensation and incentive mechanisms to renew customer interests and withstand the uncertainties and economic challenges of these projects, may result in the loss of part of the expected economic and social benefits and even in the project failure. This is why community microgrids must be managed and operated in an agile and flexible way, by a suitable entity with experience in the sector and that knows how to adapt and reconcile the interests of the very different main actors.

Reference [86] examines four types of ownership structure and operation of microgrids to conclude which are the optimal conditions for selecting between each of them, so that investment uncertainty and ownership risks can be managed most efficiently. The configurations analyzed for the ownership of the installation are as follow: managed by the utility service, by the community itself, by a private company or a hybrid between the latter two.

According to the examined conditions for each type, the most suitable configuration for the Colombian village under study would be the hybrid one, where the community and an external entity work hand in hand to manage the functioning of the energy system. The main reason for this is that both the social and economic benefits of the installation can be maximized. On the one hand, the Polygeneration system by itself has the capacity to generate economic benefits, as shown in the previous section, and, hence, to make the initial investment profitable, which can attract external capital investment. On the other hand, one of the primary objectives of the ETCR Filipinas is the social and professional development of the inhabitants of the site. Thus, it is essential to ensure that energy supply guarantees are met under favorable conditions for the community. Furthermore, the community lacks the financial resources to invest such amounts themselves. As a consequence, the involvement of both parties in the ownership and operation of the energy system facilitates decision-making and planning, as the inclusion of the preferences and values of both actors can provide relevant information that would otherwise be ignored in a purely technical and economic analysis, leading to socially poor decisions.

The external entity may be an NGO, a private sector company, a government agency dedicated to the promotion of such projects or even the electricity utility ENELAR itself. As for the community part, it could be either the village administration or a group of citizen representatives. However, due to the technical and operational complexity that a Polygeneration energy system requires, the involvement of an expert company whose main responsibility is to operate and manage the microgrid and provide the electricity service to the community is indispensable. This service provider can be the same external company that partly owns the installation or ENELAR, which provides greater efficiency in the planning and operation of the microgrid.

6.5 Implementation plan

Up to now, project reports based on the installation of renewable energy technologies have often included a proposal for an implementation plan for the selected equipment. This plan was necessary since the financial analysis normally concluded that on its own, the renewable-based energy system was not cost-competitive compared to conventional energy system, normally based on diesel. This is due to the fact that this type of project requires a high initial investment, due to the high cost of the equipment used. By means of this mechanism, the necessary capital cost is spread over the service life of the installation, making it possible to finance part of the investment with the profits obtained during the first years of system use, since operating costs are generally lower in RE systems. In this way, the amount of money to be disbursed in the first instance was reduced and the attention of investors was attracted.

However, innovation in this sector and the steadily dropping installation costs of renewable technologies have made them competitive against conventional installations and, in many cases, they now provide even higher profits. Large organizations such as IRENA (International Renewable Energy Agency) have already highlighted this change in trends within the energy sector. Its CEO recently stated that the cost competitiveness of renewable energy generation has reached historic levels. Today, where adequate resources and cost structures exist, solar PV, biomass power generation, hydropower and coastal wind installations can provide electricity competitively with fossil fuel power generation. Proof of this is that renewable energy generation technologies have accounted for more than half of all new power generation capacity additions made each year since 2011 [87].

In addition to the lower installation costs of renewables, the extensive literature surrounding Polygeneration energy system has proofed that when electrification of a rural area is desired, this type of configuration is usually a more economically competitive alternative to grid extension (depending on the distance to be covered) or the exclusive use of diesel generators, as the operation and maintenance costs are much lower, given that local resources are consumed. They also arise to solve problems normally associated with renewable installations such as security of supply and the consequent oversizing of equipment.

The financial analysis of the present project has once again clearly demonstrated the economic benefit of switching from the current energy supply system to a system based on the hybridization of renewable energies in the Filipinas ETCR. The three economic indicators were evaluated without taking into account any kind of public subsidy or implementation plan, and yet they have given very positive results, thus demonstrating the economic viability of the project itself. Therefore, it is concluded that an implementation plan dividing the capital cost of the installation over the years would not be necessary in this case.

The cash flow of the nominal costs resulting from the HOMER Pro simulation for the current energy supply system of the village and for the proposed Polygeneration system are shown in Figure 24. This graph, in itself, represents the proposed implementation plan for the new system to be installed. For reasons of ease of visualization, the total initial investment of the Polygeneration system, which is almost 700,000 USD, is not shown in the graphic.

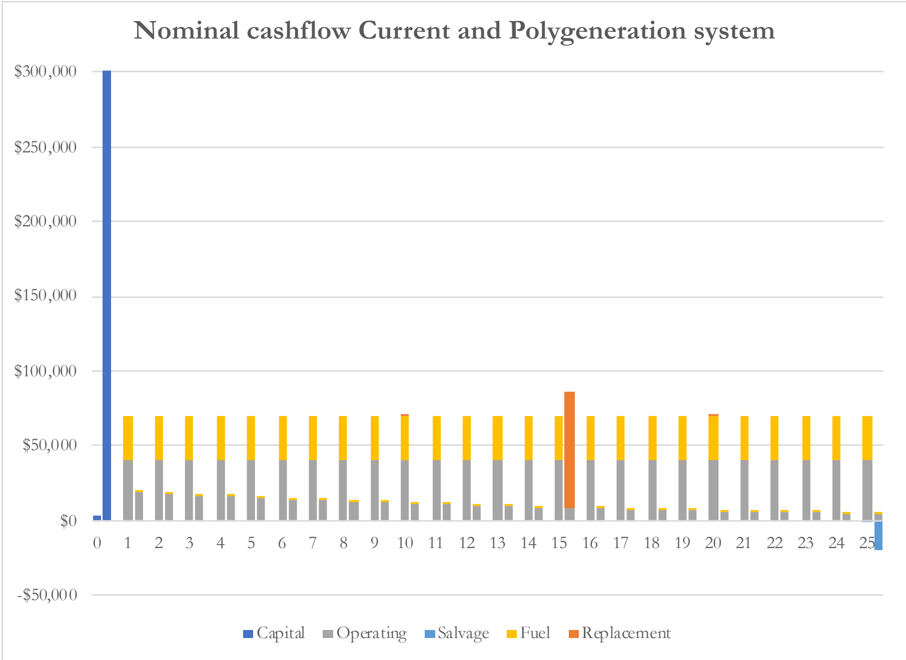


Figure 24. Nominal cashflow by cost type. First column: Current system. Second column: Optimized Polygeneration system

7 Conclusions

The analysis of the energy situation (demand, current supply system and available local resources) in the Filipinas ETCR has led to the proposal of an alternative energy provision system that guarantees a secure, equitable and environmentally friendly energy supply through a Polygeneration system based on solar photovoltaic energy, biomass residues converted to biogas and the existing electricity grid.

The new energy system enables 100% of the village's energy demand to be covered, overcoming the problem of the recurrent power cuts that currently occur. Furthermore, 73% of the total energy production would be produced from renewable resources, instead of the current 0.37%. What is more, the thermal demand would be supplied 100% by a renewable source, biomass, and, thus avoiding the use of current fuels that have a detrimental impact on health and the environment, i.e., LPG and wood waste. For electricity, PV supplies the 70%, the grid a 29% and the bio-genset is a back-up.

From a financial perspective, although the initial investment reaches almost 700,000 USD, the economic indicators calculated provide very good results. The LCOE is limited to almost 0.2 USD/kWh, the ROI is around 9.7% (higher than the 8% discount rate) and the DPB is less than 11 years (if public funding mechanisms for RES projects are applied).

Furthermore, the implementation of these project is expected to contribute to the socio-economic development of the ETCR by the increase of job and business opportunities, health, comfort and equality. These results are mainly in line with UN SDGs 7 (Affordable and Clean Energy) and 13 (Climate action) and with the objectives set out at the beginning of this project.

Finally, it is essential to highlight certain conclusions extracted from the various simulations carried out during the project. Firstly, regarding the share of the renewable fraction of the present project, it is expected to increase in the future in line with the increase in the share of the Colombian national electricity production from renewable sources. Secondly, after conducting the sensitivity analyses, it was concluded that the higher the thermal and electrical demand are, the better economic outcomes in the project. Thirdly, the biomass availability and its purchase cost are key aspects which affect to the bio-genset role in the Polygeneration system configuration. Moreover, the economic viability of the system is quite sensitive to replacement timeframes of the selected equipment. Finally, the proposed Polygeneration system would be able to guarantee the energy supply over time, despite the progressive increase in both types of energy demand, due to the high biomass availability of the area and the flexibility and maturity that the PV technology can provide.

8 Future work

The study presents very enlightening results that are in line with the findings of other similar studies reported during the literature review. This demonstrates the veracity of the conclusions and supports the method applied.

However, certain setbacks in the research process have led to the need to resort to the estimation of several input data, which were initially thought to be from a direct source of information. This method of data collection, although carried out with great care, usually offers less accuracy, and may undermine the veracity of the conclusions. Therefore, first of all, it is recommended that in the future an attempt should be made to verify the estimation of the thermal and electrical energy demand of the village with real data extracted firsthand. A slight change in this can affect the capacities required for the modelled equipment and, hence, the results of the whole system may vary.

As in the previous case, it is needed a deeper and more accurate study of biomass availability and current used fuels, a key factor to define properly the most suitable configuration due to affect to both, heat and electric, demands. Moreover, since there is no information collected on the existence of a market for biomass generated by the agro-livestock sector, the purchase price of biomass used in this study is based on an estimate of the average price at national level. Since this measure has quite a social component, as it is the residents of the ETCR themselves who benefit from its implementation, a study should be carried out to assess their willingness to make the extra effort of transporting it to the conversion plant according to its sale price.

Finally, with reference to the environmental analysis, in this study only the emission of pollutants during the operation stage of both energy systems has been evaluated. However, in order to work with greater accuracy, all stages of the life cycle of the current and Polygeneration system should be analyzed. On the one hand, agricultural waste is currently burnt on site, with the consequent pollution that this entails. The implementation of the hybrid energy generation system would provide a use for this waste and avoid the emission of polluting particles into the atmosphere after the burning process.

On the other hand, this same system of converting waste into a resource for energy generation also produces a by-product that, after being subjected to various treatments, can be used by farmers to fertilize their fields: compost. In this way, the problem of chemical fertilizers that pollute the soil and nearby water flows is tackled.

For all these reasons, although the actual installation of the Polygeneration system proposed in this report requires further investigation of certain details, the calculations and simulations carried out demonstrate the economic viability of the project, as well as its multiple environmental and social benefits, which promote the achievement of many of the targets set by the UN SDGs.

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10 Annex I. Biomass resource estimation

The purpose of this annex is to go deeper into the estimation process and to compile the data and results.

As it is said in the subsection 4.3.3, the quantity of potential biomass from residues is made by two types of sources: the atlas of UPME about residual biomass to estimate the ratios residues per production or area and more recent data to update information about production and area.

10.1 Agricultural residues

On the one hand, for the estimation of agricultural residues, the most recent information of crops is the 2019 EVA's for Arauquita (Table 21). It collected information for year 2017. On the other hand, for each crop included in the atlas, it is known its sown area, production and quantity of residue in 2006 (Table 22). It is supposed the same ratio residues per sown area and residues per production, which are obtained in the atlas, for the most recent data.

In order to avoid over- or underestimating production and area sown, data from the last four EVAs for Arauquita are selected, instead of only 2019 (Table 23). The annual average is taken for the specified period. These average values of production and area multiplied by each correspondent ratio allow to obtain the quantity of agricultural residues (Table 24). It is implemented by using production data by the following equation,

$$Agricultural\ residues\ (ton/year)\ =\sum_{i}^{n}(P_i \times r_i)$$

P_i = average production of agricultural residues (P) of each crop (i) considered

r_i = ratio residues/production for each crop (i) considered.

n = number of crops considered.

It implies an average quantity of agricultural residues of 268,375.34 ton/year or 735.27 ton/day in Arauquita.

For ETCR, an estimation has been made based on the fact that the proportion of sown area and crops is the same as for the municipality of Arauquita (Table 25). Residues per sown area in Arauquita are 24.81 ton/ha and the estimated sown area 0.41 ha. Thus, it is estimated agricultural residues for ETCR as 10.06 ton/year or 27.57 kg/day.

Table 21. 2019 EVA's results for Arauquita.

Crop	Included in UPME atlas	Sown Area (ha)	Production (ton)	Performance (ton/ha)
RICE (1st semester)	Yes	1,000	4,410	4.5
MAIZE (1st semester)	Yes	840	1,200	1.5
RICE (2nd semester)	Yes	500	2,160	4.5
MAIZE (1st semester)	Yes	500	705	1.5
AVOCADO	No	49	735	15
CITRUS	No	124	2,420	20
MARACUYA	No	172	2,736	18
PAPAYA	No	182	3,600	20
PINEAPPLE	No	59	885	15
SACHA INCHI	No	42	96	3
COCOA	No	7,075	4,160	0.6
CANE	No	166	468	3
PLANTAIN	Yes	6,936	102,240	15
TOTAL	-	17,645	125,815	-

Table 22. Sown area, production, quantity of residues and ratios for D. Arauca. Atlas UPME 2006.

Crop	Sown area (ha)	Production (ton)	Quantity of residues (ton)	Residues/production (ton/ton)	Residues/sown area (ton/ha)
RICE	3,636.00	14,190.00	36,185.00	2.55	9.95
MAIZE	16,765.00	28,634.00	40,517.00	1.41	2.42
PLANTAIN	9,399.00	73,653.00	452,966.00	6.15	48.19

Table 23. Last four EVA's results for Arauquita.

Crop	Year	Sown area (ha)	Production
PLANTAIN	2014	3,724.00	58,560.00
	2015	3,756.00	59,264.00
	2016	5,736.00	67,608.00
	2017	6,206.00	70,092.00
MAIZE	2014	3,676.00	5,325.00
	2015	3,200.00	5,589.00
	2016	3,270.00	4,845.00
	2017	3,100.00	3,930.00
RICE	2014	1,985.00	7,801.00
	2015	2,363.00	9,305.00
	2016	3,687.00	17,186.00
	2017	2,568.00	10,814.00

Table 24. Average values of sown area and production of the last four EVA and average quantity of residues for each crop selected.

Crop	Av. Sown area (ha)	Av. Production (ton)	Av. Q. residues (ton)
PLANTAIN	4,855.50	63,881.00	233,987.00
MAIZE	3,311.50	4,922.25	8,013.83
RICE	2,650.75	11,276.50	26,374.96
TOTAL	10,817.75	80,079.75	268,375.34

Table 25. Total and sown area of plantain, rice and maize in Arauquita and ETCR.

	Area (ha)	Sown area selected crops (ha)	Sown area selected crops (%)
Arauquita	304,500	10,817.75	3.6
Filipinas ETCR	7	0.41	3.6

10.2 Livestock residues

Two sources of information are used to estimate livestock residues. On the one hand, the Colombian Agricultural Institute (CAI), with the most recent information about livestock in Arauquita. On the other hand, the UPME's atlas with the manure rate production (Table 29) for poultry, porcine and bovine cattle.

Manure production rates apply to updated livestock data of poultry (Table 26), porcine (Table 27) and bovine (Table 28) livestock. However, there is a different classification between the CAI and the atlas. The CAI results are more detailed and focus on livestock age. There is no problem for poultry. For bovine, the difference consists of CAI divides into gender and UPME did not make this division. Thus, it is only necessary to join CAI's data. For porcine, there is a difference based on CAI divides data into days of life and UPME into phase of life. Therefore, there is not a perfect correlation between data.

Comparing porcine data from both sources, it is related the categories. One of the CAI categories is divided into two further categories of UPME, *lechones* in *lechón lactante* and *precebo*. The proportion is obtained by using UPME data, summing the data of the *lechón lactante* and *precebo* and divided each type by the total.

Other two CAI categories are joined in one, *hembras reemplazo* and *hembras cría* in *hembras lactantes y gestantes*. UPME data presents a division into *hembras lactantes* y *hembras gestantes*, but as it has not been found a clear relation within these pair of categories, it is decided to join in only one. Thus, it is made the proportion between both species to calculate the total manure rate production. In Table 30 is summarised the categories depending on both sources and final category selected for this study. The following equation describes how it is calculated the estimation,

$$Livestock\ residues\ (ton/year) = \sum_{i}^{n}(L_i \times m_i)$$

L_i = average production of livestock residues (L) of each one (i) considered.

m_i = ratio residues/production for each type of livestock (i) considered.

n = number of type of livestock considered.

It implies an average quantity of livestock residues of 919,118.34 ton/year or 2,518.13 ton/day in Arauquita.

For ETCR, an estimation has been made based on the fact that the proportion of livestock area and heads is the same as for the municipality of Arauquita (

Table 31). Residues per livestock area in Arauquita are 16.21 ton/ha and the estimated livestock area 3.54 ha. Thus, it is estimated livestock residues for ETCR as 57.30 kg/day.

Table 26. Quantity of poultry livestock in Arauquita. Colombian Agricultural Institute 2020.

Type of poultry	Head/year
A. Engorde	9,670
A. Postura	14,237

Table 27. Quantity of bovine livestock in Arauquita. Colombian Agricultural Institute 2020

Type of bovine	Head/year
H < 1 AÑO	25,689
M < 1 AÑO	24,001
H 1 - 2 AÑOS	21,353
M 1 - 2 AÑOS	25,647
H 2 - 3 AÑOS	19,469
M 2 - 3 AÑOS	22,983
H > 3 AÑOS	61,924
M > 3 AÑOS	9,713

Table 28. Quantity of porcine livestock in Arauquita. Colombian Agricultural Institute 2020

Type of porcine	Head/year
LECHONES 1-60 DIAS	723
LEVANTE 61 - 120 DIAS	841
HEMBRAS REEMPLAZO 120 - 240 DIAS	378
HEMBRAS CRIA >240 DIAS	569
MACHOS REPRODUCTORES / REEMPLAZO > 180 DIAS	226

Table 29. Manure rate production for each type of livestock. UPME's atlas.

Livestock	Type	Manure rate production (kg/head/year)
POULTRY	A. Engorde	25.55
	A. Postura	38.33
PORCINE	Lechón lactante	102.20
	Precebos	445.30
	Reproductor	2,051.30
	Levante	799.35
	Hembra lactantes y gestantes	2,551.98
BOVINE	< 1 year	1,460.00
	1 - 2 years	3,285.00
	2 - 3 years	5,110.00
	> 3 years	6,570.00

Table 30. Categories of porcine livestock according to UPME, Colombian Agricultural Institute and the project.

UPME category	CAI category	Selected category
Lechón lactante	LECHONES	Lechón lactante
Precebos		Precebos
Reproductor	MACHOS REPRODUCTORES / REEMPLAZO	Reproductor
Levante	LEVANTE	Levante
Hembra lactante	HEMBRAS CRIA	Hembras lactantes y gestantes
Hembra gestante	HEMBRAS REEMPLAZO	

Table 31. Total and livestock area in Arauquita and ETCR.

	Area (ha)	Livestock area (ha)	Livestock area (%)
Arauquita	304,500	155,356	50.5%
Filipinas ETCR	7	3.54	50.5%

11 Annex II. Electricity demand estimation

This annex has been created in order to provide a more comprehensive explanation of how the ETCR electricity demand estimation process has been carried out. As mentioned in Section 4.4.1, due to the lack of accurate data on energy consuming equipment at the ETCR, information from the meetings and literature review has been used in this process. Furthermore, the overall electricity demand has been built from the sum of the demand of each of the sectors that make up the ETCR. The following tables show the power values, consumption habits and other data necessary for this calculation.

11.1 Residential sector

Table 32. Electricity consumption breakdown for the residential sector in the ETCR during a weekday

Equipment	Unit power (W)	Quantity	Total power (kW)	Daily hours use (h)	Electricity consumption (kWh/day)
Light bulbs	11	5	0.055	5.233	0.288
Refrigerator	90	1	0.09	22.963	2.067
Fan	57	1	0.057	3.541	0.202
TV	100	1	0.1	3.964	0.396
Telephone	2.4	2	0.0048	4.976	0.024
Radio	100	1	0.1	0.349	0.035

Table 33. Electricity consumption breakdown for the residential sector in the ETCR during a weekend

Equipment	Unit power (W)	Quantity	Total power (kW)	Daily hours use (h)	Electricity consumption (kWh/day)
Light bulbs	11	5	0.055	5.687	0.313
Refrigerator	90	1	0.09	23.642	2.246
Fan	57	1	0.057	3.848	0.219
TV	100	1	0.1	4.308	0.431
Telephone	2.4	2	0.0048	5.408	0.026
Radio	100	1	0.1	0.380	0.038

11.2 Common rooms

Table 34. Electricity consumption breakdown for the internet room in the ETCR during a weekday

Equipment	Unit power (W)	Quantity	Total power (kW)	Daily hours use (h)	Electricity consumption (kWh/day)
Light bulbs	11	4	0.044	10	0.44
Fan	65	3	0.195	8	1.56
Plug	100	4	0.4	6	2.4
Router	25	1	0.025	24	0.6

Table 35. Electricity consumption breakdown for the nursing room in the ETCR during a weekday

Equipment	Unit power (W)	Quantity	Total power (kW)	Daily hours use (h)	Electricity consumption (kWh/day)
Light bulbs	11	4	0.044	9	0.396
Fan	65	2	0.13	8	1.04
Plug	100	4	0.4	8	3.2

Table 36. Electricity consumption breakdown for the children's room in the ETCR during a weekday

Equipment	Unit power (W)	Quantity	Total power (kW)	Daily hours use (h)	Electricity consumption (kWh/day)
Light bulbs	11	4	0.044	9	0.396
Fan	65	3	0.195	8	1.56
Plug	100	4	0.4	6	2.4

Table 37. Electricity consumption breakdown for the library in the ETCR during a weekday

Equipment	Unit power (W)	Quantity	Total power (kW)	Daily hours use (h)	Electricity consumption (kWh/day)
Light bulbs	11	4	0.044	8	0.352
Fan	65	3	0.195	8	1.56
Plug	100	3	0.3	6	1.8

Table 38. Electricity consumption breakdown for the adults' room in the ETCR during a weekday

Equipment	Unit power (W)	Quantity	Total power (kW)	Daily hours use (h)	Electricity consumption (kWh/day)
Light bulbs	11	4	0.044	10	0.44
Fan	65	3	0.195	9	1.755
Plug	100	5	0.5	6	3

11.3 Commercial sector

Table 39. Electricity consumption breakdown for the commercial sector in the ETCR during a weekday

Type of commerce	Monthly consumption (kWh/month)	Shop surface (m2)
Hairdresser	214.8	33.5
Supermarket	1014.8	38
Stationary shop	213.3	50
Restaurant	530	401
Clothing shop	148	18

12 Annex III. Agriculture and livestock energy demand

Energy demand in agriculture and livestock sector is related to their production [50]. Thus, it is essential to estimate it. It is calculated as proportion of production per area (ton/ha) and supposing the same area distribution in Arauquita and ETCR.

In

Table 40 is recollected the annual agro-livestock production and type in Arauquita and in

Table 41 its area distribution. These values allow to obtain the ratio production per area for each subsector (agriculture and livestock).

Table 40. Agro-livestock annual production and type in Arauquita

	Porcine	Poultry	Bovine	Agriculture
Production (kg/year)	47,814	258,486	69,673,600	125,815,000

Table 41. Land types, their surface and distribution in Arauquita

Type of land	Agriculture	Livestock	Forest	Other use
Surface (ha)	155,356	25,290	119,436	7,413
Surface (%)	50.5%	8.2%	38.8%	2.4%

Firstly, it is obtained the agriculture and livestock area for Filipinas ETCR (considering 153 ha as its total surface and a not exploitation of the 45% of agricultural due to fallow and rest). It is 77 ha of sown area (50.5%) and almost 13 ha livestock area (8.2%).

Secondly, applying the ratio production per surface for each subsector. For agriculture, it is 0.81 ton/ha dividing 125,815 ton/year by 155,356 ha/year. For livestock, 2.77 ton/ha, dividing the whole livestock, 69,980 ton/year by the whole livestock area, 25,290 ha/year. It results in 77.3 ton/year for agriculture and 12.6 ton/year for livestock.

Thirdly, it is necessary to estimate the specific energy consumption for each sector and each type of consumption (electric and gas). In [50], it is recollected statistical values for different agro-industrial facilities. There is a specific energy consumption distribution for each one.

For agriculture, it is considered *mixed agriculture* and *crop cultivation* as reference subsectors. For livestock, *cattle breeding* and *poultry farming*. Moreover, it is considered an electric consumption for lightning and electronic equipment and gas consumption for direct heating and spatial conditioning for each subsector. Consequently, for agriculture, it is supposed 0.5 kWh/ton for electricity and 5.4 kWh/ton for gas. For livestock, 20.0 kWh/ton and 53.2 kWh/ton, respectively.

Table 42. Electricity and gas consumption for the livestock and agriculture sectors per end use

	Livestock		Agriculture	
	Electric	Gas	Electric	Gas
Conditioning	-	36.90	-	2.60
Direct heating	-	16.26	-	2.83
Illumination	17.61	-	0.42	-
Electronic equipment	2.41	-	0.12	-

To conclude, considering the estimated production, agriculture consumes 34 kWh/year for electricity and 340 kWh/year for gas and livestock 19 kWh/year and 1,850 kWh/year.