MASTER THESIS

ENERGY TECHNOLOGY FOR SUSTAINABLE DEVELOPENT

"ANALYSIS OF ENERGY DEMAND ASSESSMENT METHODOLOGIES FOR THE DESIGN OF A HYBRID RENEWABLE MINI-GRID IN A RURAL ISOLATED COMMUNITY IN HONDURAS"

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A esta nueva etapa y a todas las personas y experiencias que han formado parte de ella.

Por hacerme crecer personalmente.

RESUMEN

En el presente Trabajo Final de Máster se analiza el impacto que tiene la estimación de la demanda de energía en el diseño de mini redes híbridas en zonas rurales aisladas de países en vías de desarrollo. Para ello, se realiza un estado del arte para identificar las metodologías, enfoques y herramientas informáticas empleadas en la actualidad para la evaluación de la demanda de energía. Entre ellas, las más utilizadas y apropiadas se analizan y se aplican en la estimación de la demanda de un caso práctico: la comunidad rural de El Santuario, Honduras. En concreto, la demanda de energía se evalúa siguiendo dos metodologías: una primera metodología, basada en definir el consumo entre los usuarios y los equipos mediante factores de simultaneidad, y una segunda metodología, haciendo uso del software LoadProGen2.0. Los resultados se utilizan para desarrollar el diseño técnico y operacional de la mini red híbrida de energías renovables. A lo largo de este proceso se identifican otros parámetros de diseño, como el contexto medioambiental, económico y social o los recursos energéticos disponibles en la zona.

Diferentes configuraciones de sistemas híbridos se simulan por medio del software HOMER hasta llegar a la solución óptima. Las diferentes alternativas obtenidas se analizan y se comparan desde el punto de vista económico, medioambiental y técnico, para así ganar nuevas ideas y enfoques que sirvan como orientación para diseñadores de futuras mini redes híbridas. Como resultado, se propone una nueva metodología para el diseño de mini redes en zonas rurales aisladas de países en vías de desarrollo. Además, se incluye en el análisis un procedimiento para la estimación de las emisiones de Gases de Efecto Invernadero (GEI) que se podrían evitar mediante la instalación de redes híbridas en zonas aisladas.

Palabras clave: Mini red eléctrica híbrida; Demanda de electricidad; Energías Renovables; Comunidades rurales aisladas; Honduras

RESUM

En el present Treball de Fi de Màster s'analitza l'impacte que té l'estimació de la demanda d'energia en el disseny de mini xarxes híbrides en zones rurals aïllades de països en vies de desenvolupament. Per a la seua consecució, es realitza una revisió bibliogràfica per tal d'identificar les metodologies, enfocaments i ferramentes informàtiques gastades en l'actualitat per a l'avaluació de la demanda d'energia. Entre elles, les més utilitzades i apropiades s'analitzen i s'utilitzen en l'anàlisi d'un cas pràctic: la comunitat rural de El Santuario, Hondures. En concret, la demanda d'energia s'avalua seguint dues metodologies: la primera basada a definir el comportament del consum entre usuaris i equips mitjançant coeficients de simultaneïtat, i una segona metodologia fent ús del software LoadProGen2.0. Els resultats s'utilitzen per a desenvolupar el disseny tècnic i operacional de la mini xarxa híbrida d'energies renovables. Al llarg d'aquest procés s'identifiquen altres paràmetres de disseny com el context medi ambiental, econòmic i social o els recursos disponibles en la zona.

Diferents configuracions de sistemes híbrids és simulen mitjançant el software HOMER fins a arribar a la solució òptima. Les diferents alternatives obtingudes s'analitzen i es comparen des d'un punt de vista econòmic, medi ambiental i tècnic, per a així obtindré noves idees i enfocaments que servisquen com a orientació per a dissenyadors de futures mini xarxes híbrides. Com a resultat, es proposa una nova metodologia per al disseny de mini xarxes en zones rurals aïllades de països en vies de desenvolupament. A banda, s'inclou a l'anàlisi un procediment per a l'estimació de les emissions de Gasos d'Efecte Hivernacle (GEH) que es podrien evitar mitjançant d'instal·lació de xarxes híbrides en zones aïllades.

Paraules clau: Mini xarxa elèctrica híbrida; Modelatge de demanda elèctrica; Energies renovables; Comunitats rurals aïllades; Hondures

ABSTRACT

Along the present Master Thesis, the impact of the energy demand estimation on the design of hybrid mini-grids in rural isolated areas of developing countries is analysed. In order to do so, a state of the art of the current methodologies, approaches and computational tools applied to the energy demand assessment process is performed. The most used, suitable and appropriate methodologies identified in the scientific literature are analysed and applied in the estimation of the energy demand of a practical case: the rural community of El Santuario, Honduras. The energy demand is assessed following two methodologies: a first methodology based on building up the consumption behaviour of users and appliances by coincidence factors, and second methodology by means of LoadProGen2.0 software. The results are used for performing the technical and operational design of a hybrid renewable mini-grid. Along this process, further design parameters are identified and studied such as the environmental, economic and social context or the available energy resources of the area.

By means of HOMER software, different configurations of hybrid systems are simulated until reaching the optimal solution. The different optimal alternatives obtained are analysed and compared from the economic, environmental and technical point of view, in order to gain insights and guidance for designers of future mini-grids. As a result, a new methodology for the design of hybrid mini-grids in rural isolated areas of developing countries is proposed. Moreover, a procedure for estimating the avoided Green House Gases (GHGs) emissions with the installation of mini-grids in rural isolated areas is included in the analysis.

Keywords: Hybrid electric mini-grid; Electricity demand modelling; Renewable Energy; Isolated rural communities; Honduras

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LIST OF SYMBOLS

Symbol	Description	Unit
$\overline{std}$	Average standard deviation	same as variable
$\overline{y}$	Average load profile value	W
A	Adult literacy rate	%
CF	Coincidence Factor	%
D	Demand	kWh/day
D	Distance to local town	Km
D	Functioning cycle	min
E	Energy	kWh
E_{FV}	Solar photovoltaic energy	kWh
E_G	Gasifier energy	kWh
h	Hour	h
h	Daily functioning time	min
I	Income per capita	USD/capita
i	Type of electrical appliance	none
j	User class	none
k	Profile time steps	Sec, min, hour
L	Agricultural land area	ha
$LCoE$	Levelized Cost of Electricity	USD/kWh
LF	Load Factor	%
Lps	Lempiras	Lps
L_T	Total Load	W or kW
m_v	Amount of biomass	kg
N	Number of users	number
n	Type of appliance	none
P	Power	W or kW
P	Population	none
P_N	Nominal Power	W or kW
R	Inland communication length	km
Rh	Random variation of functioning time	%
RWf	Random variation of functioning window	%
T	Period of time	sec, min, h or yr
Wf	Functioning window	min

GLOSSARY

Abbreviation	Definition
ARE	Alliance for Rural Electrification
ATP	Ability to Pay
BAU	Business as Usual
CEPAL	Economic Commission for Latin America and the Caribbean. *Comisión Económica para América Latina y el Caribe*
CIDA	Canadian International Development Agency
CH_4	Methane
CIF	Climate Investment Funds
CNE	National Energy Commission. *Comisión Nacional de Energía*
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_2eq	Carbon Dioxide Equivalent
CREE	Electric Energy Regulatory Commission. *Comisión Reguladora de Energía Eléctrica*
EEH	Energy Company of Honduras. *Empresa Energía Honduras*
ENEE	National Electric Energy Company. *Empresa Nacional de Energía Eléctrica*
ESMAP	Energy Sector Management Assistance Programme
ESMAP	Energy Sector Management Assistance Programme
FAO	Food and Agriculture Organization of the United Nations
FOSODE	Electrical Development Social Fund. *Fondo Social de Desarrollo Eléctrico*
GEF	Global Environmental Facility
GHG	Green House Gases
GIZ	German International Cooperation Agency. *Gesellschaft für Internationale Zusammenarbeit*
GMT	Greenwich Mean Time
GTF	Global Tracking Framework
H_2	Hydrogen
H_2O	Water
IADB	Inter-American Development Bank
IEA	International Energy Agency
IEG	Independent Evaluation Group of The World Bank
IRENA	International Renewable Energy Agency
kW	Kilowatt

kWh	Kilowatt hour
MER	Regional Electric Market. *Mercado Eléctrico Regional*
MSMEs	Micro, Small, & medium enterprises
N_2	Nytrogen
NRECA	National Rural Electric Cooperative Association
O_2	Oxygen
OLADE	Energy Organization of Latin America. *Organización Latinoamericana de Energía*
PIR	Rural Infrastructure Project. *Proyecto de Infraestructura Rural*
RECP	Africa-EU Renewable Energy Cooperation Programme
RISE	Regulatory Indicators for Sustainable Energy
SDG	Sustainable Development Goal
SEforALL	Sustainable Energy for All
SERNA	Secretariat of Environmental and Natural Resources. *Secretaría de Recursos Naturales y Ambiente*
UNDESA	United Nations Department of Economic and Social Affairs
UNDP	United Nations Development Programme
USAID	United States Agency for International Development
WB	The World Bank Group
WHO	World Health Organization
WTP	Willingness to Pay

CHAPTER 1. INTRODUCTION

1.1. BACKGROUND

In a world in continuous growth and development, ensuring universal access to electricity in a sustainable way is essential in order to achieve the Sustainable Development Goals (SDGs). Electricity access has been considered as one of the key elements to achieve society development and improve livelihoods (Mandelli, *et al.*, 2016; Aevarsdottir, Barton, & Bold, 2017). Indeed, electrification can help to reduce poverty and migration, to ensure gender equality or to improve education and health, among others. Aspects with significant impacts, especially for populations of rural isolated areas of developing countries. Moreover, in order to satisfy the energy demand of a continuous growing population without endangering natural resources, clean and renewable energy solutions should be promoted.

As a result, significant efforts for rural electrification in developing countries have been observed in the last years. However, the lack of financial resources and appropriate policy, regulatory and institutional frameworks, are among the main barriers to the progress. Therefore, there is a need of sustainable and cost-effective solutions for the electrification of rural areas (IRENA, 2018). Among the solutions, mini-grids have been considered as the least-cost option for rural electrification (ARE, 2015; IEA, 2017a) as they present several benefits, including technical and operational flexibility as well as wider power operation rates (RECP, 214; GIZ, 2016; IRENA, 2017).

The design of hybrid mini-grids should provide solutions that are safe, efficient, scalable and adequate (SEforALL, 2019). In that regard, the energy demand is one the parameters with greater impact in the design, influencing the system´s size, costs and operational parameters (GIZ,2016). In spite of that, no common methodology for the assessment of the energy demand of rural areas in developing countries has been defined yet, mainly due to the difficulties and unavailability of data (Blodgett, *et al*., 2017; Louie & Dauenhauer, 2016; Stefano Mandelli, Merlo, & Colombo, 2016).

In the last years, mini-grids' designers and research institutions have tested and applied different methodologies, approaches and models implemented in computational tools aiming at reducing uncertainty in the data and obtaining more accurate estimations of the energy demand, hence more reliable mini-grids' designs.

1.2. OBJECTIVES

The main objective of this Master Thesis is to analyse the impact of the energy demand estimation on the design of mini-grids in order to propose a general and replicable methodology for the assessment of the energy demand of rural isolated areas in developing countries.

In order to achieve the main objective, different specific objectives are proposed:

1) To perform a state of the art of current methodologies, approaches and computational tools applied to the energy demand assessment process. And to identify the most used and suitable for rural isolated areas of developing countries.
2) To analyse, test and compare two methodologies in the estimation of the energy demand of the rural community of El Santuario, Honduras. Methodology 1 of building up the coincidence behaviour among users and appliances and Methodology 2 by means of LoadProGen2.0 software.
3) To describe the current environmental and socio-economic context of the rural community of El Santuario and to identify the most suitable renewable energy resources available in the area.
4) To simulate different configurations of hybrid systems in HOMER until reaching the optimal solutions.
5) To compare from the technical, environmental and economic point of view, the optimal configurations of mini-grids obtained with the energy demand results of both methodologies.
6) To collect results in order to gain insights for the energy demand assessment process and design of mini-grids.
7) To propose suggestions and guidance to mini-grids designers along the process. Specifically:
    a) Initial energy demand assessment through surveys and measurements.
    b) Preliminary estimation of the energy demand and load profile by building up the coincidence behaviour among users and appliances.
    c) Use of LoadProGen2.0 software for future demand forecasting
    d) Simulation and optimization of the mini-grid for the design in HOMER.
    e) Procedure for estimating the avoided GHGs emissions with the renewable mini-grid.

1.3. RATIONALE

Small-holder famers and inhabitants of rural areas of developing countries are among the most vulnerable groups to the effects of climate change, as their resources and infrastructures are extremely climate-dependent. In the last years, climate change effects left more than 3.5 million people with need of humanitarian help along the area of the Mesoamerican Dry Corridor (MDC) of Central America (FAO, 2016b), from which 40% live in rural areas of Honduras.

As a result, seeking for solutions for these vulnerable populations, a cooperation among FAO and UPV emerged. It aims at enhancing climate resilience, well-being and livelihoods of rural isolated communities through actions that enable the adaptation and mitigation to climate change. These actions include the facilitation of access to energy through a hybrid mini-grid based on renewable energy. The present Master Thesis is developed under the mentioned cooperation and the first practical case of the initiative that is carried out in the rural community of El Santuario, Honduras.

When carrying out the design of the hybrid mini-grid of the rural community of El Santuario, most of the difficulties were found in the estimation of the energy demand of the community, mainly due to the lack of previous access to electricity in the community. It was found out that the inaccurate or even unavailable data strongly influences the demand characterization, obtaining differing load profiles with slight variations of the parameters, such as number and type of appliances or usage hours and schedule.

Therefore, this Master Thesis is performed in order to maximize the accuracy and assurance in the estimations of the energy demand and load profiles, thus avoiding unreliable, costly and unsustainable energy generation systems.

1.4. STRUCTURE OF THE DOCUMENT

The present Master Thesis is structured in Chapters as follows: Chapter 2 presents an overview of the general context of Honduras focused on the energy sector and the area of the Mesoamerican Dry Corridor (MDC). Along Chapter 3 a state of the art of rural electrification in developing countries is presented, which includes the main characteristics of rural areas and the justification of the importance of access to electricity, as well as the different electrification options and technologies. Chapter 4 includes the literature review about the design of hybrid mini-grids, with focus on methodologies, approaches and models used for performing the energy demand assessment; the HOMER software, as a powerful tool for designing mini-grids, is described. In Chapter 5 the main characteristics of the rural community of el Santuario, as the practical case for this study, are presented together with a preliminary estimation of the energy demand. Chapter 6 includes the application, analysis and comparison of the results of two methodologies for assessing the energy demand of the community: Methodology 1 of building up the coincidence behaviour of users and appliances, and Methodology 2 by means of LoadProGen2.0 software. Consequently, in Chapter 7, the evaluation, sizing and modelling of the hybrid renewable mini-grid for the community are described. The obtained load profiles and energy demand from the two methodologies are used as inputs for the simulation and optimization of different configurations of mini-grid. Chapter 8 presents the discussion of the results and way forward. A methodology for the design of mini-grids in rural isolated areas is proposed along with recommendations for its application and its potential replication and scalability to other rural communities of the Mesoamerican Dry Corridor area and worldwide. Chapter 10 reports the outcomes and conclusions gained from the analysis. The final Chapter presents the bibliography.

CHAPTER 2. GENERAL CONTEXT OF HONDURAS

2.1. HONDURAS

Honduras is located in the north-central area of Central America. The country has boundaries to its north and east with the Caribbean Sea, south with El Salvador and west with Guatemala, with a total land area of 112,492 km^2.

According to (INE, 2019) Honduras' total population is 9,119,914 inhabitants, from which an average of 45.5 % is currently living in rural areas, this being the highest rate in Central America after Belize. It is a middle-low income country with a GDP of almost 23 billon USD in 2017 and 66% of people living in poverty in 2016 (The World Bank, 2018). Around 20% of inhabitants of rural areas have incomes lower than 1.9 USD/day, thus facing extreme poverty.

2.2. ENERGY SECTOR IN HONDURAS

The energy sector in Honduras emerged in 1957, when the military Governing Board created the National Electric Energy Company (ENEE) through the Decree-Law No. 48 that is in charge of developing national electrification including production, transmission and distribution of electricity in the country (ENEE, 2019). Since then, the sector has continued growing through policies and governmental reforms.

The reforms started with the "*Ley Marco del Sub-Sector Eléctrico*"[1], which defines the structure of the electricity sub-sector, and was enacted in 1994 with the objective of overcoming the negative effects of the crisis of 1994, caused by a fast-growing demand that the electric system of that time was not able to supply.

Even though the liberalization of the generation sector was achieved in the 90's, the Government still has a strong power within electricity tariffs and fuel price regulation, as well as the operation of the transmission and distribution systems. The National Energy Commission (CNE) is in charge of the regulation of the electricity sector; and the policies' formulation is carried out by ENEE and the Secretariat of Environmental and Natural Resources (SERNA), which was created by Executive Decree No. 218 in 1996 and is currently known as "MiAmbiente" (IADB, 2013).

The current regulatory framework is based on the "*Ley General de la Industria Eléctrica*"[2] (2013). This law was designed to improve the regulation of the national electricity market (generation,

[1] *English translation:* Framework Law of the Electric Sub-sector.

[2] *English translation:* General Law of the Electric Industry.

transmission, distribution, commercialization and operation of the electric system) besides allowing its interconnection with the Regional Electric Market (MER) of Centro America, through the establishment of the Electric Energy Regulatory Commission (CREE), which replaces the older CNE.

The electrical interconnection system is composed by transmission lines of three different voltage levels: 69, 138 and 230 kV, which carry the electric power from the generating plants to the substations located along the country. This line allows also the interconnection to the regional transmission line (SIEPAC line), which enables the electricity exchange, through 1.793 km of 230kV transmission lines, among the different Latin-American countries.

Over time, the electric distribution grid has been characterized by electrical losses that reached 15% in final commercial users, and blackouts that lasted more than 35 hours (World Bank, 2007). In 2016, trying to seek a solution for these limitations, ENEE developed its "*Plan Estratégico del Grupo ENEE 2016-2020"*[3] which includes an investment plan to improve the electrical infrastructure. The Energy Company of Honduras (EEH) has the responsibility to improve, operate and maintain the distribution lines.

Distribution lines are divided in a primary line of around 30,000 km and a secondary line of almost 20,000 km. The most developed and robust lines belong to San Pedro Sula, Puerto Cortés, El Progreso, Tela, La Ceiba, Tegucigalpa y Choluteca, as the main consumer centres, whereas distribution lines in rural areas and small communities are too old and in bad conditions to ensure a reliable energy supply. Moreover, it is shown in the Fig. 1 , many rural areas still lack access to the national electric grid.

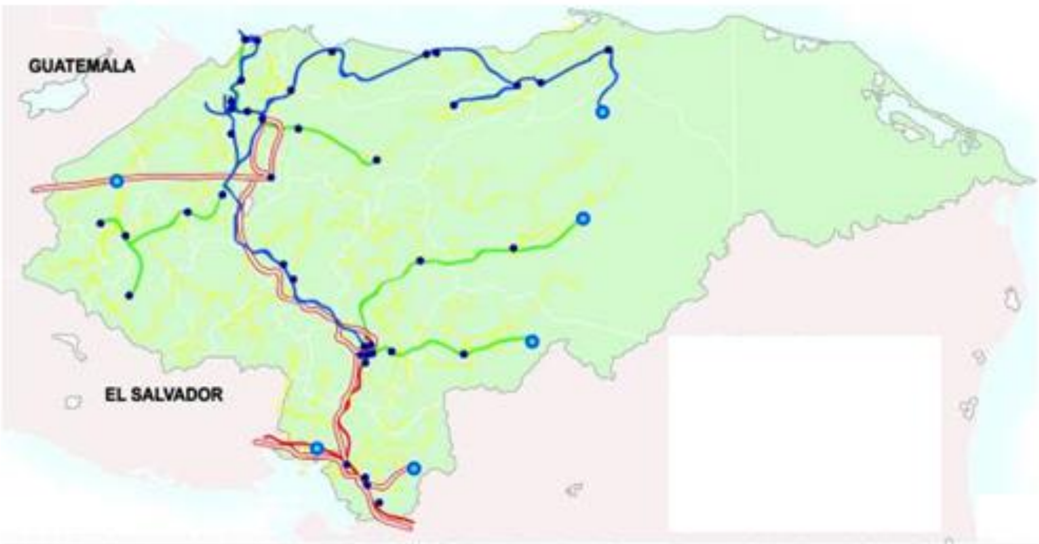


Figure 1. Electrical Interconnection System of Honduras. Source: Adapted from El Heraldo (2016)

[3] *English Translation:* Strategic Plan ENEE Group 2016-2020

2.2.1. Generation and renewable energy

The country's interest in renewable energy generation emerged in 2007 with the "*Ley de Promoción a la Generación de Energía Eléctrica con Recursos Naturales*"[4], seeking to promote private and public financial investments in renewable energy generation projects, as a result of the hydrocarbon prices' increase. As a consequence, the Regulations to the Biofuels Law were published in 2008. Another driving law was the Special Regulatory Law for Renewable Energy Public Projects of 2010 (IADB, 2013).

During its early years, the electricity generation mix of Honduras was dominated by hydroelectric and thermoelectric plants. In 2009, the installed electricity capacity reached 1,610.3 MW, from which 52.4% of electricity was generated by thermoelectric plants operated with liquid fuels, 47.5% by hydroelectric power plants and only 0.1% by non-conventional renewables.

In January 2010, Honduras' Government published the Country's Vision 2010-2038 and its National Plan 2010-2022, with the goal of achieving 60% shares of renewables in the electricity generation mix in 2022 and an 80% in 2038.

Since then, the installed capacity of renewable energy has kept growing (IRENA, 2018a). The first wind power installation, known as "Cerro de la Hula" and located 24 km south from Tegucigalpa, was built in 2011 with 102 MW of installed capacity (OLADE, 2012). However, as it is shown in Fig. 2 , it was not until 2015 that solar photovoltaic started to gain popularity, increasing from less than 1 MW of installed capacity in 2014 to around 450 MW in 2015. This market shift could be associated with the tax incentives of 3UDS/kWh that the government introduced in 2013 for the first installed 300 MW until August 2015 (PV Magazine, 2016). In 2016, Honduras took the leadership as the first country with more than 10% of solar energy in its electricity mix (López, 2017).

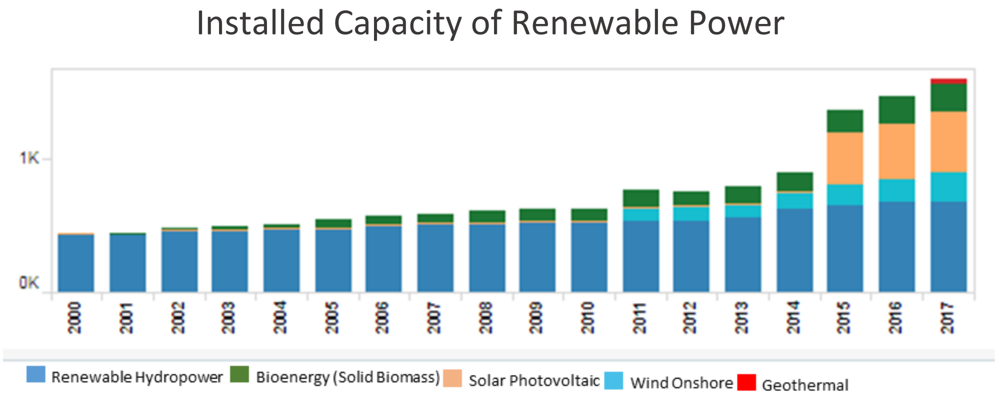


Figure 2. Evolution of installed capacity of renewable power in Honduras from 2000 to 2017. Source: IRENA (2018)

According to the last statistical bulletin of ENEE (ENEE, 2018), by December 2018 the total installed capacity reached 2703.36 MW. Thermoelectric with liquid fuels and hydroelectric plants dominate, without significant difference, both public and private sectors, reaching 882.1 and 705.8 MW respectively. Biomass, wind, solar photovoltaic and coal energy belong to the

[4]*English Translation:* Law of Promotion of Electric Energy Generation trough Natural Resources

private sector, which in total owns 62.7% of the electricity generation plants in the country. Renewable energy, without considering hydroelectricity, represents 36% of the installed capacity. The percentage in terms of installed capacity per energy source is shown in Fig. 3.

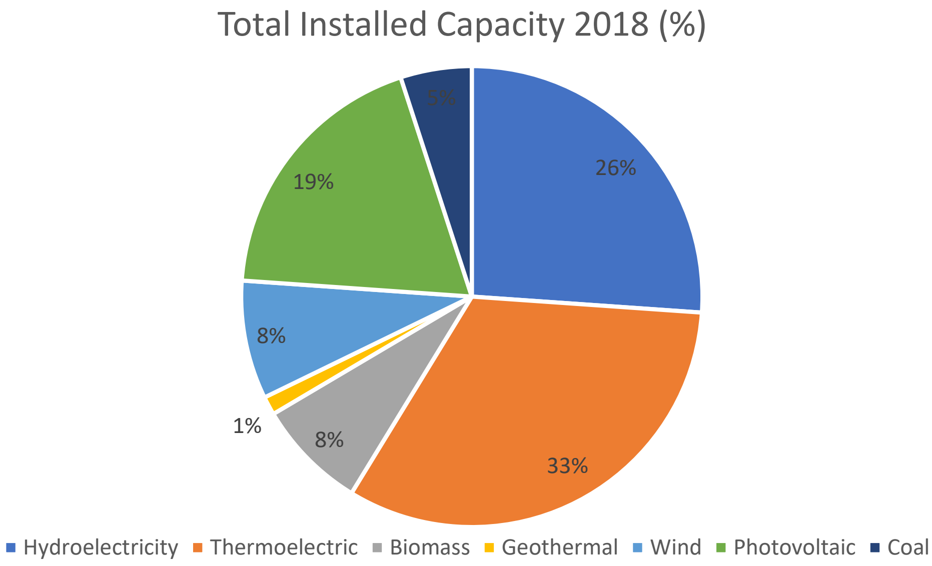


Figure 3. Total installed capacity by source in percentage in Honduras. Source: Own elaboration adapted from ENEE's statistical data (ENEE, 2018).

During 2018, around 10.5 TWh were generated in the electricity system of ENEE. More than 60% of electricity generated still comes from thermoelectric and hydroelectric plants. However, according to ENEE's statistical data from December 2018, it can be deduced that electricity generation from renewable sources in 2018 increased by 9% compared to 2017.

2.2.2. Consumption

ENEE's last statistical bulletin (ENEE, 2018) also shows that the electricity generated in the national electric system fuelled a total of 6.2 TWh of energy consumption. The most consuming sector was residential, with 39.8% of the total, followed by commercial and industrial sectors, with 26.8 and a 12.6% respectively (Fig. 4). On average, the number of customers registered reached 1.8 million, from which the large majority, 91.72% are residential users. This results in approximately 3.4 MWh of energy consumption per capita in 2018. The demand peak for the year 2016 was of 1,560.5 MW, reached in April around 7 p.m., which is similar to the values recorded during the previous years (ENEE, 2016).

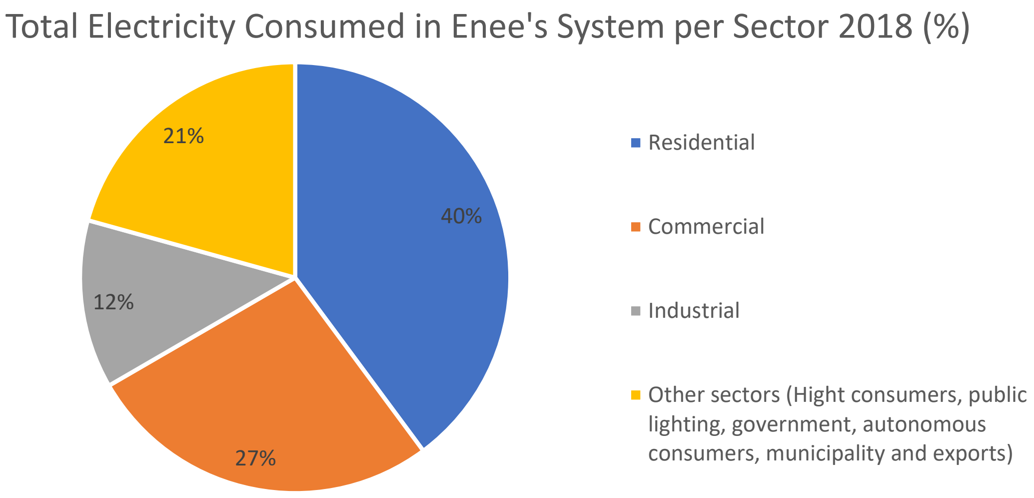


Figure 4. Total electricity consumed in ENEE's System per sector in %. Source: Own elaboration based on ENEE's statistical data (ENEE, 2018).

The electricity sales per sector have been generally increasing since 2000 as it is shown in Fig. 5 below (CEPAL, 2016). However, it can also be observed that from 2010 to 2015 this growth is more slow, which may be due to tax avoidances and power theft (ENEE, 2016).

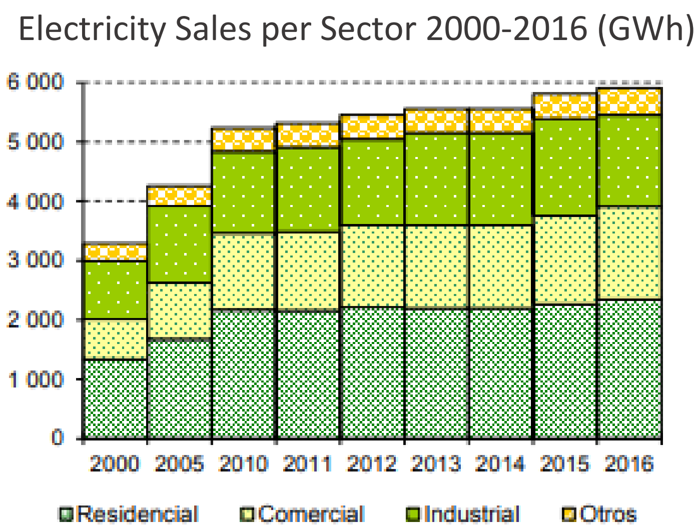


Figure 5. Honduras' electricity sales per sector 2000-2016 in GWh. Source: CEPAL, (2016).

The tendency shows that whereas the number of users connected to the national electric system increases, the MWh consumed per capita decrease (Fig. 6). This fact could be related with the electricity tariff trend over time, which will be explained below.

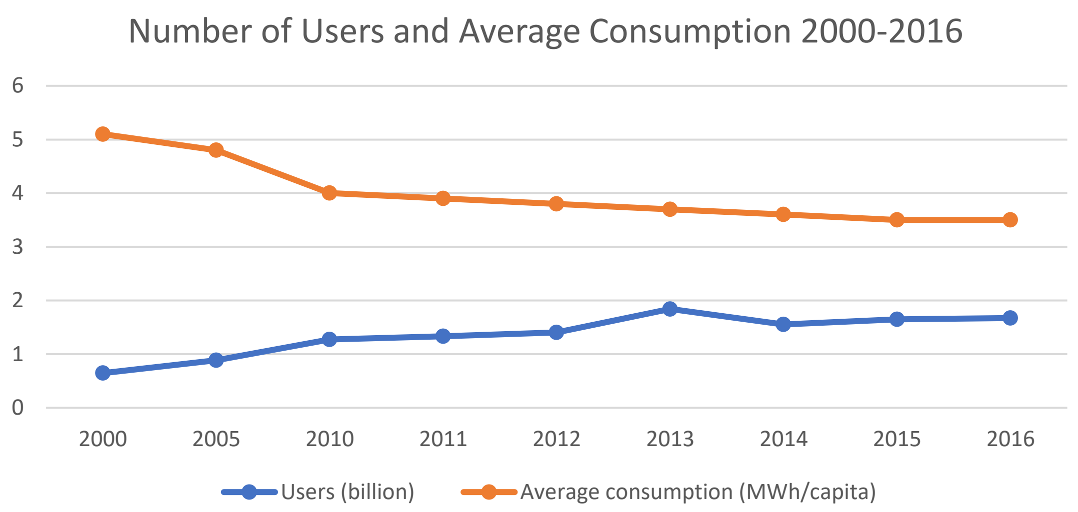


Figure 6. Evolution of users (in billions) and average consumption of electricity (in MWh/capita) 2000-2016. Source: Own elaboration based on data from (CEPAL, 2016).

Fig. 7 shows the evolution of electricity tariffs per sector in the last years (CEPAL, 2016). An increase in prices, especially until 2011, besides a notable difference in the tariff depending on the type of customer, can be observed. This evolution could be explained by the electricity subsidies and financial losses that ENEE's electric system faced. In 1994, a direct subsidy for residential users with less than 300 kWh consumption per month was established, estimated in an average of 279 million Lps./year in 2006. Additionally, ENEE's inefficient operation processes resulted in high supply costs, reaching financial losses of 2,643 million Lps./year (ESMAP, 2010). It was not until 2013, when the subsidies where abolished with the "*Ley General de la Industria Electrica*[5]", that the electricity prices started to decrease. The introduction of private thermoelectric plants also contributed to this fact during lasts years (ENEE, 2016).

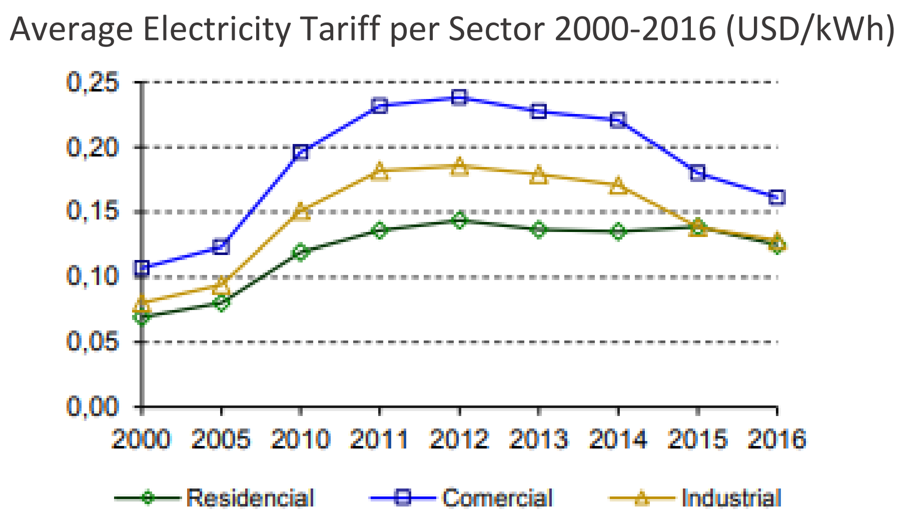


Figure 7. Honduras' average electricity tariff per sector 2015-2016 in USD/kWh. Source: CEPAL (2016)

[5] *English Translation:* General Law of Electric Industry.

2.2.3. Rural electrification

Although Honduras' energy sector strongly influences the economic, social and productive sectors' growth (Direcon, 2016), the country still has one of the lowest electrification rates in Central America. In 2016, still around 24% of the population, 1.9 million people, had no electricity access (IEA, 2017; CEPAL, 2016).

In this context, Honduras has channelled its efforts to the electrification of isolated rural areas. The interest started from the creation, in 1994, of the Electrical Development Social Fund (FOSODE) and the Social Electrification Office (OES). Due to the success, ENEE created in 2002 the "*Plan Nacional de Electrificación Social*"[6] (PLANES), supported by the Canadian International Development Agency (CIDA), through which the Government set a goal of 75% for the rural households' electrification rate. However, ENEE statistics of 2005 showed that 37.5 % of people living in rural areas still lacked electricity access.

Therefore, other programs and initiatives were launched. For instance, the Rural Infrastructure Project (PIR) (2005-2016), financed with World Bank (WB) and Global Environmental Fund (GEF) appropriations, with the objective of reducing rural poverty through basic infrastructure (roads, water supply systems, sanitation network and electrification). Through it, around 150,000 people from rural areas were provided with access to electricity (The World Bank, 2016).

Moreover, in November 2018, the Inter-American Development Bank (IADB) approved the Rural Electrification Program in Isolated Areas, with the aim of providing electricity for rural isolated areas of Honduras though mini-grids with diesel generators.

Fig. 8 below shows the evolution and growth of the electrification rate in Honduras since 1994. However, in spite of the efforts, the electrification rate in urban areas has stagnated around 82% whereas almost 40% of the population in rural areas still lack electricity (IEA, 2017; CEPAL, 2016).

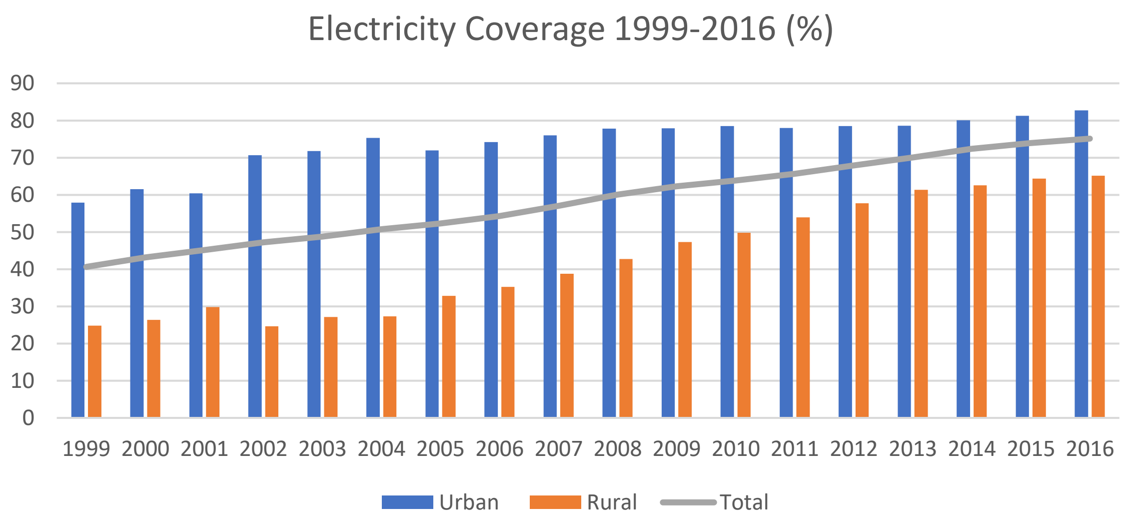


Figure 8. Urban, rural and total electricity coverage 1999-2016 in %. Source: Own elaboration from CEPAL, (2016)

[6] *English Translation:* Social Electrification National Plan

Similar trends have been observed across all Latin American Countries (LAC), where electrification rates increase as the countries' economy grows until it reaches 80-90% and then it stagnates due to difficulties when accessing isolated areas. Moreover, the most vulnerable sectors and countries are those with lower incomes as can be seen in Fig. 9, which contains the results of national surveys across LAC regarding rate of electrification, with Quartile 1 ("Q1") as the poorest quartile interviewed (Jimenez, 2016).

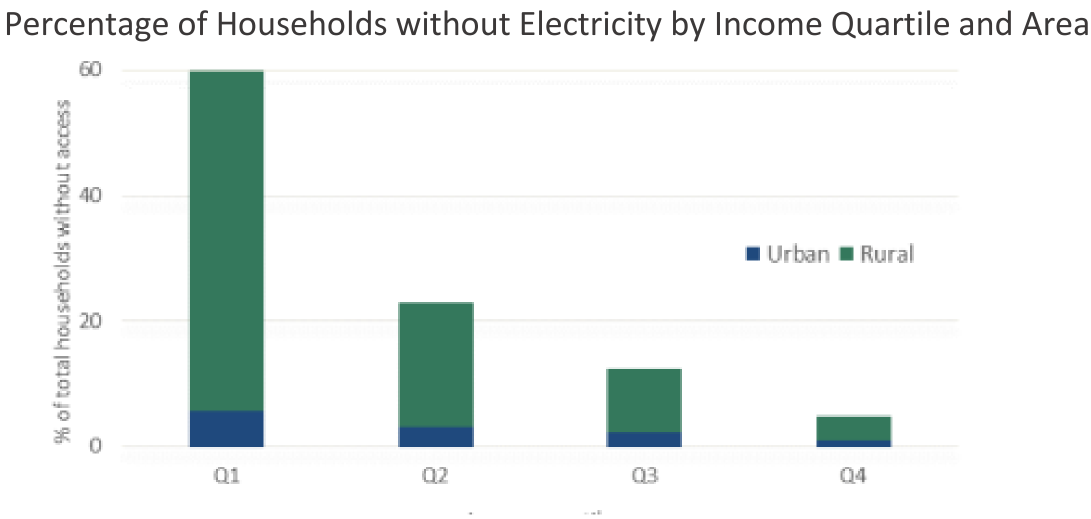


Figure 9. Percentage of households without electricity by income quartile and area. Source: Jimenez (2016).

Although IEA (2017b) foresees a change in this situation with the New Policies Scenario (2017-2030) including decentralized renewable systems, improvement of policies and financial resources, for the time being, there is still a need of programs and projects supporting rural electrification and institutional capacity strengthening not only in Honduras but across all LAC countries in order to enhance livelihoods of vulnerable populations and avoiding energy poverty.

2.3. MESOAMERICAN DRY CORRIDOR

The Mesoamerican dry corridor reaches an area from Chiapas (Mexico) to Guanacaste (Costa Rica), passing through Guatemala, El Salvador, Honduras and Nicaragua. Its climate category is tropical dry or sub-humid forest.

The region is characterized for experiencing the cyclical phenome event of El Niño-Southern Oscillation (ENSO), causing prolonged drought periods followed by heavy rains and floods, thus a lack of availability of hydric resources, as well as landslides and soil erosion. The intensity and frequency of these extreme climate events has increased in the last years due to climate change effects, and the socio-economic and environmental vulnerability of the area (FAO, 2017).

The most susceptible areas are characterized by drought periods of more than 6 months, with low rainfalls (between 800 and 1,200 mm/year). Whereas Guatemala and Nicaragua have 11.5% of their land located within the most affected zone, most of the territory of Honduras (50%) and

El Salvador (100%) is under the effects of ENSO. Fig. 10 (FAO, 2012) shows the distribution of areas according to the degree of severity:

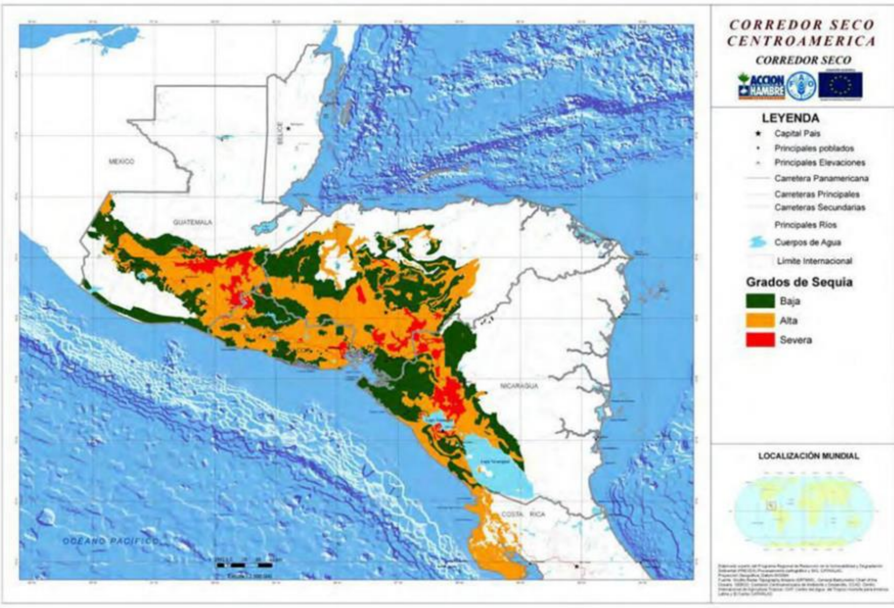


Figure 10. Mesoamerican Dry Corridor distribution according degree of droughts severity. Source: FAO (2012)

Small-holder producers and inhabitants of rural communities are the most affected populations, as their resources and infrastructure are not enough to cope with these extreme climate events. Therefore, vulnerable populations are losing crops, causing malnutrition among 10% of population mainly concentrated in children (FAO, 2017)., and livelihoods, increasing the migration to urban areas as the as only solution for subsistence.

FAO (2016b) estimated that there are more than 3.5 million people with need of humanitarian aid along the Mesoamerican dry corridor, from which almost 40% are located in Honduras. The main economic activity of 45.5% of inhabitants of rural areas in the country is corn and bean subsistence agriculture. Corn has experienced a yield decrease of around 60% (Calvo-Solano, *et al.*, 2018; FAO, 2016), whereas losses of bean yield reached 80% (FAO, 2016b) with a 132% price increase in 2014 compared to the previous year (Proyecto Mesoamérica, 2015; WFP, 2015)

In this regard, there is a need of solutions that contribute to enhance the resilience of rural communities to climate change, promoting a shift in the current agricultural and economic systems. To this effect, the electrification of these areas plays an important role in improving adaptation to climate change as well as contributing to its mitigation.

CHAPTER 3. RURAL ELECTRIFICATION IN DEVELOPING COUNTRIES

According to IEA, (2017b) an estimated 1.1 billion people, which represent 14% of the population, lack access to electricity. Even though the number of people is 97 million lower than in 2016, there is still an urgent need for providing universal access to modern energy. Among people without energy access, 84% dwell in rural areas of developing countries, with Sub-Saharan Africa the most affected with just a 23% of electricity access. Moreover, it is estimated that if we do not act and continue under a Business-As-Usual (BAU) scenario, around 600 million people will still not have access to electricity by 2040 (IRENA, 2017).

Satisfying the energy demand of both rural and urban areas presents high costs. (IEA, 2017b) states that 52 billion USD of additional investment between 2018 and 2030 will be required to achieve universal electrification. As a result, policy-makers and governments must face high costs with limited budgets.

Nevertheless, the adoption of the United Nations Sustainable Development Goals (SDGs) in 2015, especially with SDG 7 (Ensure access to affordable, reliable, sustainable and modern energy for all by 2030) provided, for the first time, political recognition has been given to energy and its importance for sustainable development. Indeed, access to modern energy will contribute to other SDGs as end poverty (SDG 1), improve air quality and health services access (SDG 3), end hunger (SDG2), economic growth and employment (SDG 8), climate change adaptation and mitigation (SDG 11), sustainable industrialisation (SDG 9) and gender equality (SDG 5) (IEA, 2017b).

As a result, significant efforts for rural electrification have been observed in the last years. International organizations have increased their attention to poverty reduction (Kanagawa & Nakata, 2006), thus targeting developing countries for electricity access. Besides, electrifying rural communities off grid make them more liveable, prevents their population from migrating to the metropolis, and may even appeal to those who already migrated to come back.

The UN is promoting sustainable energy with the program Sustainable Energy for All (SEforALL), boosting SDG7 and looking for universal energy access, renewable energy use and energy efficiency improvement. Among others, the World Bank Group, the International Renewable Energy Agency (IRENA), the International Energy Agency (EIA) and the World Health Organization (WHO) are joining efforts to end energy poverty. Not only by measurement and statistical programs such as Global Tracking Framework (GTF) or Regulatory Indicators for Sustainable Energy (RISE), but also implementing initiatives and managing funds such as the Energy Sector Management Assistance Programme (ESMAP) or the Climate Investment Funds (CIF).

More effective regulatory and financial frameworks, along with technology improvements, cost reductions and positive environmental and social impacts, are helping to build a promising future for rural electrification in developing countries.

3.1. CHARACTERISTICS OF RURAL AREAS

Rural areas are characterized by being isolated (Lahimer *et al.*, 2013) and scattered. This results in limited accessibility to fuel suppliers (Mandelli, *et al.*, 2016).and high costs when electrification is done through national grids (Grimsby, Aune, & Johnsen, 2012). Furthermore, the main economic activity is small-scale agriculture (Rahman *et al.*, 2013), followed by others such as livestock farming, fishing, forestry or tourism (Lahimer *et al.*, 2013), providing low household incomes. The location inaccessibility also reduces the opportunities for participating in local, regional or national markets. Other characteristics are lack of education and health services, gender inequality, small infrastructure and lack of clean water supply (Mandelli, *et al.*, 2016).

3.1.1. Rural energy uses

Main energy sources in rural areas are kerosene, batteries and wood, depending on household incomes and affordability, what results in pollution affecting both the environment and the inhabitants´ health.

According to Mandelli, *et al.* (2016) and IEG of The World Bank (2008), energy uses in rural areas can be classified in domestic, community and productive:

3.1.1.1. Domestic uses

Most of the energy consumed in rural areas is accounted in households, with load power ranges between tens to hundreds of W.

The energy is mainly used for cooking, heating water, lighting, heating and use of small electrical devices such as mobile phones, radios or TVs (Djanibekov & Gaur, 2018). Up to 80-100% of it is consumed for cooking and heating water using traditional biomass. Other requirements such as lighting, cooling and heating are only affordable for some households, due to accessibility and high capital and maintenance costs, and are usually covered with other sources of energy as electricity from the grid, gas or petroleum.

3.1.1.2. Community uses

In education and health services, electricity is the main source of energy and the power requirements range from a few kW for rural small installations, to dozens of kW for large schools or hospitals.

Electricity is mainly used for lighting, and to maintain the cold chain for vaccines in health services.

3.1.1.3. Productive uses

As stated, agriculture is the main economic activity in rural areas. Although humans, animals and tractor engines have been the main power sources for agricultural activities, the number of motor engines is increasing (FAO, 2016a). For this agricultural mechanization, fossil fuels are the main energy source. The agricultural activities include land preparation, cultivation, irrigation, weeding, planting, harvesting or drying.

Furthermore, other productive activities such as milling, vegetable and fruit processing, tobacco-curing, pottery making, packing etc. are being developed in these communities. Other communities also present small businesses like shops, bakeries, kiosks and beer bars. As there is a variation of activities, the power requirements range from few to hundreds of kWs.

3.2. IMPORTANCE OF RURAL ELECTRIFICATION

Rural electrification is essential to end poverty and ensure the well-being of people from rural areas. Through history, electrification has played an important role in society development and improving living standards (Stefano Mandelli, Barbieri, *et al.*, 2016). Poverty and household head's gender have shown a high correlation with rate of access to electricity (IEA, 2017b).

Several studies have analysed the beneficial effects of rural electrification in developing countries. For instance, Kumar, Santosh & Rauniyar (2018) determined that rural electrification in Bhutan improved nonfarm income in up to 76% and education, estimated in 0.72 additional studying years. Barron & Torero (2017) calculated a 66% reduction of fine particulate matter concentration in a rural electrification program in El Salvador and a solar lamps electrification project in Tanzania (Aevarsdottir, Barton, & Bold, 2017) resulted in 25% higher income due to the development of new activities.

Overall, it has socio-economic benefits that influence poverty, health, incomes and environment (Kanagawa & Nakata, 2006). The literature shows that main beneficial impacts of rural electrification can be classified in poverty reduction, education and health, gender and environment.

3.2.1. Poverty reduction

Several studies agree that the average annual incomes for households with electricity access is higher than in those with lack of electricity (Farman, Alam, & Sharma, 2011).

Indeed, the access to reliable and affordable energy may lead to develop productive activities and reach the needs of agricultural and rural industries, thus providing employment and new sources of household incomes. The productivity in agricultural activities such as irrigation, crop-processing or harvesting increases, saving resources (mainly water waste), human labour hours and increasing food production, thus food security. Moreover, micro, small, & medium enterprises (MSMEs) may be developed, contributing to eradicate poverty.

3.2.2. Education and health

Lighting improves concentration and comfort at schools, allows more teaching hours and extra time for studying at home, with parents support (Welland, 2017). Therefore, students obtain higher scores and the educational performance is improved. For instance, UNDESA (2014) found out that the rate of education's completion reached 100% in villages of Sudan and Tanzania after electrification.

Moreover, electricity enables IT connections. This provides more information access and knowledge gain not only for students, exposing them to new cultural information hence developing creativity and own opinions, but also for professors, improving their teaching skills and knowledge (Welland, 2017).

According to The World Health Organization (2019), electrification prevents vaccine spoilage and interruptions of medical services. Emergencies can be quickly solved with communication systems access, which also allows to increase knowledge in medical treatments or procedures. Furthermore, patients can have healthcare during no-sun hours and services to other services such as hot and clean water.

The comfort also promotes the arrival of more professionals to work on educational or health centres.

3.2.3. Gender equality

Electrification has also positive impacts in gender equality, as women and girls in rural areas generally suffer discrimination. The arrival of electricity appears as an opportunity for involving women in decision-making processes and managing incomes, expenses and savings. Increase of education and communication services, provide awareness of legal issues regarding gender inequality (UNDP, 2016).

However, as in rural areas women typically perform household chores, the increasing of lighting hours may result in an increase in working hours (Ashden, 2012). To avoid this, specific policies and practices that empower women must be developed.

3.2.4. Environment

The energy access directly reduces the dependence on fossil fuels or other pollutant sources such as kerosene lamps or batteries. Besides reducing emissions, fire risks problems are avoided, and indoor air quality is improved.

Using renewable energy sources, such as photovoltaic or wind, contribute to mitigate the effects of climate change besides providing adaptation and resilience to inhabitants of rural areas. It also avoids climate migrations. It can also reduce the wood dependence that in many cases is gathered from protected lands and causes deforestation problems.

3.3. ELECTRIFICATION OPTIONS

The Alliance for Rural Electrification (ARE) is an international business association, which collaborates with other international entities such as RECP or SEforALL, and promotes reliable, cost effective and sustainable rural electrification. The Alliance for Rural Electrification (2015) defines rural electrification as “the process of bringing electrical power to rural and remote areas”.

The electrification process in rural areas can have two approaches: *on-grid* or *off-grid* systems. Whereas centralised grids have a large size (from thousands of GW to MW) and high voltage transmission lines to reach consumers over a country or a continent, *off-grid* systems have a small size and cover residential or small commercial users (IRENA, 2015). Moreover, as rural areas are characterized by being isolated and scattered, the extension of the national grid is often not economically feasible (Stefano Mandelli, Barbieri, *et al.*, 2016), only when the population has a high demand and the investment cost of transmission lines (around 22,750 €/km) and distribution lines (12,000 €/km) can be justified (RECP, 2014). Despite of the fact that fossil fuels for energy generation are generally expensive for dwellers of these areas, they have access to other clean energy resources, which implies high potential for decentralized renewable energy systems.

Therefore, *off-grid* systems are presented as the best solution for rural electrification, being cost-effective, environmentally sustainable and modular, with quick deployment potential (IRENA, 2016). The interest in off-grid systems in developing countries is increasing, mainly in hybrid micro-grid systems (Stefano Mandelli, Barbieri, *et al.*, 2016). This, together with cost reductions, technology advancements and enabling policies is giving rise to increasing interest in *off-grid* electrification: IRENA estimated that around 133 million people were consuming energy from off-grid technologies in 2016, with 100 million using Solar lights and Home Systems and 9 million with mini-grid systems (IRENA, 2018b).

It is shown in Fig. 11 that off-grid renewable energy capacity increased from under 2 GW in 2008 to over 6.5 GW in 2017, with Asia and Africa as the regions that account for the most part of the growth. Moreover, 83% of this capacity covers the industrial, commercial and public sectors, and just 17% is used for household electrification. Bioenergy, with agricultural and forestry residues, is the most used technology for industrial sector end-uses, whereas Solar Photovoltaic is used for commercial, public, residential or agroforestry sectors.

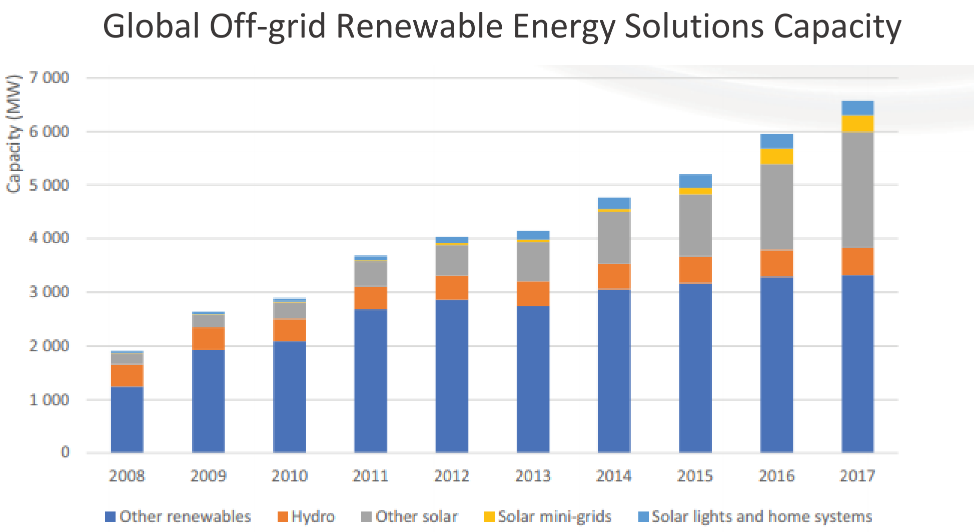


Figure 11. Capacity of off-grid renewable energy solutions globally. Source: IRENA (2018b)

3.3.1. Off-grid systems classification

Regarding the concept of *off-grid* systems, there is currently no consensus about the definitions and classifications. Nevertheless, according to the literature the main *off-grid* systems can be classified in Stand-alone Systems, Mini grids and Hybrid Mini grids (Mandelli *et al.*, 2016).

Fig. 12 shows a proposed classification of off-grid systems for rural electrification based on multiple sources.

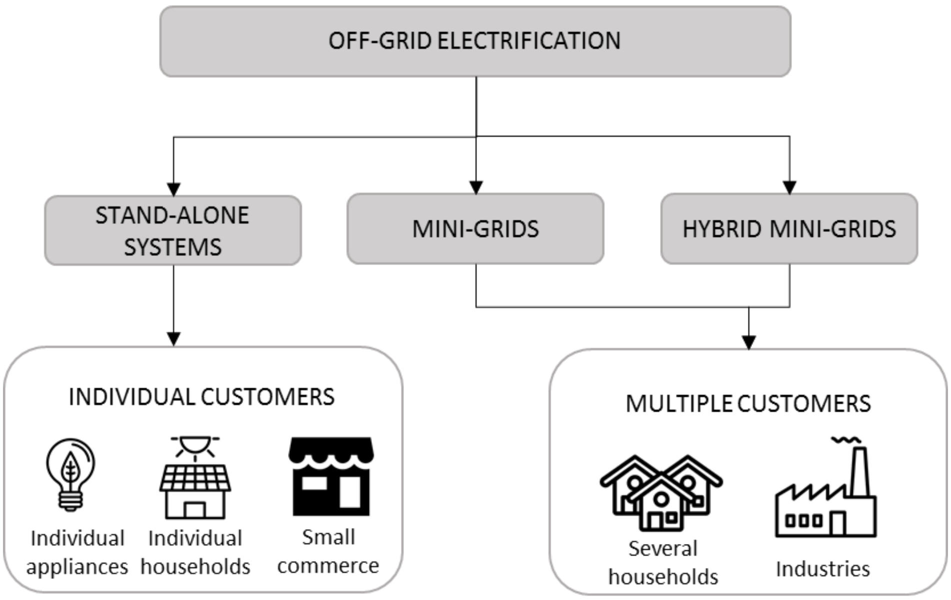


Figure 12. Classification of options for rural electrification. Source: Own elaboration based on Mandelli et al. (2016); RECP (2014); GIZ (2016); ARE (2015)

The main characteristics of the different options are summarized as follows:

3.3.1.1. Stand-alone systems

Decentralised small electricity systems that supply electricity to individual consumers. According to the Alliance for Rural Electrification (2015), they can be divided in Pico Systems (individual appliances), Home Systems (households) or Productive Systems (small communities or businesses). The technologies used are mainly small diesel generators and small photovoltaic systems with up to 150Wp (RECP, 2014).

An example of a Solar Home System is shown in Fig. 13:

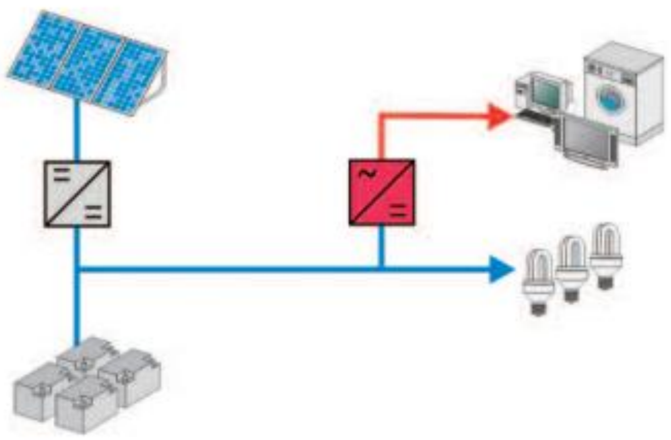


Figure 13. Solar Home System. Source: Strauß *et al.*, (2009)

These systems are affordable and have direct climate benefits, because they usually replace other sources of energy such as kerosene or batteries, provided that diesel is not the main source of power but a backup for PV panels. Nevertheless, the electrical power and thus the loads to connect are limited (RECP, 2014). Furthermore, their immediate economic, social and climate benefits promote the importance of electricity access and the further development of larger mini-grids or national grid extension (IRENA, 2017).

3.3.1.2. Mini-grids

Mini-grids are small-scale generation systems (from 10 kW to 10 MW), which supply electricity to a several group of customers (a few households, small rural industries or businesses, rural schools or hospitals.) (RECP, 2014)with a distribution network. Mini-grids can operate isolated or connected to the national grid (GIZ, 2016). Also known as micro-grids (operating from 1-10 kW (RECP, 2014) or isolated grids.

Fig. 14 shows an example of a mini grid based on solar photovoltaic energy that supplies a group of customers (agricultural facility and residences):

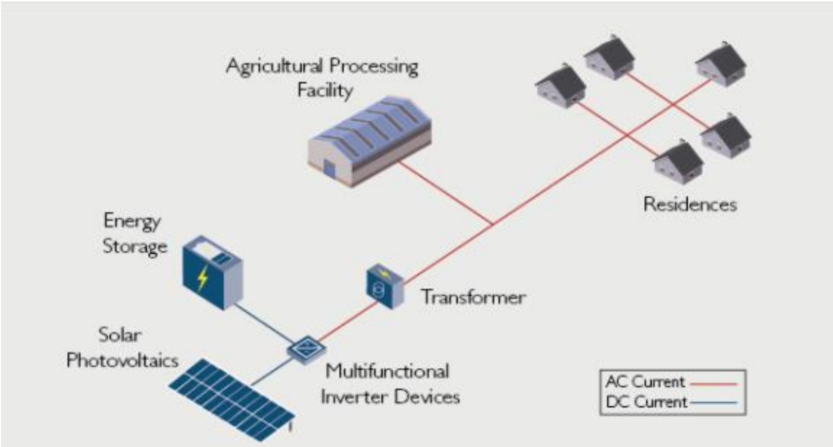


Figure 14. Mini-grid based on solar photovoltaic energy. Source: USAID, 2017

One of the benefits of mini grids is their flexibility, as the technology used (solar, wind, hydro or biomass) can vary depending on the availability of local resources. Moreover, despite the investment cost is higher than for Stand-alone Systems, they can boost the growth of private sector regarding the construction, operation and maintenance of the grid (RECP, 2014). As the power range is higher, productive activities can be also developed.

3.3.1.3. Hybrid mini-grids

The concept of hybrid mini grids appears when mini-grids are constituted by more than one technology for energy conversion (Stefano Mandelli, Barbieri, *et al.*, 2016). Mini-grids can be 100% renewable by using renewable energy technologies such as solar, wind, hydro or biomass (Alliance for Rural Electrification, 2015), or include a back-up Diesel generator or a storage system.

In Fig. 15 a large mini-grid combining wind, photovoltaics, a biogas generator and a Diesel generator is shown:

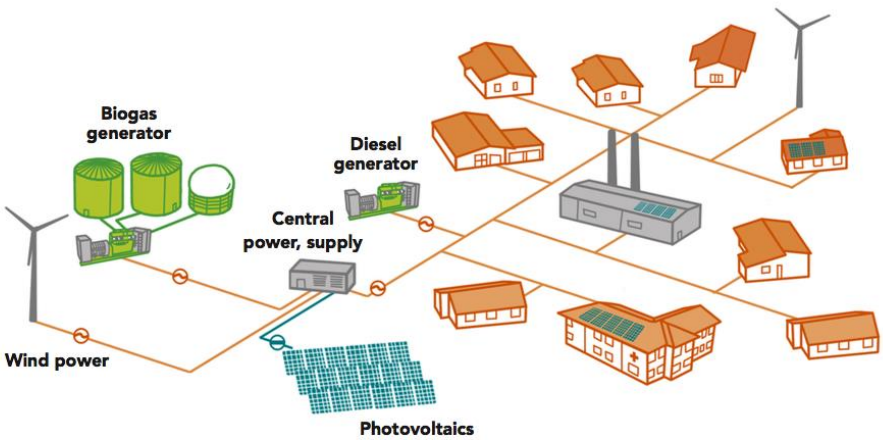


Figure 15. Hybrid mini-grid scheme. Source: BINE Information Service, 2011

Overall, mini-grids appear as the most suitable option for rural electrification for a wide range of amount of energy demanded (from 200 to 10,000 Wh/day/household) and number of consumers, as it is shown in Fig. 16.

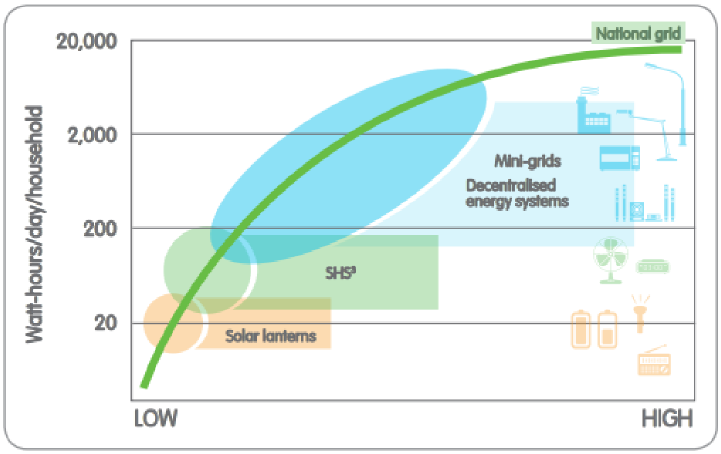


Figure 16. Possible Electrification Strategies depending on the number of off-takers. Source: ARE (2015)

Mini-grids are also considered as the most beneficial option for rural electrification because they can be deployed fast, facilitate private sector development and have flexible technical and operational models (RECP, 2014). They are in the long-term the least-cost option for rural electrification (Alliance for Rural Electrification, 2015; IEA, 2017a).

3.3.2. Renewable technologies for mini-grids

Overall, the technologies used in renewable Mini-grid systems strongly depend on the local context. This means availability of resources, economic capacity and socio-economic development of the area.

IRENA (2018b) estimates that the most developed technology for mini-grids is Small-hydro, reaching the 6 million people connected in 2016. Fig. 17 shows the growth in the use of solar photovoltaic technology during the last years, reaching 2.1 million people connected in 2016. It has been estimated an increase in the installed capacity of solar photovoltaic from 11 MW in 2008 to 308 MW in 2017 (IRENA, 2016).

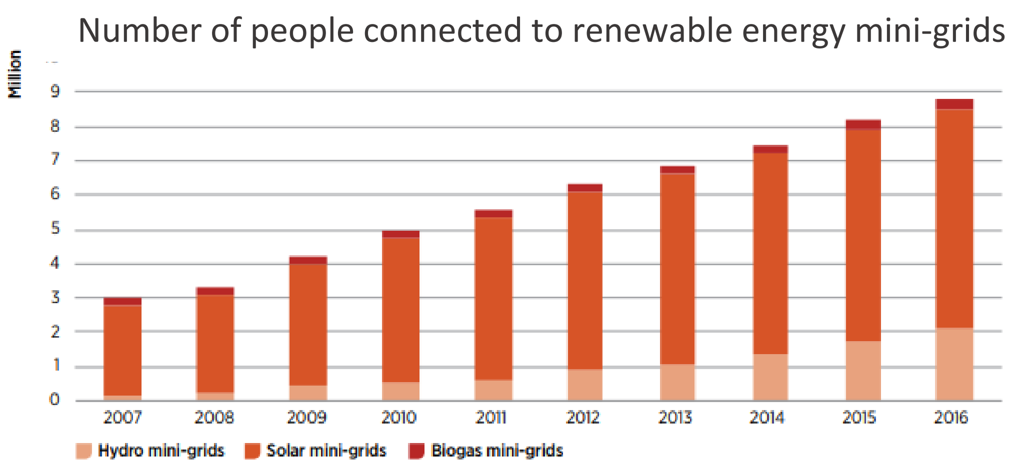


Figure 17. Number of people connected to renewable energy mini-grids, by technology, 2007-2016 (IRENA, 2018).

Mandelli *et al.* (2016) conducted a review of more than 350 scientific papers and found out that for Stand-alone systems, photovoltaic is the most used technology with ranges of some W. Regarding micro-grids, small-hydro is the most studied technology, and the systems´ size varies from some kW to 20 kW; wind and solar based technologies are also addressed. Combining a renewable technology with a conventional one (photovoltaic and diesel generator) is the most simply and common technology in Hybrid micro-grids design, followed by its extension for instance with batteries or wind turbines, with a wide range of size (from some kW to hundreds).

The most used technologies, which include small-hydro, solar photovoltaic and wind, as well as storage and back-up generators options are described here below.

3.3.2.1. Small-hydro

Hydroelectricity is the production on electrical energy from the conversion of the potential energy of a water flow passing through a hydraulic turbine connected to an electric generator. As it is based on the natural cycle of water, it is considered renewable, but big hydroelectric plants have high environmental impacts due to the construction of reservoirs and the diversion of the river course.

Small hydro power plants have a low capacity, up to 10 MW, and for rural electrification the typical sizes rate from 10 kW to 1 MW (Alliance for Rural Electrification, 2015).

It is the technology with less costs and operation & maintenance requirements, therefore the most reliable, and normally it can be fully dispatched. However, the installation requires a lot of space and the availability of a river with enough flow rate.

3.3.2.2. Solar Photovoltaic (PV)

Solar Photovoltaic (PV) technology is the conversion of the sun light, through solar panels made of semiconducting materials, into electrical power. Direct Current (DC) is generated.

Is easy to install and to add when possible future mini-grid's extensions, but it has high investment costs not affordable for everyone in rural areas. In general, rural areas of developing countries are characterized by high solar resource, thus there is a high potential for its installation. However, energy storage is necessary as energy generated cannot be fully dispatched.

3.3.2.3. Small wind turbines

Wind turbines are devices that convert the kinetic energy resulted from the rotor blades' movement into electrical energy through a generator creating Direct Current (DC) or Alternate Current (AC). Wind turbines of less than 100 kW are categorized as "small" (IRENA, 2015).

Often used in hybrid systems with Solar Photovoltaic in order to reduce costs. The main disadvantage is that wind resource is not available in every location and it requires a proper study. Moreover, storage is also necessary to manage the energy generated, as the electricity demand does not always match the supply.

3.3.2.4. Storage

The storage component of the installation is necessary to ensure the availability of the energy resource when necessary. For instance, in a photovoltaic mini-grid, during no-sun hours. Furthermore, they provide power balance, thus ensuring stability of voltage and frequency (IEA, 2011). There are different storage technologies: batteries (lead-acid, lithium-ion, sodium-sulphur etc.), fuel cells, hydrogen hydrolysis and kinetic storage.

Batteries have been the most used, developed and researched for mini-grids, but they are a source of waste after their life-cycle, because of limited cycles of charge and discharge (Hirsch, Parag, & Guerrero, 2018). Among the technologies, lead-acid are the most common used and less priced, but other technologies such as Lithium-ion have a longer lifetime and higher efficiency (USAID, 2018).

Batteries are devices composed by electrochemical cells that allow the energy storage, as chemical energy, and its conversion to electrical energy. They are especially important for mini-grids based on renewable energy, as they allow to store the energy surpluses and supply energy, as Direct Current (DC), when is needed.

3.3.2.5. Generators

Engines that convert the fuel's thermochemical energy into electricity. The fuel's combustion is produced in the motor engine, converting its thermal energy in mechanical energy. The generated movement drives the electric alternator, producing electrical energy as Alternated Current (AC).

Diesel generators are also important when installing a Mini-grid, in order to ensure reliable energy supply, when there is a lack of renewable resources to cover demand peaks. However, their use has to be minimized due to fuel's high price (ARE, 2015), GHG emissions and noise.

Other technologies extended in mini-grids, especially for rural communities, are based on bioenergy, due to the high amount of biomass resources of these areas. The amount of biomass feeding the gasifiers or combustion stoves has to be properly managed in order to avoid deforestation and ensure carbon neutrality, what requires specific capacities difficult to sustain in rural areas (Mandelli, 2016; Barbieri, *et al.*, 2016).

Automatic management measures are recommended to implement so as to ensure the long-life and sustainable use of the components. For example, automatic disconnection of batteries' when level of discharge gets below a certain percentage, or automatic charge of batteries if energy generation exceeds the demand needs.

3.4. BARRIERS AND CHALLENGES

The World Bank (2018) states that for mini-grids in off-grid electrification the main challenges are enabling policies and regulatory framework, lack of financial resources, lack of institutional support and financial resources of households.

Other challenges, as shown in Fig. 18 below, include technological solutions, financing models, capacity building and cross-sector linkages. Gender equity must be included in the different elements, as well as a multi-stakeholder approach, to ensure the long term sustainability and socio-economic impacts of electrification (IRENA, 2018).

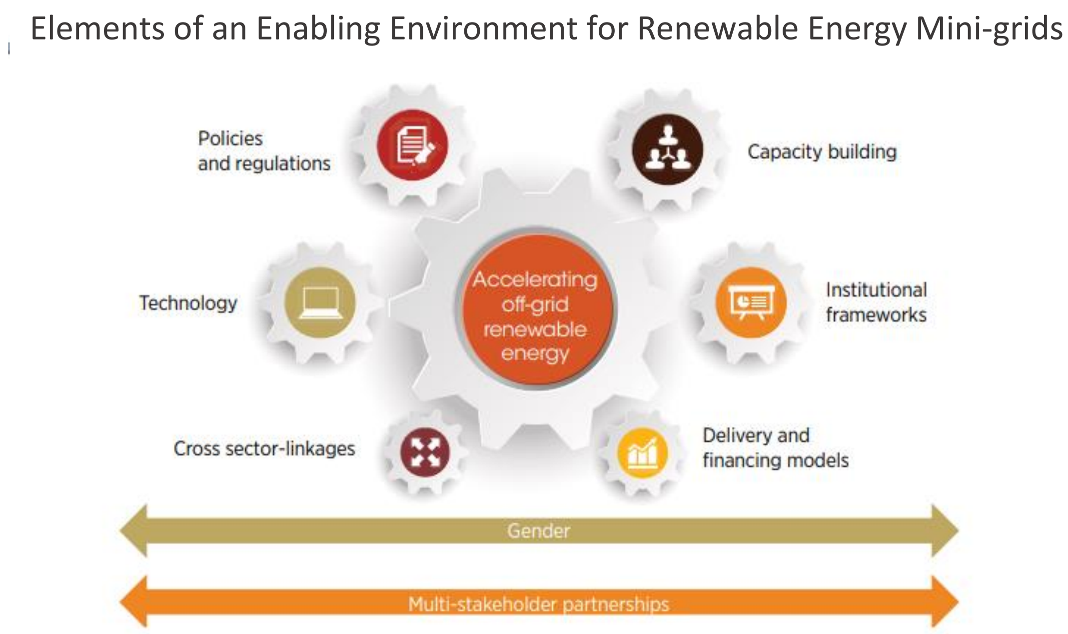


Figure 18. Elements of an enabling environment for renewable energy mini-grids. Source: IRENA (2018).

In conclusion, decentralized mini-grids based on renewable energy can be considered as the main solution for ending energy poverty in rural areas. Electrification will also provide a wide set of benefits to the inhabitants of these areas. However, in spite of the efforts of several international organizations, still a billion of people lack electricity access due to several barriers and challenges that need to be overcome.

CHAPTER 4. THE PROCESS OF DESIGNING HYBRID MINI-GRIDS

The growing interest in off-grid rural electrification through hybrid renewable energy mini-grids directly implies the necessity of methods for evaluating, sizing and modelling these systems. According to SEforALL (2019), the technical design of mini-grids should be: safe, in terms of frequency and voltage levels; adequate for the type of consumers; scalable, for possible demand growth; and efficient, thus meeting the demand with the most suitable technology and the lowest possible costs.

When designing hybrid mini grids, the energy demand assessment step appears as a key element in order to ensure the proper sizing of the components. This fact is strongly accentuated in rural isolated areas of developing countries where lack of previous electricity and uncertainty in the data directly influence the quantification of the energy demand, thus resulting in under and over-dimensioned mini grids.

4.1. ENERGY DEMAND ASSESSMENT

NRECA (2016) defines the energy demand as the amount of energy and power that the area where the project is being implemented requires, measured in kWh or MWh. Its assessment appears as one of the most important steps when designing mini-grids, as it has direct impacts on the size and type of components, the costs of the system, the operation schedule or the life-time of the equipment, among others (GIZ, 2016). Likewise, it is also a laborious and challenging work, especially for off-grid rural areas in developing countries, as they are characterized by unavailability of load data (Blodgett, *et al.*, 2017; Louie & Dauenhauer, 2016; Stefano Mandelli, Merlo, & Colombo, 2016). It is thus difficult to analyse electricity demand in a community that never had electricity before.

Therefore, a proper demand analysis must be done as it directly affects the cost of producing energy and the reliability of the system. On the one hand, oversizing it will increase investment and operational and maintenance costs and thus the payback period, besides reducing the operational life of the components as a result of overusing. On the other hand, an undersized system will result in lack of reliable and continued energy supply, generating discontent on the customers and forcing the component´s operation. Thus increasing operational and maintenance costs (GIZ, 2016). Consequently, a balance to provide cheaper and more accurate but also reliable designs may attract more private investments. Uncertain demand and unused systems are one of the main barriers for mini-grid´s development (Blodgett *et al.*, 2017).

Nevertheless, among the scientific literature, only few studies evaluate the energy needs and load profiles (Mandelli, Merlo & Colombo, 2016). Moreover, they do no reach an agreement in terms of a common accepted approach to predict the load (Mandelli *et al.*, 2017). This fact is mainly due to the several factors affecting the demand profile. One approach is to consider any community or village is exactly alike to another (GIZ, 2016). Therefore, varying the number of consumers, consumer type and activities, consumer penetration or growth rates can help to predict the load.

Some studies base the demand assessment on expert knowledge in similar installations´ experiences (Blodgett *et al.*, 2017), usually assuming averaged daily constant load profiles (Louie & Dauenhauer, 2016). However, other researchers propose mathematical models based on statistics, which will be described in the subsequent sections. These models require input data specific for each area and can only be gathered trough on-site surveys and measurements, therefore providing more detailed results for more reliable project design.

4.1.1. Load profile concepts

GIZ (2016) defines the electrical load profile as "*the electrical load on a certain time axis, which varies according to customer type, temperature and seasonal effects*". Load also depends on other factors such as economy or preferences for a specific customer type (Mandelli, 2015). Its graphic representation is time-dependent (daily, monthly or yearly). In Fig. 19, an example of a daily load curve for a large mini-grid is shown:

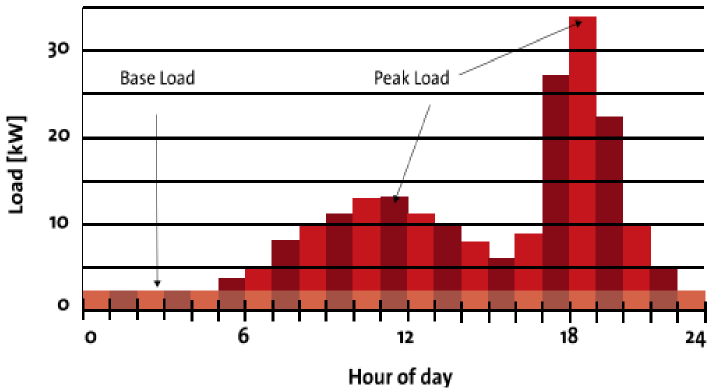


Figure 19. Typical load curve of a large mini-grid. Source: RECP (2014).

In order to characterize load profiles for off-grid systems, some concepts are introduced:

4.1.1.1. Demand, average and peak load

The demand is the amount of energy that the power system requires during a certain period of time (NRECA, 2016). It can be obtained as the integral of the power demand over time or as the sum of the load power requirements for each interval within the considered period (Eq. 1).

$$Demand = \int_0^T P_{LOAD}(t)dt \qquad (1)$$

Where P_{LOAD} represents the power demanded in W or kW for each interval, and T is the period of time considered for the calculation, which can vary from seconds to years.

Throughout the time interval considered, the peak load is the maximum demand measured. The average demand is the result of dividing the demand accumulated in a period of time in kWh by the number of hours of the period.

4.1.1.2. Load factor

Another parameter that can be obtained is the load factor (%), defined by USAID (2019) as "*the ratio of the average electric load (measured across one billing interval, typically one month) relative to the peak load (measured in intervals, typically 15 minutes, consistent with the grid code) averaged over a period of time corresponding to the billing interval*".

For the demand of the community the Load Factor (LF) can be obtained as in Eq. 2:

$$LF = \frac{Average\ electric\ load\ (kW)}{Peak\ load\ (kW)} \tag{2}$$

It can be calculated daily, monthly or yearly, and expresses the percentage of time that the area is demanding the peak load, for a certain period (Kronebrant, 2017), which strongly influences the system´s design and operation, thus the costs (Robert, Sisodia, & Gopalan, 2018).

4.1.1.3. Coincidence and diversity factor

The Coincidence Factor (CF) is "*the ratio of the maximum coincident total power demand of a group of consumers to the sum of the maximum power demands of the individual consumers comprising the group, both taken at the same point of supply and for the same period of time*" (Singh, 2011). It is therefore a measure of how likely all the loads are demanded by the consumers at the same time, and can be obtained as in Eq. 3:

$$CF = \frac{Peak\ load\ of\ the\ system\ (kW)}{\sum Individual\ peak\ demands\ \ (kW)} \tag{3}$$

The coincidence factor rates from 0 to 1, then a value of 1 represents that the customers are consuming the maximum demand of the system at the same time. This happens when the sample of customers has similar consumption patterns or less-diversity among them: the diversity factor is the complementary of the coincidence factor.

4.1.2. Demand assessment process

GIZ (2016) in its manual *"Which size shall it be?"* proposes recommendations for mini-grids designing, mostly based on the demand assessment step, as it is crucial for system design and sizing, especially for obtaining proper results through simulation tools such as HOMER Software. Fig. 20 shows a flow chart that contains the different actions required and the results obtained for the electrical demand assessment process.

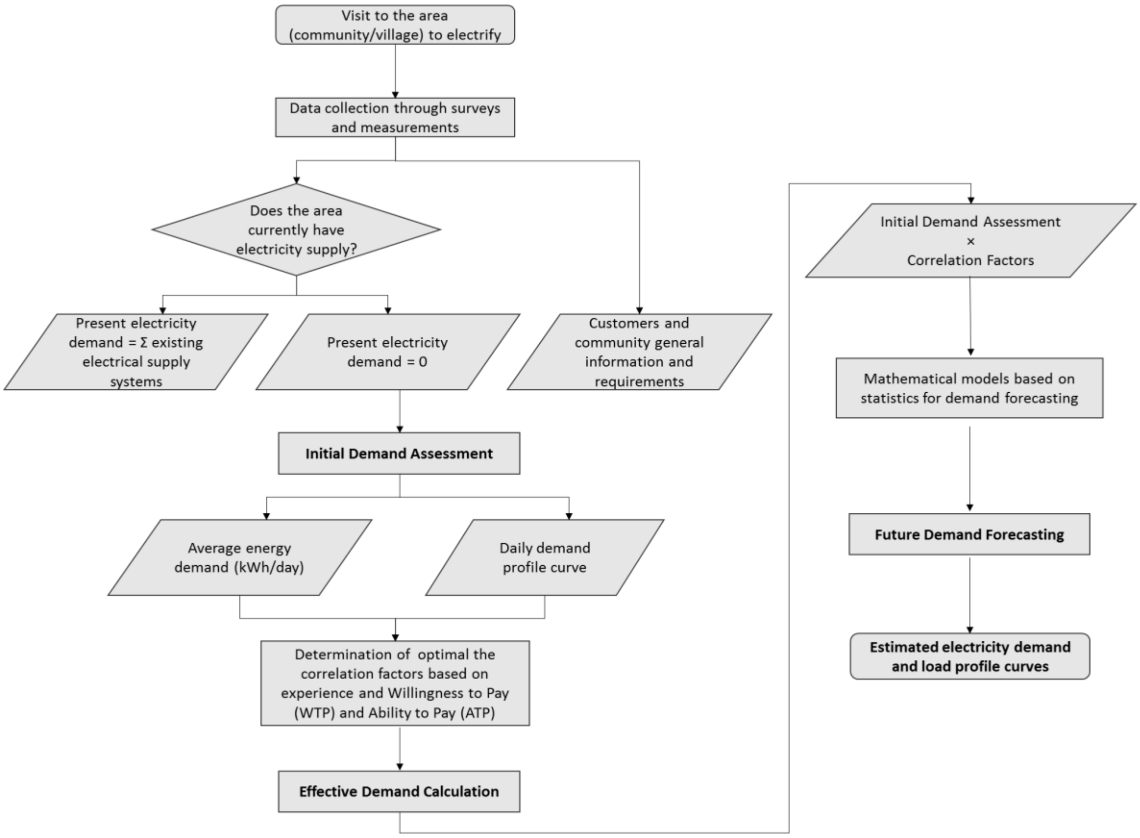


Figure 20. Demand assessment process flow chart. Source: Own elaboration adapted from GIZ (2016)

4.1.2.1. Initial demand assessment

The demand assessment process starts with an initial assessment of the requirements of the area or community:

Surveys

Overall, surveys are the most common approach and have been widely used for energy demand assessment (Blodgett *et al.*, 2017; Oladeji & Sule, 2016; Sahu, Shandilya, & Bhardwaj, 2013; Singh, 2011). However, questions need to be well defined specifically for each area (GIZ, 2016). Due to unfamiliarity with energy services or data, surveys can cause prediction errors, which can result in improper design of the energy installation.

The questionnaires should be designed in order to evaluate both general information about the customers and their load requirements, as well as their present electricity demand, in case the area was already electrified or had electricity consuming devices. Therefore, the factors given in Table 1 should be considered:

Table 1. Recommended questions and content of surveys. Source: Own elaboration based on GIZ,2016; Blodgett et al., 2017; Islam, Akhter & Rahman, 2018; Sahu, Shandilya & Bhardwaj, 2013; Oladeji & Sule, 2015; Singh, 2006

Community Information	• *Total population of the area.* • *Main productive activities (agriculture, fishery, farming, forestry, etc.).* • *Number of households and GPS coordinates.* • *Number of community facilities and GPS coordinates (schools, health services buildings, religious buildings etc.), usage schedule, load requirements (type, quantity and power (W)).* • *Distance among the consumers.* • *Street lighting requirements (load type, quantity and power (W)).* • *Land conditions and available area for installing the mini grid.*
Customers Information	• *Serial number.* • *Name, age and contact.* • *Type of customer (Household, Business or other).* • *Current energy sources, usage schedule and cost (if any):* *-Solar Home Systems (SHS): installed power (W) and battery capacity (Ah and V).* *-Electric generators: power (W) and consumption (diesel/month or year)* *- Other: Kerosene, batteries, wood etc. and daily/monthly/yearly consumption.* • *Current or desired electricity consuming devices:* *-Type of load (most common for rural communities are: lights, TVs, radios, fridges, fans, water heaters, motors for pumping, etc.).* *-Power for each (in W).* *-Usage hours.* • *Average monthly or yearly incomes (USD) and ability to pay for energy services (USD/kWh).* • *Willingness and ability to pay for energy services.*

Based on this gathered data, the initial demand assessment can be carried out. The **average daily energy demand** of the area in kWh/day can be obtained as shown in Eq. 4, as a result of the sum of the load´s power requirements multiplied per the number of usage hours within a day of all the consuming devices that the community and individual customers are expected to use (Mandelli, 2015):

$$D = \sum_{j}^{User\ class} N_j * \left(\sum_{i}^{Appliance} n_{ij} * P_{ij} * h_{ij} \right) \quad [kWh/day] \qquad (4)$$

Where *i* refers to the type of electrical appliances and *j* to the type of customer, thus N_j is the number of users and n_{ij} the type of appliance of each customer class; P_{ij} represents the nominal power of the different type of appliances for each customer, and h_{ij} the daily hours that are turned on

The **daily demand profile** of the area can be obtained from the aggregation of hourly load's power requirements for each individual customer or sector (residential, commercial, productive activities, communitarian or street lighting, among others). Load peak and load factor can be also obtained from the analysis. A representative example of daily demand profile of a rural community is shown in Fig. 21 (GIZ, 2016):

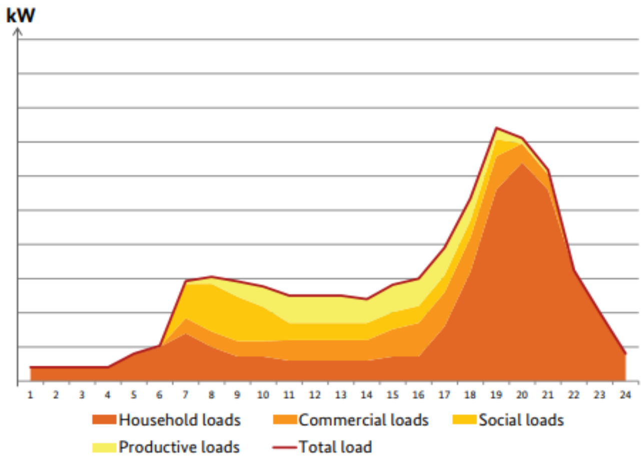


Figure 21. Curve of average demand profile as the aggregation of different customers´ load profiles. Source: GIZ, 2016.

This daily load profile can be assumed constant and extrapolated to the whole year. However, other segmentations, for instance depending on the season (summer/winter, rainy/dry) are also possible and will result in more accurate and reliable system´s design (Sahu *et al.*, 2013).

4.1.2.2. Effective demand calculation

According to RECP (2014), the electricity demand depends also on other factors such as the incomes of the customers and their ability to pay for electrical services. These factors are known as Ability to Pay (ATP), which depends on incomes and current energy sources expenses (GIZ, 2016), and Willingness to Pay (WTP): "*the maximum amount that an individual indicates that he or she is willing to pay for a good or service*" (NRECA, 2016).

GIZ (2016) proposes three correlation factors depending both on ATP and WTP, which multiplied by the Initial Demand Assessment will result in the **Effective Demand Calculation** ("*demand for goods and services that are backed by the resources to pay for it*" (NRECA, 2016):

- Current demand factor (C1): Considers that some customers may have current energy sources and may not be willing to pay for energy from the mini-grid.
- Commercial demand factor (C2): Takes into account the ability to pay of the community regarding the incomes of commercial or productivity activities.
- Data collection factor (C3): If the interview sample of customers is lower than the total population it may cause errors in demand assessment.

It is important to highlight that these factors are examples of estimations to minimize the error associated to the demand assessment in rural areas. Therefore, they can be simplified or expanded depending on the amount of data or experience in the assessment process.

4.1.2.3. Future demand forecasting

Once the Effective Demand has been calculated, other complementary approaches or tools are needed in order to forecast the future demand of the community, what is defined as Future Demand Forecasting. This will allow to minimize as much as possible the prediction error and ensure accuracy, reliability and economic sustainability in the hybrid mini-grid design.

In that regard, the term of "forecasting" is used as a generic concept, but it is intended to refer to the "estimation" of the future energy needs and the formulation of load profiles by means of models or methodologies. Therefore, both terms will be used throughout the document.

Future Demand Forecasting depends on several factors that may vary during the lifetime of the mini-grid. Not only socio-economic factors (Blodgett *et al.*, 2017; GIZ, 2016) as population growth, economic growth, lifestyle and consumption patterns, what will result in an increased number of customers and kWh consumed per year, but also other factors such as time factors (season, type of day, hour of the day, day of the week) or climate conditions variations (mainly temperature and humidity) should be considered (Feinberg & Genethliou, 2005).

When estimating the demand and load profile of an area, the period which is going to be considered has to be determined. For temporary extension, demand forecasting can be divided in (Mandelli *et al.*, 2016; Mohiuddin, 1997):

- **Long-term:** applied in large grid installations in order to assist the electrical companies to predict the energy consumption patterns, for a period of 15 to 25 years, and management of the grid (needs of more staff, equipment), due to a growth in the energy consumption.
- **Medium-term:** used for forecasting the schedule of fuel supply and installation´s maintenance, for a period of 5 to 15 years.
- **Short-term:** used for prediction of component´s daily use and operation for less than 5 years. The prediction can be done for a specific day, week, month or year.

Short-term is the optimal and most used approach for energy demand forecasting, as for medium- and long-term historical series and data are needed, which are not often available for isolated rural areas and when assumed as known, can cause errors in the amount of energy demand estimated or the load profiles formulated (Islam A., Hasib, & Isalm S. Md., 2013).

Demand forecasting can also be classified depending on the ranking of study (Hong & Shahidehpour, 2015; Mandelli, 2015):

- **Top-down:** It is used for long-term forecasts. The data is gathered from groups of customers of a region or territory (in a macroscopic way), grouped in different customer classes, and the results are applied to each individual customer by similarity with the classification.

- **Bottom-up**: It is used for estimations performed at short-term. Data from each consumer or group of consumers is collected (in a microscopic way), to analyze the specific requirements of each area. Then, the results can be extrapolated to other similar groups of users.

According to their characteristics, it can be noticed that, despite being inefficient in terms of amount of data to be gathered and analysed, the bottom-up approach provides more accurate results.

Basically, short-term and bottom-up have been the main used approaches in order to estimate the future energy demand in rural isolated areas, implemented by statistical or mathematical models, as will be described in the following section.

4.1.2.4. Models for demand forecasting

The state of the art analysis has shown that there is still no classification of potential methods to be used for estimating the energy demand on rural isolated areas, as well as no agreement on a common one, as has been stated at the beginning of the section. Only Mandelli (2015) performed a literature review regarding models used for demand forecasting. From the analysis it can be concluded that the current approaches for future demand estimation are mainly based in statistics (random, deterministic, probabilistic) besides the estimation of the coincidence load factor based on the data gathered through surveys and socio-economic, climate or time factors of the area serve as input for demand forecasting.

Therefore, the research has been carried out with the purpose of identifying the main models and methods that have been used for future demand prediction in isolated areas. Examples of the main approaches and models identified are described below.

Deterministic Models: Linear regression analysis and Inverse matrix calculation techniques

Deterministic models assume that there is an exact relation among the variables, thus there is no error when obtaining the results. This fact directly implies the necessity of specific and enough initial data. Even though obtaining accurate data to ensure precise results is specially complicated in rural isolated areas of developing countries without previous electricity access, deterministic statistical models have been used in order to estimate the energy demand in different cases.

Linear regression analysis (LRA) has been widely studied for demand forecasting among several scientific papers (Islam *et al.*, 2013; Mahmud, 2011) or combinations with other techniques (Miswan *et al.*, 2017). It is a statistical technique developed by Dr. A. Hoque in 1990 based on the identification of the factors on which electrical load growth depends that may vary depending both on the type of load and the area (Mohiuddin, 1997).

Inverse matrix calculation analysis also considers the dependence of the total load of an isolated area on certain variables. The difference is that in this method, the variables are expressed by a matrix and the results are obtained from its inverse.

Islam A., Hasib, & Isalm S. Md. (2013) considered the two methods for short term load forecasting on isolated areas worldwide with a lack of previous load data, inverse matrix calculation and linear regression analysis, obtaining similar results for both.

For an isolated area, the total load can be divided into domestic load, commercial load, irrigation load and industrial load. For those loads, the following factors are considered to have an influence in the determination of the energy consumed on an area: population (P), income per capita (I), adult literacy rate (A), inland (or sea route) communication length (R), distance from local town (D) and agricultural land (L).

Then, the total load of an isolated (L_T) area is expressed as a function of these factors (Eq. 5):

$$L_T(t) = f(P(t), I(t), A(t), R(t), D(t), L(t)) \tag{5}$$

And the results will be obtained by applying linear regression or inverse matrix calculation[7].

The main advantage of these statistical methods is that the demographic data needed for the calculation can be gathered from countries' statistics offices or other sources, so the process is simplified. However, the predictions are more general and thus the mini-grid design less reliable (Blodgett, *et al.*, 2017), and the methods require both data from the area to be analysed and from another similar area, which increases the prediction error.

Non-deterministic Models: ESCOBox load model

Non-deterministic models assume that different results can be obtained from the same input data. These approaches are more suitable for demand estimation in rural isolated areas due to the uncertainty in the input data (Mandelli, Merlo, & Colombo, 2016).

The ESCOBox mini-grid load model is a tool developed by De Montfort University under the ESCOBox program, which seeks for reliable and economic sustainable rural mini-grids *(Boait et al.*, 2017). The project has been developed with the objective of managing the balance between supply and demand as the number of consumers grows in order to reduce the costs of electricity in a sustainable way, therefore used as an energy controller. Moreover, given a certain group of consumers and their appliances, the software can predict the peak and average electricity demand, acting as a decision support tool for sizing the system (Boait *et al.*, 2017).

[7] More information about these methods can be found at "*Short Term Electricity Demand Forecasting for an Isolated Area using Two Different Approaches*" by Islam A., Hasib, & Isalm S. Md. (2013).

The model is compiled in Python 2.7.9 and can be downloaded[8] (P. Boait, Advani, & Gammon, 2015). Two simplified Excel files for mini grids using photovoltaic or hydro energy are also available[9]. Fig. 22 shows an visual example of the ESXOBox User´s Interface.

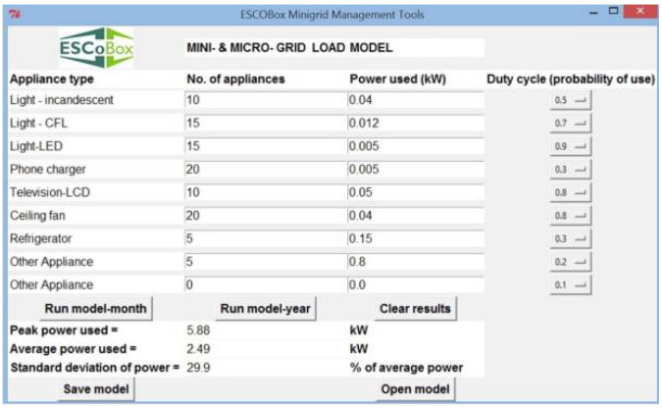


Figure 22. ESCOBox Mini-grid load model. User´s Interface. Source: Boait, Advani & Gamon (2015).

The tool is based on a non-deterministic statistic method that is used for the simplification of the evaluation of complex mathematical expressions through approximation. In particular, for the prediction of the energy demand curve the central limit theorem can be used. The result is that the variation of the total electric consumption decreases as the number of connected appliances increases, by a factor of $1/\sqrt{n}$ (Boait *et al.*, 2015), as represented in Fig. 23.

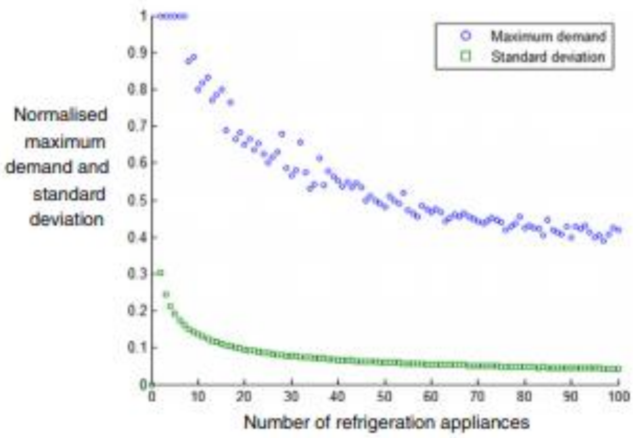


Figure 23. Example of effect of number of power-consuming appliances on observed peak demand as a proportion of maximum possible demand. Source: Boait, Advani & Gamon (2015).

According to Boait *et al*. (2017) the data needed to obtain through audits, surveys or other methods for the simulation includes:

- Population "N" that consumes each type of electrical appliance.
- Nominal power or typical load "E" for each electrical appliance.

[8] https://github.com/peterboait/ESCoBox_Load_Model

[9] https://www.dmu.ac.uk/research/research-faculties-and-institutes/institute-of-energy-and-sustainable-development/research-projects/escobox.aspx

- Assessment of the probability “p” that the electrical appliance will be used at a given time of the day.

Based on this information, the software determines randomly if each appliance (with power “E” and probability “p”) is being used or not for all the consumers “N” for each time interval and generates the aggregate demand curve. It also provides the possible maximum demand in case all the appliances were being used.

DEMAND ANALYST© Software

Demand Analyst© is a tool developed by a consulting and engineering firm, the *Innovation Énergie Développement* (IED) of France. The tool estimates the future energy demand and how it with grow during the years for different customers of a community or village (residential, public services and economic activities) based on on-site surveys’ data and regional socio-economic parameters. A visual example of the user´s interface of Demand Analyst software is shown in Fig. 24.

Figure 24. Demand Analyst(C) Software User´s Interface. Source IED

The Software is recommended by SE4ALL for demand assessment and load forecasting for designing mini-grids and has been tested by IED in several countries. A license is required for using the software[10], and there is lack of scientific research and specific methodology implemented on the model.

Variation of scenarios based on probability

GIZ (2016) assumes that-all the factors on which future load depends will result in a growth of the electricity demand calculated, due to population growth and economic development of the area. This can also be justified with the Jevons Paradox. This effect is the result of an increased energy consumption, due to the reduction of the energy services’ for improvements in the energy supply system (Freire-González & Puig-Ventosa, 2015; Polimeni & Iorgulescu, 2007), which may be especially strong in rural areas without previous electrification. For instance, Roy, (2000) calculated a 50 to 80% of consumption rebound when introducing solar lanterns replacing kerosene lamps in Indian rural residences. Therefore, different scenarios can be

[10] https://www.geosim.fr/index.php?page=demand-analyst-en

considered by assuming a certain percentage of increase per year for forecasting the future load requirements.

This probabilistic method has been used for load forecasting (Oladeji & Sule, 2016), as it has the advantage of simplifying the process but may turn into oversized or undersized mini-grids (Blodgett, *et al.*, 2017). Therefore, it appears as a good method for complementing the results obtained through mathematical tools.

4.1.3. LoadProGen2.0: Stochastic procedure for load forecasting in rural areas

Load Profile Generator (LoadProGen2.0) is a software developed by the Energy4Growing research group of *Politecnico di Milano* that is implemented in MATLAB and generates possible realistic load profiles (electricity, gas, cold water and hot water) for households.

This new tool is especially useful during the predesign stage for isolated areas in developing countries where the data uncertainty is high. It generates load profiles from field information about the area (audits or interviews) using a stochastic approach by considering the different profile parameters and building up the coincidence behaviour of the appliances and the power peak value (Mandelli *et al.*, 2017).

Among the different models for load forecasting identified in the literature review, the Software LoadProGen developed by the Energy4Growing group of Polytechnic of Milano has been identified as the most complete and functional tool for forecasting the demand of rural isolated communities in developing countries, especially for those off-grid areas without previous access to electricity.

The main features of the Software include (Mandelli, Merlo & Colombo, 2016):

- It is based on data easy to obtain through on-site surveys or assumed based on practical experiences and similar context conditions.
- It has a rigorous mathematical formulation that generates the load profile but avoids that the designer judgements influence the load profile shape.
- It is based on a bottom-up approach; thus, it refers to the microscopic data of a specific group of customers.
- It builds up the coincidence behavior of the appliances and power peak value considering the existing correlation between number of users, load factor and coincidence factor.
- It is stochastic in order to approach the uncertainty of load profile forecasting. The Software formulate a number of different realistic profiles within the given input data.

According to Mandelli, Merlo & Colombo (2016) who reviewed the scientific literature regarding the most common approaches used to formulate load profiles for off-grid rural areas, two main characteristic approaches are found. These approaches differ in the way of distributing the daily electric consumption of the customers and their devices throughout the usage schedule in a day.

The first approach considers that the sum of the duration in which the appliances of the customers are on covers all the usage schedule. This means that all the devices will be operating at the same time for all the customers, with a coincidence factor of 100%. Therefore, resulting in overestimated load curves with high peaks of demand.

The second procedure is more accurate as it considers a certain coincidence factor. It distributes the maximum power required of a type of appliance for all the customers along all the usage schedule, thus considering that not all the customers are always going to turn on the appliances simultaneously. This approach leads to underestimated load curves and flat profiles.

However, in both approaches, only one single profile is generated for the estimation of the load curve. Therefore, the intrinsic uncertainty in the input data for non-electrified areas is not approached. By contrast, LoadProGen2.0, as a stochastic procedure, generates a certain number of possible realistic profiles from the input data in order to address uncertainty.

4.1.3.1. Input data

The input data to introduce in the software in order to obtain the daily load profile curves is listed below:

- ***i:*** Type of electrical appliances (TVs, radios, lights etc.).
- ***j:*** User classes (residential, school, commercial, agriculture etc.)
- N_j: Number of users within each class *j*.
- n_{ij}: Number of appliances of each type *i* within each user class *j* (number of TVs per household, number of lights per school, etc.)
- P_{ij}: Nominal power of each electrical appliance in W.
- D_{ij}: *Functioning cycle* (min) of each type of appliance *i* for each user class *j* (minimum time that an appliance is functioning after it is turned on).
- h_{ij}: *Daily functioning time* (min) of each type of appliance *i* for each user class *j* (amount of time during a day that a type of appliances is turned on).
- Wf_{ij}: *Functioning window* (min) of each type of appliance *i* for each user class *j* (periods during the day, between a starting window time and an ending window time, that the appliances can be turned on).
- Rh_{ij}: Percentage that represents that the functioning time h_{ij} of the appliance may experiences a random variation.
- Rwf_{ij}: Percentage that represents that the functioning window W_{ij} of the appliance may experiences a random variation.

However, whereas some data can be assumed or collected through field surveys or audits (i.e. *type of electrical appliances (i), user classes (j), number of users* (N_j), *number of electrical appliances* (n_{ii}) *and nominal power needed* (P_{ij})), the intrinsic characteristic of isolation in rural areas result in need of some values´ assumptions (Mandelli *et al.*, 2017).

The *functioning cycle* (d_{ij}*), functioning time (*h_{ij}*)* and *functioning window (*wf_{ij}) parameters may be set up based on similar context´s assumptions or information provided by the customers. However, following the Software´s logic formulation to address uncertainty (Mandelli, Merlo & Colombo, 2016), the *functioning cycle* (d_{ij}*)* must be shorter than the *functioning time (*h_{ij}*) (Eq. 6)*; and the *functioning time (*h_{ij}*)* must be shorter or equal to the total duration of the *functioning window (*wf_{ij}) (Eq. 7):

$$d_{ij} \leq h_{ij} \qquad \forall ij \tag{6}$$

$$\sum duration(wf_{ij}) \geq h_{ij} \qquad \forall ij \tag{7}$$

The random parameters Rh_{ij} and Rwf_{ij} allow to consider a certain degree of uncertainty in the values of *functioning time (*h_{ij}*)* and *functioning window (*wf_{ij}), and may be set according to assumptions or intrinsic characteristics of each *type of electrical appliances (i)* and *user class (j).*

4.1.3.2. Outputs

Once the input data is introduced in the software, the number of profiles to generate and the sample time (1 second, 1 min, 15 min or 1 hour) must be defined. Consequently, the simulations are carried out. The output file of the software is MATLAB file in the form of a $m \times n$ matrix, in which the number of rows (m) is equal to the number of profiles generated and the number of columns (n) depend on the selected sample time. The software also allows to visualize the generated profiles in the users´ interface.

Overall, from the analysis it can be concluded that it is extremely important to ensure the optimal size of the system. Therefore, it becomes necessary to reduce costs and ensure a long lifetime of the components. To do so, on-site visits to the area to be electrified are essential, as load profiles and demand requirements can vary from one community to another. However, basing the demand assessment of rural isolated areas only on data gathered through surveys will not fully minimize the prediction error. To overcome this problem, correlation factors based on economic data or specific characteristics of the area are recommended to be applied.

Forecasting the future demand of a non-electrified area is a challenging but also necessary process. Short-term load forecasting models based on statistics have been developed and applied. Among them, the LoadProGen2.0 Software appears as the most complete and functional tool and has been applied to real practical cases. Moreover, different scenarios of future demand growth can be applied to the results obtained through the software.

4.2. DESIGN OF HYBRID MINI-GRIDS

Once the energy demand assessment step has been performed, this will allow to design the components of the hybrid mini-grid so as to ensure the reliability on the energy supply.

Currently, several options for evaluating, sizing and modelling hybrid mini-grid systems have been identified in the literature. These options can be classified into three groups:

- **Mathematical models.** These models rely on characteristic equations for modelling each component independently and integrate them into the whole hybrid system (Farahat, Jahromi, & Barakati, 2012; K. Lal, B. Dash, & K. Akella, 2011). They can be used as pre-design for a further analysis through a simulation tool.
- **Specific techniques such as algorithms, artificial neural network or fuzzy logic** (Kyriakarakos, *et al.*, 2012)
- **Computational tools: HOMER, TRNSYS, HYBRID2 etc.** These tools enable the simulation of hybrid mini-grid systems and analyze their response to several parameters and possible settings and are the most used for the design of mini-grid hybrid systems (Micangeli *et al.*, 2017).

Among the computational tools, HOMER Software has been considered as one of the most useful tools for simulation and optimization of both off-grid and grid connected mini-grids. Examples of publications that point out this fact include (Connolly, *et al.*, 2010) that did a review of the different computational tools that can be used to analyze the integration of renewable energy in different energy systems, or Turcotte, Rossb, & Sheriffa (2001) who selected and analysed different software tools according to feasibility, sizing and simulation aspects. Moreover, several studies and researches make use of the software for the design of mini-grids systems (Ahmad *et al.*, 2018; Casarotto, C.F, Romano J.S., Collihuin, 2011; Datto, Roshid, & Rahman, 2013).

4.2.1 HOMER Software Description

The HOMER Software is a powerful tool developed at the National Renewable Energy Laboratory (NREL) from the United States that enables the pre-design, optimization and sensitivity analysis of both off-grid and grid-connected mini-grids. Given different input variables such as energy demand, available natural resources, energy generation technologies, restrictions, etc., a techno-economic analysis of the possible configurations is carried out. The tool simulates the system's operation, considering the energy requirements, for the 8760 hours of the year and orders the optimal solutions according to the lowest Levelized Cost of Electricity (LCoE), also known as life-cycle cost expressed in USD/kWh.

The LCoE is defined by USAID (2019) as a "*measure of the average total cost of electricity over the life of a generation type/technology/asset, expressed per kWh or MWh. LCoE is used to compare the cost of different methods of electricity generation (e.g., natural gas versus coal)", as shown in Eq. 8.*

$$LCoE\ \left(\frac{USD}{kWh}\right) = \frac{sum\ of\ all\ costs\ over\ lifetime}{total\ electricity\ produced\ over\ lifetime} \qquad (8)$$

However, in last version of the software, HOMER Pro, the optimal solutions are ordered according to the Net Present Cost (NPC) expressed in USD. According to EESC glossaries (EU, 2019), the NPC is the "*sum of the present value of all costs over the period of interest, including residual values such as negative costs*". It is therefore a measure of the actualized economic cost of the project taking into account the interest rate and the cashflows (positive and negative) during the duration period of the project. In HOMER software it represents the life-cycle cost of a system.

The reason why the HOMER Pro selects the optimal solutions according to the NPC is because the LCoE only considers the cost of generating electricity, excluding any thermal energy generation in case the system includes thermal loads to supply. Therefore, in systems without thermal loads, the economic analysis of the solutions according to the LCoE is suitable. However, if the system includes heat generation it is recommendable to order the solutions according to the NPC.

In Fig. 25, a schematic overview of main inputs and outputs of HOMER Software is shown:

Figure 25. Schematic overview of inputs and outputs of HOMER Software. Source: Own elaboration

4.2.1.1. Input Variables

Energy Demand

The energy demand, both electrical and thermal, of the area appears as one of the most important input variables to introduce in HOMER, as well as energy resources and energy technologies. The load profile curves directly influence the simulation's results, as HOMER compares hourly the demanded energy with the energy that the system is able to supply.

Therefore, defining the annual load profile curve results is essential. However, isolated rural areas are characterized by unavailability of real load consumption data. Thus, the characterization of the energy requirements of the area becomes difficult. One alternative is forecasting a daily profile curve for the specific region (Bahramara, Moghaddam, & Haghifam, 2016). For that, HOMER allows to introduce a daily profile from which generates the hourly annual value. It has also the possibility of adding a deviation percentage from these values for instance depending on the type of day (weekday/weekend) and season.

Components and technologies of the system

The HOMER software allows the inclusion of different generation technologies. For that, the software provides a database catalogue, which includes models from different manufacturers that the user can select if they meet the type, size and cost requirements, among others. The user can also introduce the parameters of specific technologies.

In this context, it has to be highlighted that the simulations are performed according to the technologies included. Therefore, the configurations are limited, and, in some cases, the most optimal combination may be missed.

Fig. 26 shows a visual example of this fact. After defining the unitary costs of a 1kWp PV array, the user has also to define the sizes that the software must consider. In this case, the software will only simulate a PV array of 0, 2, 4, 6 or 8 kWp, but never an upper or intermediate value, which in some cases could be a more optimized result.

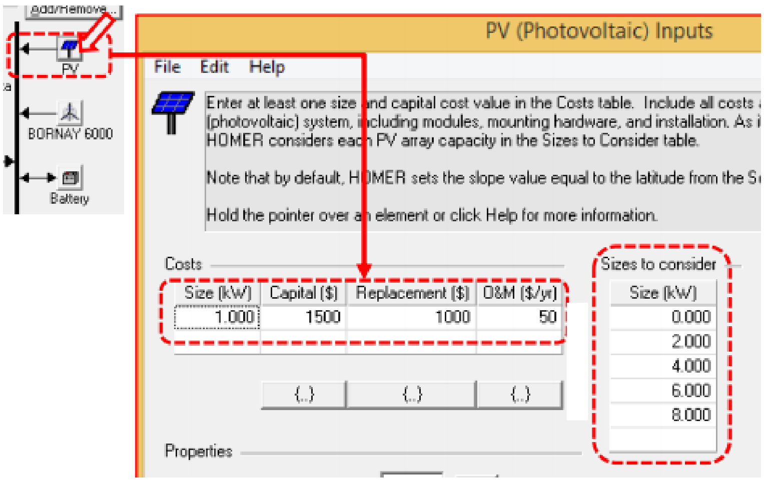


Figure 26. Visual example of technology's parameters introduction in HOMER Software.

- Diesel Generator. Diesel generators for hybrid off-grid systems are mainly used as a back-up in order to ensure reliable and continuous energy supply, but their use has to be minimized due to fuel's high costs and polluting emissions.

Several parameters of diesel generators may be introduced in HOMER. For instance, size, cost, fuel type and characteristics, fuel price, operating schedule and emissions factors. Some of them are defined by default and can be modified by the user. Remarkable parameters are defined by the *HOMER Help Manual*:

- **Lifetime:** number of hours that the generator will run without needing replacement.
- **Minimum load ratio:** minimum allowable load on the generator, as a percentage of its rated capacity.
- The **heat recovery ratio** is the percentage of waste heat produced by the generator that can be used to serve the thermal load.

-Boiler. When introducing a thermal demand, a boiler for satisfying it must be introduced together with its characteristic parameters (fuel's type, costs, size or emissions factors).

-Wind Turbine. HOMER has different types of turbines and manufacturing brands by default. However, specific ones are possible to introduce as well as their parameters (costs, lifetime, height, power curve or current type generation)

- Solar Panels. Input variables that may be introduced in HOMER are similar to the wind turbine's case (costs, lifetime, etc.) as well as specific solar panel variables like orientation, tracking system or losses. According to *HOMER Help Manual* Maximum Power Point Tracker (MPPT) can be added as a DC/DC Converter, what will be described below. MPPT maximizes the PV output as it identifies for each instant the maximum power (function of solar radiation, ambient temperature and solar cell temperature) that the PV can provide by comparing the PV to the DC bus/batteries/grid voltage.

-Batteries. As in the case of photovoltaic and wind turbines, HOMER provides different models of batteries that can be selected, but also permits the introduction of specific models. To ensure the operative life of batteries, a limit in the minimum state of charge in percentage must be defined. It is also possible to fix the minimum battery life in the software in order to avoid unacceptable short time replacements.

-Converter. Converters can act as inverters (DC/AC) or rectifiers (AC/DC) or both and are required in mini-grids design as components that work with different types of signals. For instance, photovoltaic panels and wind turbines produce DC and batteries store DC current but loads usually consume AC current. Parameters can be defined in HOMER for both operation types: as inverter for grid synchronization or connection with other generators, or as rectifier for charging the batteries.

-Electric Grid. HOMER also analyses scenarios in which the mini grid may be connected to the electric grid. Specific rates depending on the period (hourly, daily or monthly) and properties (power/energy terms and energy sale price) can be introduced. For the optimization, the software will compare the costs of producing and consuming energy from the grid and will consider the option of selling electricity to the grid when there is an excess of production.

Energy Sources

The available energy resources depend on the area where the mini-grid will be placed and that will be used for determining the energy output for the different technologies. Location may be introduced. Energy resources data (fuel, wind speed, solar radiation or air temperature) can be entered manually as monthly averages or imported as files from databases as PVGIS, NASA POWER, Energy+, etc.

Restrictions

User can also introduce restrictions that HOMER will apply to the hybrid system modelling:

-**Economic.** Input variables used for calculating the Net Present Value (NPV) of the project (project lifetime, annual interest rate, fixed costs, or capacity shortage penalty, among others).

-Generator Control. Different dispatch strategies can be fixed in order to control the operation of the generator and batteries:

- **Load following**: the generator produces the specific energy to cover the demand.
- **Cycle charging:** the generator produces its maximum power and the energy surpluses are used for charging the batteries.

- **Set point state of charge:** the generator charges the batteries until their specified state of charge.

-Emissions. Penalties and annual limits of emissions can also be introduced.

-Constraints. Other restrictions allow the possibility of choosing the minimum renewable energy fraction or the maximum annual energy not covered by the system. The "operating reserve" section simulates the reserved part of the energy produced for satisfying possible peaks of demand.

4.2.1.2. Simulation and Optimization

Once all the input variables have been introduced, HOMER carries out the simulation of the different possible scenarios, taking into account the restrictions and looking for the lowest Levelized Cost of Electricity (LCoE), which includes the cost of energy purchased from the grid, initial cost, replacement cost, operation and maintenance cost and the fuel cost (Bahramara *et al.*, 2016). The feasible scenarios (demand supplied for the 8760 hours/year) are ordered according to the lowest LCoE. Then, the software shows the size in kW and operation parameters of each component, the energy transacted with the grid, the renewable energy fraction, the costs and the emissions produced for each scenario.

4.2.1.3. Sensitivity analysis

The sensitivity analysis shows how the system responds as a result of input variation (Salmani, Sadeghzadeh, & Naseh, 2014). When designing hybrid mini-grids, the sensitivity analysis is especially important as it illustrates the degree of sensitivity in the outputs resulting from input uncertainty, thus helping the decision making process (Hossain *et al.*, 2017).

Among the input variables, there are several parameters that do not have specific values. Therefore, this uncertainty has a strong influence on the system's configuration. Those most relevant and with highest impact on the system design variables should be determined, as they depend on the location and type of components (Bahramara *et al.*, 2016). For instance, solar radiation, wind speed, fuel, electricity and components' cost, interest rate or components size could be such parameters

For all those sensitivity variables, an independent sensitivity case is generated, from which HOMER performs the optimization. Once the simulation of each case has been performed, the feasible scenarios for each sensitivity case are plotted according to the lowest LCoE.

CHAPTER 5. PRACTICAL CASE: RURAL COMMUNITY OF “EL SANTUARIO”

The rural community of El Santuario is taken as case study for the development of a methodology to assess the energy demand that will serve as a basis for the design of an off-grid hybrid mini-grid.

Along this section the context of El Santuario in terms of social, economic and environmental characteristics are described, as well as the identification of potential renewable energy sources and the initial energy demand assessment.

5.1. CHARACTERISTICS AND CONTEXT

The rural community of “El Santuario”, belonging to the San Ramón de Arriba Village, is located in the department of Choluteca, Honduras, with coordinates 13° 29' 22.92'' N, 87° 13' 14.879''W. Fig. 27 shows the location of the community. The area is part of the Mesoamerican Dry Corridor region, which is especially vulnerable to climate extreme events. FAO (2016) recognised this area as one of the most affected by climate change effects, with 3.5 million people in need of humanitarian help.

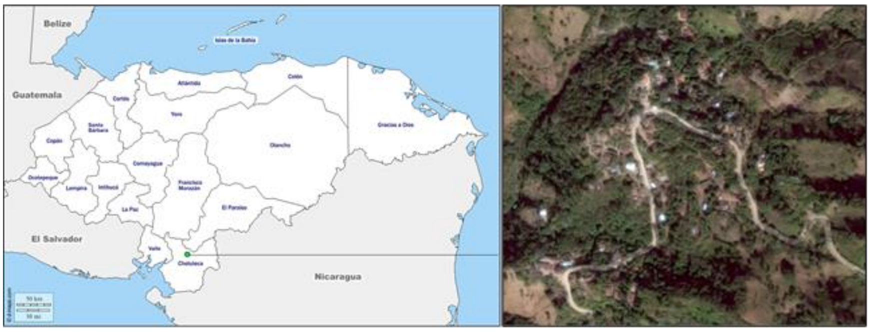


Figure 27. Location of the rural community of "El Santuario". ©d-maps.com. ©2018 Google

The community is located in an area of slopes surrounded by a dry forest, with pine and holm oak as predominant forest species. It has streams as main water sources, which remain dry during summer period. It is characterized by a sub-humid ecosystem with two well differentiated seasons: a dry season (between November and April) and a wet season (between May and October). The temperature is stable during the whole year with an average maximum of 27ºC and an average minimum of 16ºC. Rainfalls are very irregular instead: January is the driest month, with 0-5 mm, and September the wetter one, with 400-500 mm. The average annual rainfall is around 1,800 mm.

The main economic activity is subsistence agriculture with limited production surpluses. Corn and beans are the most extended agricultural species, but new crops, such as cassava, sweet potatoes and vegetables family gardens have been recently introduced in a process of agro-diversification. However, inhabitants still have to migrate to other regions to work on temporary coffee farming.

The access to the community is difficult as it is limited to a poorly maintained ground road. For this reason, it has been isolated and without access to the national electricity grid either, which is not expected to change in the short or medium term.

5.2. FIELD VISIT AND SURVEY

In October 2017, team members from FAO and ACICAFOC visited the community in order to identify the viability of the project, the energy needs and the energy resources. The questions and model of survey was based on the guide "*Which size shall it be?*" developed by the German Cooperation GIZ in 2016. The model used is included in the Annexes. Overall, questions were orientated to gather information about demographic status, current energy sources and use, energy requirements, potential of renewable energy resources, incomes and ability to pay for electricity services, among others.

The community is composed by 77 households, 71 in the main urban area and other 6 located 1.75 km from the rest. Households have on average 5 members and 4.4 rooms each. Communitarian buildings include a church, which the inhabitants use for meetings and other activities, a school and a kindergarten.

Inhabitants use kerosene, fuel cells and candles for generating electricity and for the illumination of the households. Firewood is the main energy source and is used for cooking, lighting and heating; fuel cells are used for radios and lanterns. Moreover, 7 households have small photovoltaic systems, with 50 W panel, inverter and storage, which cover part of the lighting and phone charging needs.

Overall, inhabitants showed support to the electrification project. Among the 69 surveyed representatives of each family, 93% state that electricity access would improve their livelihoods, the other 7% did not know and none of them showed upset or opposition to the electrification process.

The current monthly average expenditure in energy sources is 116 Lps./household (with a standard deviation of 64.45 lps. among household). Moreover, the inhabitants expressed a willingness to pay around 43 Lps./month for electricity services. Therefore, considering the current expenditure in energy sources, the total ability to pay per household obtained is 169 Lps./month.

5.3. ENERGY RESOURCES

The analysis of the available renewable resources of the area for energy generation potential was performed taking into account the information gathered on the surveys and informal conversations with the inhabitants during the visits to the community.

5.3.1. Solar Resource[11]

Honduras' is characterized by a large photovoltaic power potential. As it can be shown in Fig. 28, along the department of Choluteca the yearly average global horizontal radiation reaches more than 2100 kWh/m^2.

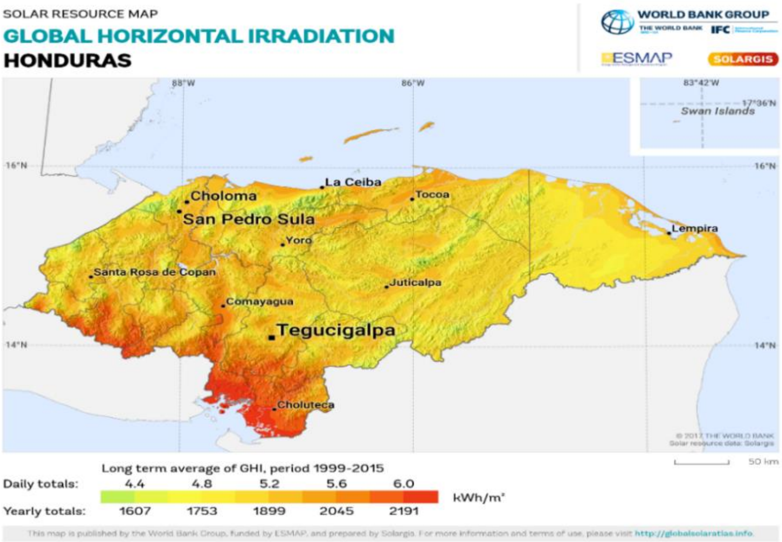


Figure 28. Solar Resource Map. Global Horizontal Radiation in Honduras in kWh/m2. Source: The World Bank, 2018.

The software PVSYST has been used to estimate the solar resource potential in the community. The simulations have been based on the meteorological data from the municipality of San Ramon de Arriba, located few kilometres far from the community. The yearly average global horizontal solar radiation of the area obtained is 1986 kWh/m2, which represents approximately 1600 hours of effective generation considering the efficiency of the panels and other losses.

For the location of the PV panels the inhabitants of the community suggested a 500 m^2 land plot on the center of the community. The chosen land plot is suitable as it is a well orientated and community own land. Thus avoiding renting issues or any shading elements.

5.3.2. Biomass Resource

Wet biomass resource for biogas generation through anaerobic digestion has been discarded for two main reasons. On the one hand, the water shortage during the dry season, and on the

[11] Only solar photovoltaic resource for electricity generation is considered. Solar thermal resource is not considered because the tropical climate characteristics of the area make unnecessary heating as will be described below.

other hand, the current use of livestock manure as fertilizer, which would require a cultural shift and measures to ensure soil fertility.

However, the dry biomass resource presents high potential for energy generation. The community owns a forest of about 150 ha from which they currently collect the wood. The inhabitants confirm that there is no notable difference in the amount of resource during the year. Currently, the dry biomass resource consumption per household is around 35 kg/day during the whole year, thus making 12.8 ton/year/household.

5.3.3. Wind Resource

As it can be observed in Fig. 29, the wind power density is higher along the Mesoamerican Dry Corridor, thus wind energy has high potential in the area. The inhabitants of the community informed about the availability of a small hill where a small wind turbine could be installed. According to data from the DTU Global Wind Atlas, the average wind speed of the area is around 7 m/s. However, wind energy was discarded due to the lack of detailed analysis and data of the wind resource in the area, which complicates the design.

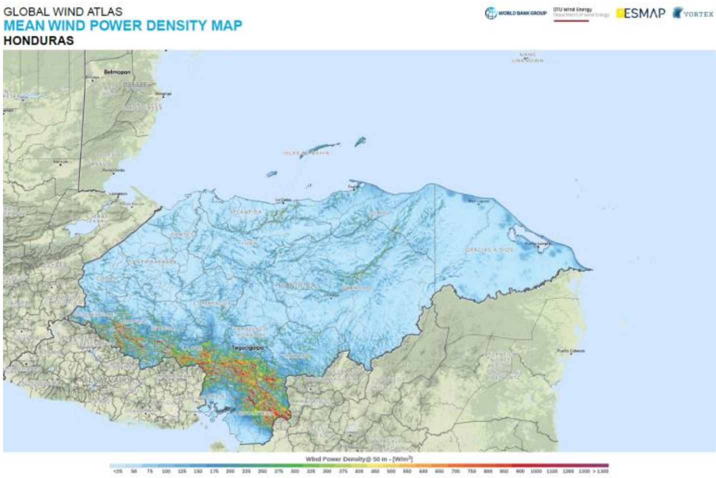


Figure 29. Mean wind power density map in Honduras. Source: DTU Global Wind Atlas

5.3.4. Hydric Resource

The generation of electricity by small-hydro technology has been discarded for similar reasons as for the anaerobic digester. The variability on the water resource in the area with the season due to the orography would cause also a varying power generation and may also endanger water security during the dry season.

5.4. INITIAL ENERGY DEMAND ASSESSMENT

The initial energy demand assessment was carried out considering the data gathered through the surveys. The energy needs identified and expressed by the inhabitants of the community were limited to electricity. On the one hand, regarding the thermal energy needs, the tropical climate characteristics of the area make unnecessary both the heating of the households. On the other hand, the mechanical energy needs were also discarded as currently the agriculture is not mechanized in the community and other sources of mechanical energy needs such as construction or transport were not identified.

The electricity needs of the community were identified in the survey. As it is a non-electrified community the inhabitants were asked for their current or desired electrical appliances and the expected usage hours once they had access to electricity. A quantitative approach based on previous experience in similar contexts has supported the information gathered in the surveys in order to determine the usage hours that the appliances are expected to be used by the inhabitants.

5.4.1. Households

Table 2 shows a summary of the expected electricity needs in the households. The power of the loads in W was estimated based on data from typical electrical appliances of the area and ENEE's publications.

Table 2. Summary of expected electricity needs in households

ELECTRICITY NEEDS IN HOUSEHOLDS					
Electrical Appliances	**Units**	**Power (W)**	**Units/household**	**Usage hours (h/day)**	**Total Energy Consumption (kWh/day)**
Lighting	267	15	3.76	8.50	34.0425
TV	40	150	0.56	5.20	31.200
Radio	43	20	0.61	14.00	12.040
Phone	39	10	0.55	6.00	2.340
Fan	34	50	0.48	3.75	6.375
Fridge	16	500	0.23	1.24	9.920
Other electrical appliances	19	1,000	0.27	2.40	45.600
Computer	1	200	0.01	4.30	0.860
Total					142.3775

It has to be considered that currently most part of the electrical appliances does not exist in the community; thus the acquisition will not be immediate. Moreover, if the economy of the community grows, the number of devices and usage hours may increase. Among the interviewees, the 78% agreed in the possibility of paying for electricity services, which would contribute to cover the costs of the installations such as the replacement, operation and maintenance costs or further extensions.

The preliminary total energy consumption estimated in households per day is 142.375 kWh/day, reaching a value of 51.967,8 kWh/year.

5.4.2. Community Services

Regarding the community energy needs, they were also identified according to the needs expressed by the inhabitants. The 86% of the interviewees expressed interest in using the electricity in agricultural applications, especially in the irrigation of the small family gardens. Other electricity needs were identified in the church, school, kindergarten and street lighting.

Therefore, the technical proposal includes the installation of 20 street lights, 2 fans per building and lighting for the church, school, and kindergarten according to international standards, as well as IT equipment, including a computer and a printer, for the improvement of communications in the community.

The water pump for irrigation activities has been selected for a pumping head of 80 meters. It will pump the groundwater located 14 meters deep to a small water reservoir used for gravity-fed irrigation of the family gardens. Its usage is estimated in 4 hours per day.

Finally, as it is expected to include a biomass gasifier in the energy installation, it has also been considered the energy requirements of a biomass chipper. It is expected to be used 2 hours per day, as will be explained later.

Table 3 summarizes the electricity needs in the community.

Table 3. Summary of expected electricity needs in the community

ELECTRICITY NEEDS IN THE COMMUNITY

Electrical Appliances	Units	Power (W)	Usage hours (h/day)	Total Energy Consumption (kWh/day)
Water Pump	1	2,000	4	8.00
Street Lighting	20	50	10.50	10.05
Fan	8	100	10.00	8.00
Lights School, Kinder and Church	78	15	8.25	9.652
IT (Computer and Printer)	3	300	12.50	11.25
Biomass Chipper	1	7,500	1.50	11.25
Total				58,202

It is important to highlight that whereas some of the community needs, such as street or school lighting, have a fixed usage schedule, others such as the water pump or the biomass chipper have more flexibility. For instance, it is preferable that the two devices are not used simultaneously (i.e. one can be used in the morning and the other in the afternoon) in order to contribute to balance the demand curve and ensure the optimum operation of the energy installation.

The daily preliminary energy consumption estimated per communitarian services is 58.65 kWh/day, making 21.408 kWh/year.

In total, the preliminary estimation of the energy demand of the community has a value of approximately 201 kWh/day and 73,000 kWh/year.

CHAPTER 6. ENERGY DEMAND ASSESSMENT

The energy demand assessment, which includes the quantification of the energy demand of the community in kWh/year besides the formulation of the expected load profile, has been performed according to the electricity needs identified in the initial energy demand assessment.

This section includes the application, analysis and comparison among two methodologies for assessing the energy demand of the community. Methodology 1 is based on the GIZ (2016), which builds up the coincidence behaviour of the different consumers and appliances according to the available information and designers´ previous experience. Through Methodology 2 a stochastic approach implemented in the software LoadProGen2.0 has been used.

6.1. METHODOLOGY 1: Coincidence Factors

Based on the information of the electricity needs identified and showed in the initial energy demand assessment, it is necessary to characterize the hourly demand for each type of appliance. Firstly, the usage schedule for the appliances has been defined according to the typical schedule of the inhabitants of the community and previous experience in similar rural electrification projects. Consequently, the coincidence behaviour among the users and electrical appliances has been built up.

The coincidence behaviour is built up from the different coincidence factors, as a measure of how likely all the loads are demanded by the consumers at the same time.

In that regard, different coincidence factors have been considered for each hour of the day because not all the appliances are expected to be used simultaneously. In essence, the maximum power for a certain type of appliance for all the customers is distributed along the daily usage schedule. Table 4 shows the example of the practical application of this procedure to the estimation of the consumers' daily demand of tree type of appliances: household's lights, fridge and water pump. For instance, it can be observed that for the household's lights, although the maximum power is 4,005 kW (267 units of 15 kW), it is only reached during the first hours in the day and after the working hours in the evening, thus the coincidence factor will be equal to 1. The total installed power for fridges is 8,000 kW but they will be working at low power during most of the day, thus the energy consumption is reduced. Another example is the water pump that is expected to be used at maximum power only during central hours on the day to take advantage of the solar resource. The assumed coincidence factors for all the appliances can be found in the Annexes.

Table 4. Application of Methodology 1: Coincidence Factors to Household´s Lights, Fridge and Water Pump. Building up coincidence behavior among appliances and users. Source: Own elaboration.

Hour	HOUSEHOLDS' LIGHTS		FRIDGE		WATER PUMP	
	Coincidence Factor	Power (kW)	Coincidence Factor	Power (kW)	Coincidence Factor	Power (kW)
0:00	-	-	0.01	80	-	-
1:00	-	-	0.01	80	-	-
2:00	-	-	0.01	80	-	-
3:00	-	-	0.05	400	-	-
4:00	0.50	2,003	0.10	800	-	-
5:00	1.00	4,005	0.10	800	-	-
6:00	1.00	4,005	0.10	800		-
7:00	0.75	3,004	0.05	400		-
8:00	0.50	2,003	0.01	80	-	-
9:00	0.05	200	0.01	80	-	-
10:00	0.05	200	0.05	400	-	-
11:00	0.05	200	0.10	800	-	-
12:00	0.05	200	0.10	800	-	-
13:00	0.05	200	0.05	400	1.00	2,000
14:00	0.05	200	0.01	80	1.00	2,000
15:00	0.05	200	0.01	80	1.00	2,000
16:00	0.05	200	0.05	400	1.00	2,000
17:00	0.50	2,003	0.10	800	-	-
18:00	1.00	4,005	0.10	800	-	-
19:00	1.00	4,005	0.10	800	-	-
20:00	1.00	4,005	0.05	400	-	-
21:00	0.50	2,003	0.05	400	-	-
22:00	0.25	1,001	0.01	80	-	-
Total	0.10	401	0.01	80	-	-

The load curve represents the temporary evolution of the electrical power requirements of the community throughout a typical day. The area enclosed under the load curve represents the amount of energy consumed in a typical day. The differential points of the load curve are represented by the sum of the individual power demanded at each time step (Eq.9):

$$D_h = \sum_i P_{ih} \tag{9}$$

Where

- *h:* Time-step. In this case hourly time-steps have been considered, i.e. 24 daily time-steps.
- *i:* Individual appliances, e.g. TVs, lights, phones, etc.
- D_h: Point on the curve for each time-step *h*.
- P_{ih}: Electrical power demanded by each individual appliance *i* for each time-step *h*.

Considering the defined coincidence factors for all the appliances, the daily load curve is the result of the sum of the hourly power demanded by each appliance multiplied by the coincidence factor of each appliance every hour (Eq. 10):

$$D_h = \sum_i P_{ih} * f_{ih} \tag{10}$$

In the analysis, the load curve has been divided in two: one for households and other for communitarian consumptions, according to the electricity needs identified, and it is assumed that does not change during the year. Fig. 30 shows the preliminary load curve estimated for households and community services, as well as the total consumption of the community.

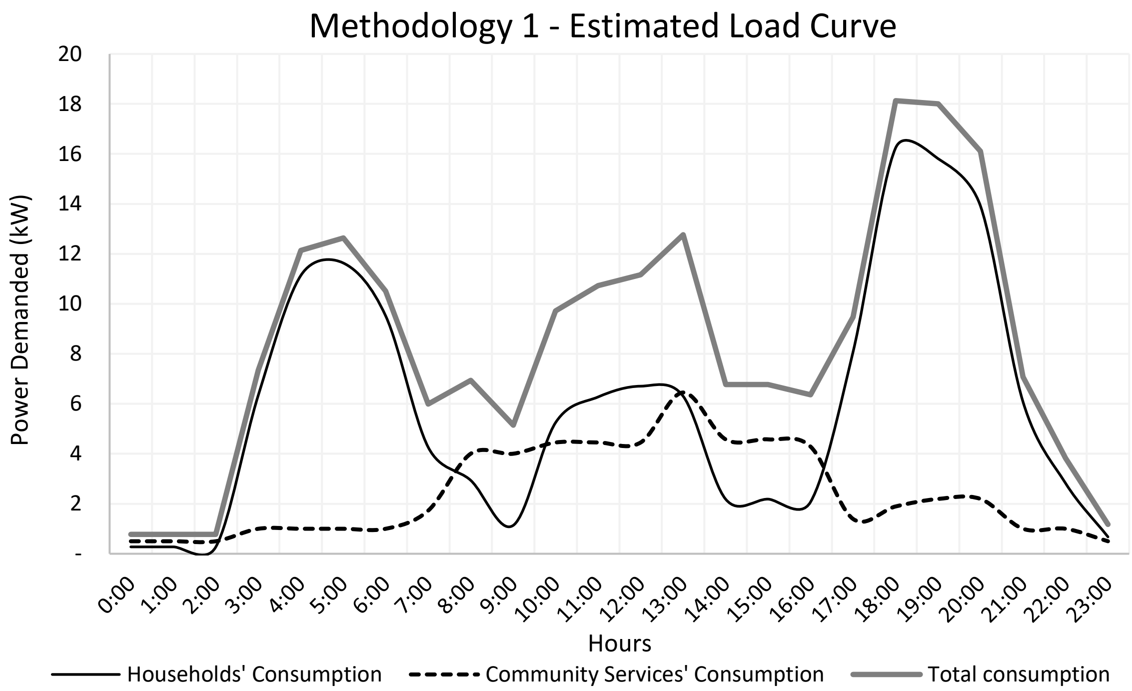


Figure 30. Preliminary estimation of the load curve of the community "El Santuario".

It can be observed that the maximum load peak is produced between 6 p.m. and 9 p.m., by the end of the day, and has a value of approximately 18 kW. Another load peak is observed around 4 a.m., when starts the activity in the community. The increased power consumption between 10 a.m. and 2 p.m. is due to the biomass chipper and water pump, which were programmed to work non-simultaneously and to take advantage from the sun hours.

Finally, the total daily energy consumption of the community is obtained as the sum of all the hourly load consumptions throughout a day. The total yearly energy consumption is obtained by multiplying the total daily energy consumption by 365 days:

$$E_{year} = 365 \times E_{day} = 365 \times \sum_{h=1}^{24} D_h \tag{11}$$

The estimated daily energy consumption per family in households is 2.83 kWh/day, and 0.06 kWh/day per communitarian services. The results are in line with the global data on basic energy needs for ensuring human well-being[12]. The total yearly energy consumption of the community is approximately 73,000 kWh/year and would be the energy that the hybrid mini-grid system should generate.

[12]Data from UNDP adapted from Krugman, H and Goldemberg, J.(1983). Average energy consumption per capita on basic needs of 30 kcal/day http://hdr.undp.org/sites/default/files/goldemberg-energy-1.pdf

6.2. METHODOLOGY 2: LoadProGen2.0

The software LoadProGen2.0 requires certain input data for performing the simulations. In line with the first methodology, the input data is obtained from the information gathered in the surveys and the initial demand assessment. The information requires to be processed in order to match the specific parameters and be introduced in the software, as detailed below.

The users have been divided in three *user classes (j)*: Households, Communitarian Services and Productive Services. Each class includes a certain *number of users (N_j):* The Household user class includes the 71 households of the community; the Communitarian Services include the communitarian buildings (church, school and kindergarten); and the Productive Services category is divided in water pump and the biomass chipper.

Fig. 31 shows the user´s graphical interface of the Software, in which the different user classes and the appliances introduced for the Households user class can be observed.

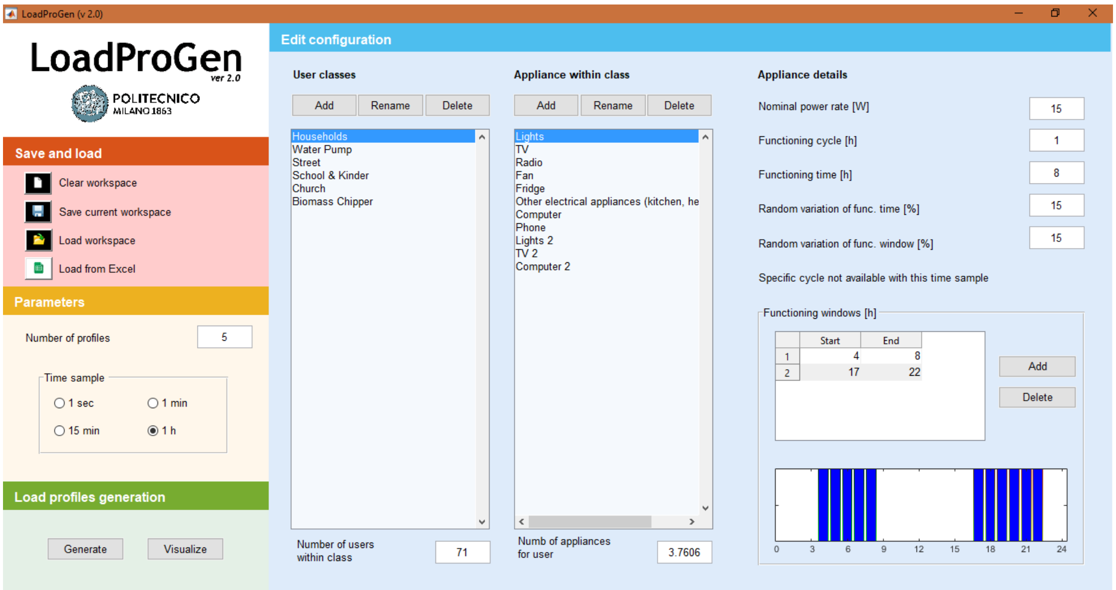


Figure 31. Inputs introduced in LoadProGen. User´s graphical interface.

- **Households:** For the Households user class, the *type of electrical appliances (i)* required coincides for most of the users. However, the number of applications varies depending on the Household. In order to avoid long runtimes of the software for the generation of 71 different profiles, an average value per household has been considered. Overall, whereas all the inhabitants required light bulbs, not all of them showed interest on other devices such as TV, radios, etc., mainly due to the lack of this devices nowadays. Only one of the interviewed showed interest on a computer. The *nominal power* needed (P_{ij}) of each device was estimated considering typical electrical appliances of the area and ENEE's publications. Regarding the daily *functioning time (h_{ij})* of each appliance, it has been defined taking into account the equivalent hours per day that the devices are expected to be used according to the typical daily schedule of the inhabitants. The same assumption was considered for the *functioning window (wf_{ij})*. In addition, for some devices, such as lights or TVs, users have notable difference in the power requirements depending on the time frame, thus presenting different *functioning time (h_{ij})* and *functioning window (wf_{ij})* that must be considered in the analysis in order to obtain more accurate results.

he random variation of the functioning time and windows (*Rh_{ij}* and *Rwf_{ij})* has been fixed in 15% following other similar cases of LoadProGen application (Berti, 2016), except for the fridge in which the variation of both parameters has been fixed in 5% as it is expected to be turned on during the whole day with minimum variation. The *functioning cycle* (*d_{ij})* would be less than 1 hour for most part of the devices, but when performing hourly simulations is the minimum possible value to set.

All the parameters are summarized in Table 5 as follows.

Table 5. Input data for the Households User Class

HOUSEHOLD USER CLASS

Type of appliance (i)	Num. of users (j)	Number of electrical appliances per user (n_{ij})	Nominal Power of appliances (*P_{ij}*) (W)	Functioning cycle (d_{ij}) (hours)	Functioning time (h_{ij}) (hours)	Variation of Functioning time (Rh_{ij}) (%)	Variation of Functioning window (Rw_{ij}) (%)
Lights	71	3.76	15	1	8	15	15
TV	71	0.56	150	1	5	15	15
Radio	71	0.6	20	1	14	15	15
Fan	71	0.478	50	1	4	15	15
Fridge	71	0.22	500	1	1	5	5
Other	71	0.267	1000	1	2	15	15
Computer	71	0.014	200	1	3	15	15
Phone	71	0.55	10	1	6	15	15
Lights 2	71	3.76	15	1	1	15	15
TV 2	71	0.56	150	1	1	15	15
Computer 2	71	0.014	200	1	1	15	15

Type of appliance (i)	Functioning window 0 (*wf_0)*		Functioning window 1 (*wf_1)*		Functioning window 2 (*wf_2)*	
Lights	4	8	17	22	-	-
TV	3	5	18	23	-	-
Radio	3	21	0	0	-	-
Fan	4	18	0	0	-	-
Fridge	1	24	-	-	-	-
Other	3	6	10	16	17	20
Computer	3	4	18	22	-	-
Phone	1	5	18	24		-
Lights 2	9	16	23	24	-	-
TV 2	11	17	-	-	-	
Computer 2	11	17	-	-	-	-

- **Communitarian Services:** For the Street Light class, 20 units of 50W were identified during the field visit as approximately required for lighting the main street. It is assumed that the devices will be working continuously during the first hours of the morning and last of the evening, during no-sun hours. A certain random variation of the functioning window has been fixed to 10%.

The lighting requirements for the school and kindergarten have been defined according to international standards. Moreover, 2 units of fan per building have been considered in order to ensure good conditioning. IT services (computer and printer) have been also added to the analysis considering its importance to enhance communication and learning in the community. Both buildings have an almost fixed schedule from 7am to 8 pm, but a random variation of the functioning window of 30% has been assumed according to similar rural electrification projects (Mandelli, Merlo & Colombo, 2016).

All the parameters are summarized in Table 6, Table 7 and Table 8 as follows.

Table 6. Input data for the Street Lights User Class.

STREET LIGHTS USER CLASS							
Type of appliance (i)	Number of users (j)	Number of electrical appliances per user (n_{ij})	Nominal Power of appliances (P_{ij}) (W)	Functioning cycle (d_{ij}) (hours)	Functioning time (h_{ij}) (hours)	Variation of Functioning time (Rh_{ij}) (%)	Variation of Functioning window (Rw_{ij}) (%)
Ext. Lights	1	20	50	1	11	10	10

Type of appliance (i)	**Functioning window 0 (wf_0)**		**Functioning window 1 (wf_1)**		**Functioning window 2 (wf_2)**	
Ext. Lights	1	6	18	24	-	-

Table 7. Input data for the School and Kindergarten User Class.

SCHOOL AND KINDERGARTEN USER CLASS							
Type of appliance (i)	Number of users (j)	Number of electrical appliances per user (n_{ij})	Nominal Power of appliances (P_{ij}) (W)	Functioning cycle (d_{ij}) (hours)	Functioning time (h_{ij}) (hours)	Variation of Functioning time (Rh_{ij}) (%)	Variation of Functioning window (Rw_{ij}) (%)
Lights	1	72	15	1	8	5	5
Fans	1	4	100	1	10	5	5
IT	1	3	300	1	13	5	5

Type of appliance (i)	Functioning window 0 (wf_0)		Functioning window 1 (wf_1)		Functioning window 2 (wf_2)	
Lights	7	20	-	-	-	-
Fans	7	18	-	-	-	-
IT	7	20	-	-	-	-

Table 8. Input data for Church User Class

CHURCH USER CLASS							
Type of appliance (i)	Number of users (j)	Number of electrical appliances per user (n_{ij})	Nominal Power of appliances *(P_{ij})* (W)	Functioning cycle (d_{ij}) (hours)	Functioning time (h_{ij}) (hours)	Variation of Functioning time (Rh_{ij}) (%)	Variation of Functioning window (Rw_{ij}) (%)
Lights	1	6	15	1	8	30	30
Fans	1	4	100	1	10	30	30

Type of appliance (i)	Functioning window 0 (*wf_0)*		Functioning window 1 (*wf_1)*		Functioning window 2 (*wf_2)*	
Lights	7	20	-	-	-	-
Fans	7	18	-	-	-	-

- **Productive Services:** This category includes the water pump, selected for a pumping head of 80m, and the biomass chipper, with a power of 7,500 W according to the results of the first estimation of energy needs. Currently, the main economic activity of the community is subsistence agriculture. For these devices, the functioning windows and time are more flexible. Therefore, the functioning window has been fixed during sun hours and trying that both devices do not work simultaneously. The value of random variation has been fixed in 40%, as its usage depends on other parameters e.g. if solar resource is not enough during a certain period of time, it will be necessary to use the biomass chipper out of the expected usage schedule.
  These parameters are summarized in Table 9 and Table 10.

Table 9. Input data for Water Pump User Class

WATER PUMP USER CLASS							
Type of appliance (i)	Num. of users (j)	Number of electrical appliances per user (n_{ij})	Nominal Power of appliances *(P_{ij})* (W)	Functioning cycle (d_{ij}) (hours)	Functioning time (h_{ij}) (hours)	Variation of Functioning time (Rh_{ij}) (%)	Variation of Functioning window (Rw_{ij}) (%)
Water Pump	1	1	200	1	4	40	40

Type of appliance (i)	Functioning window 0 (*wf_0)*		Functioning window 1 (*wf_1)*		Functioning window 2 (*wf_2)*	
Water Pump	13	16	-	-	-	-

Table 10. Input data for the Biomass Chipper User Class.

BIOMASS CHIPPER USER CLASS							
Type of appliance (i)	Number of users (j)	Number of electrical appliances per user (n_{ij})	Nominal Power of appliances (P_{ij}) (W)	Functioning cycle (d_{ij}) (hours)	Functioning time (h_{ij}) (hours)	Variation of Functioning time (Rh_{ij}) (%)	Variation of Functioning window (Rw_{ij}) (%)
Chipper	1	1	7,500	1	2	40	40

Type of appliance (i)	Functioning window 0 (wf_0)		Functioning window 1 (wf_1)		Functioning window 2 (wf_2)	
Chipper	8	13	-	-	-	-

6.2.1 Results

The simulations were performed hourly, in line with the analysis performed in the Case Study. The processing time required by the Software to obtain the load profiles was around 9 hours. The number of load profiles was set randomly in 300, thus the Software LoadProGen generates 300 different possible realistic load profiles from the input data. The output file of the Software is a 24x300 matrix (i.e. 24 columns representing the 24 hours per day, and 300 rows representing the 300 different possible load curves), graphically represented in Fig. 32.

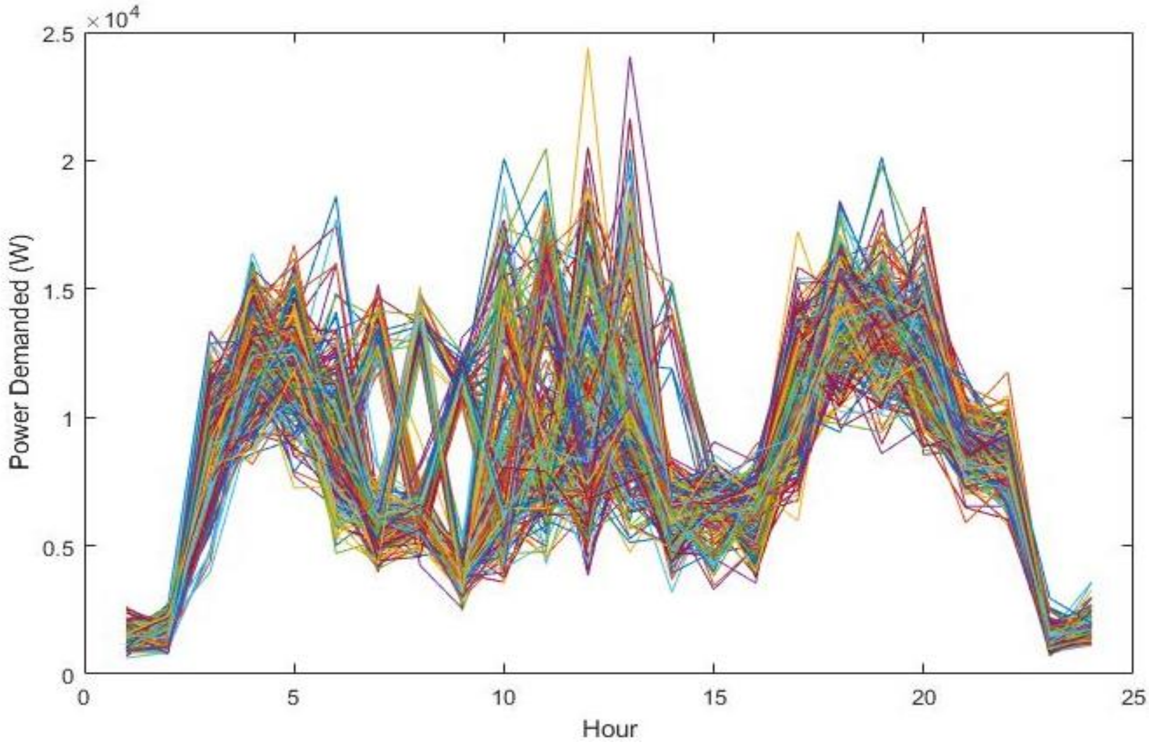


Figure 32. Results of LoadProGen2.0. 300 different possible realistic load profiles generated from the input data. Source: Adapted from LoadProGen2.0 results.

Due to the stochastic nature of the Software, the more number of profiles *n* that are simulated, the more accurate the results will be. In order to determine the optimal number of profiles to be formulated, the convergence criteria proposed by Mandelli, Merlo & Colombo (2016) has been used. This criterium establishes that the percentage variation of the average load profile values generated, and its average standard deviation must be less or equal to 0.25% for more than a 95% of the values generated or time-steps. The convergence conditions are defined as in Eq. 12 and Eq. 13:

$$\frac{\overline{y}(k)_n - \overline{y}(k)_{n+1}}{\overline{y}(k)_n} \leq 0.25\% \quad for\ \ k \geq 95\%\ of\ time\ steps \tag{12}$$

and

$$\frac{\overline{std}[\overline{y}(k)_n] - \overline{std}[\overline{y}(k)_{n+1}]}{\overline{std}[\overline{y}(k)_n]} \leq 0.25\% \quad for\ \ k \geq 95\%\ of\ time\ steps \tag{13}$$

Where,

- k: Profile time steps. In this case, the load profiles are constituted by averaged values over 1-hour time-steps.
- $\overline{y}(k)_n$: Average load profile value of the n generated profiles at the time step k.
- $\overline{std}[\overline{y}(k)_n]$: Average standard deviation of the average load profile value of the *n* generated profiles at the time step *k*.

In order to evaluate the convergence criteria, a MATLAB code was used. From the 300 number of profiles set up primarily, the convergence is reached at 211 profiles. Therefore, the optimum number of realistic profiles and that will be used for the load profile analysis is 211.

Fig. 33 shows the estimated future load curve for the rural community of “El Santuario”. The black line represents the average value of the total 211 profiles simulated. The uncertainty band (area between the maximum and minimum load curve) represents the maximum and minimum values among which the Software has evaluated scenarios, but do not present significant probability of occurrence. As can be seen, the uncertainty band is very broad. According to Berti (2016) this might be due to the large number of profiles simulated. It can also be due to different load with variable usage times.

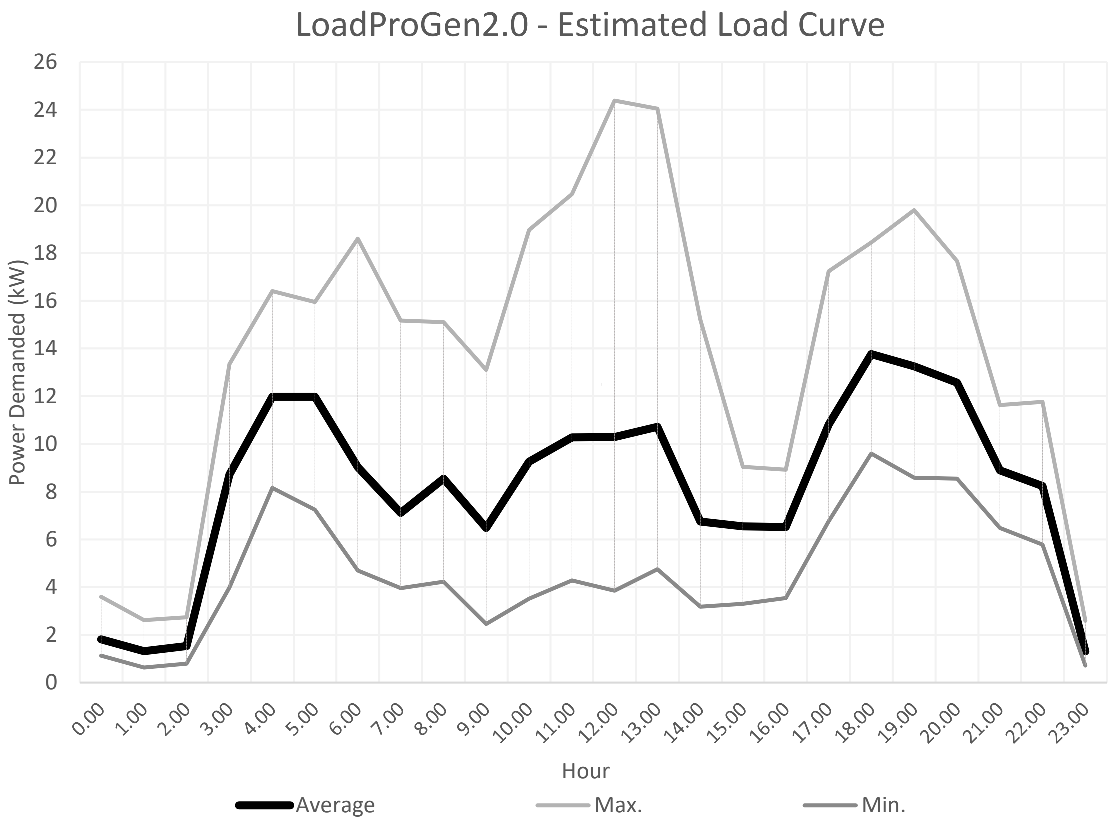


Figure 33. Estimated Load Curve using LoadProGen2.0

As can be observed in Fig. 33, the load peak occurs around at 6 p.m. in the evening, when inhabitants come back home after the working hours. There is also another peak early in the morning, between 4 a.m. and 5 a.m., time in which the activity starts in the community. Both peaks are in line with the trend observed in load curves estimation for rural isolated communities. Moreover, another peak occurs between 10 a.m. and 14 p.m., due to the productive services that include the water pump and the biomass chipper, which are high-energy consumption devices. Even though a wide random variation of the functioning window has been considered for these devices, for further studies it would be interesting to consider different scenarios, e.g. weekday/weekend or dry/wet season, as the operating hours will differ for both devices.

6.3. COMPARISON OF ESTIMATED LOAD PROFILE FOR BOTH METHODOLOGIES

Fig. 34 shows the comparison between the load curves estimated with Methodology 1 of capacity factors, and Methodology 2 using the LoadProGen2.0.

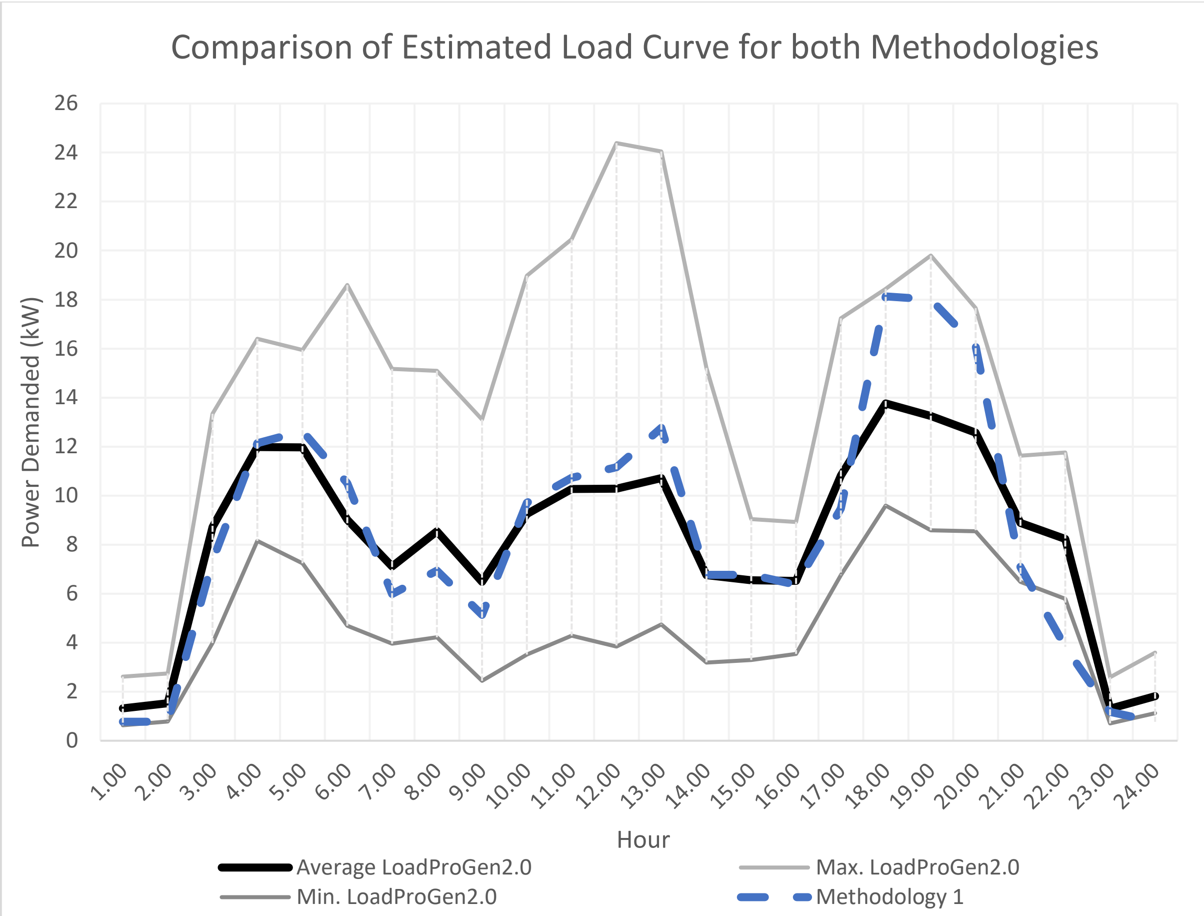


Figure 34. Comparison between the estimated Load Curve for Methodology 1 and LoadProGen2.0.

Regarding the daily energy demand estimation, represented by the area below the load curve, no significant differences in the values are observed between the two cases. The total demand reaches 201.09 kWh/day for the Methodology 1, value a 2% higher than the obtained with LoadProGen2.0 simulation: 197.752 kWh/day.

However, some differences can be observed on the shape of both curves. In spite that the load peak occurs between 6 p.m. and 8 p.m. for both curves, the value of the load peak reaches 18.13 kW for the Methodology 1, and 13.76 kW for the estimated with LoadProGen2.0. For the other load peaks in the morning and during central hours of the day, it can be also notice that the value reached with the software is slightly lower. Only at 8 a.m. the peak is higher for the LoadProGen2.0, with a value of 8.55 kW in comparison with the value of 6.95 kW for the Methodology 1.

The fact that the load curve estimated with the LoadProGen2.0 is flatter is extremely linked with the stochastic nature of the procedure. The formulation of load profiles for rural isolated areas without previous access to electricity brings aside the intrinsic uncertainty of the input data due to the users' subjectivity in its definition. Therefore, the common approaches for load profile formulation in rural areas should consider uncertainty in the input data, thus formulating a certain number of profiles for representing a more realistic situation (Mandelli, Merlo & Colombo, 2016)). In the Methodology 1 only one single profile is formulated whereas the simulation with LoadProGen2.0 included 211 different probable profiles based on a convergence criterion. Indeed, the load peak value obtained by Methodology 1 around 6 p.m. (18.12 kW) is close to the maximum value obtained during the simulations at the same time (18.43 kW), although the software determines that this value has low probability of occurrence.

In conclusion, the amount of energy demanded estimated has practically the same value for both cases. However, the load curve estimated in Methodology 2 with the LoadProGen2.0 is flatter, thus the load peaks are reduced in comparison with the Methodology 1. This fact will be reflected positively in the mini-grid design phase as the required capacity of the plant strongly depends on the peak values.

CHAPTER 7. DESIGN OF THE HYBRID MINI-GRID IN HOMER

Along this chapter the evaluation, sizing and modelling of the hybrid renewable mini-grid for the community is performed. For the design, the software HOMER has been used, analysing the results obtained when introducing the load curves obtained with the two methodology. In advance, a preliminary estimation of the energy generation needs and components of the system is studied as a reference point for starting the simulations.

7.1. PRELIMINARY ESTIMATION OF ENERGY GENERATION NEEDS

In order to achieve more accurate simulations in HOMER in less time, a mathematical preliminary estimation of the energy that the mini grid needs to generate to cover the demand is performed.

As described in previous sections, according to the analysis of available energy resources of the area and information provided by the inhabitants, the proposed hybrid renewable mini grid will be composed by solar photovoltaic (PV) and a biomass gasifier, supported by a battery bank. The system will operate in grid with a network manager that will allow to optimize both the resources and the equipment.

The energy that the system will generate will be the obtained from the two sources of electricity generation, given by Eq. 4:

$$E_{year} = E_{PV} + E_G \tag{14}$$

As solar photovoltaic is the most sustainable technology in terms of social, economic and environmental aspects, the mini grid is designed in order to maximize the solar photovoltaic generation system. It will use the battery bank for ensuring the energy supply when the solar resource is not available, and the biomass gasifier in order to cover demand peaks or charge the batteries when the solar system is not capable.

The electric energy generated by the solar system is calculated by means of the Software PVSYST. Based on the average global horizontal irradiation data in El Santuario (1,984 kWh/m2), an area of collection of 6.05 m^2/kW, and assuming an efficiency of the photovoltaic panels of 16.5% and combined physical, electrical and electronic losses of 18.89%; the effective hours of generation (h_{g-PV}) of the photovoltaic panels during one year they rise to 1626.8 h/year. Therefore, the photovoltaic energy power to install would be given by Eq. 15:

$$P_{PV} = \frac{E_{PV}}{h_{g-PV}} \tag{15}$$

The amount of dry biomass (kg) for feeding the gasifier has been estimated proportional to the energy generated (kWh) in a ratio: R = 1/1. Therefore, the amount of dry biomass that each of the 71 households must provide daily (m_v) is obtained as in Eq. 16:

$$m_v = \frac{E_G * R}{365 * 71} \tag{16}$$

7.1.1. Assumptions and results

From the initial energy demand assessment step, the value obtained in the preliminary estimation of the energy demand of the community was approximately 73,000 kWh/year. Then, different assumptions were considered in order to evaluate possible scenarios of energy generation. The first scenario considers that all the energy is generated by solar PV, whereas second and third scenarios consider the installation of a 25-kW and 18-kW gasifiers respectively, as the most common commercial power outputs found nowadays for biomass gasifiers´ models.

a) Provided that solar PV is going to be the prioritised technology, a first approximation consisted on assuming that all the energy would be generated by solar PV. In this case, following Eq. 15, the installed capacity of solar PV without the gasifier would be around 45 kW.
b) On the other hand, it was considered the installation of a 25-kW gasifier operating 4 hours per day. With that, the energy generated would be 36,500 kWh/year with a biomass consumption of 515.08 kg/year/household, calculated following Eq. 16. Therefore, the rest of the energy that should be generated in order cover the demand (36,500 kWh/year) would be produced by solar PV, thus requiring an installed capacity of approximately 23 kW following Eq. 15.
c) In addition, the installation of a 18-kW operating 4 hours per day was analysed. In this case, the energy generated by the gasifier would be 26,280 kWh/year with a biomass consumption, given by Eq. 16, of 370.14 kg/year/household. Consequently, the amount of energy that the solar PV needs to generate in order to cover the demand is higher, with a value of 46,720 kWh/year, for which 29 kW of installed power are required as per Eq. 15.

Table 11 summarizes the results of the three scenarios assumed for the analysis.

Table 11. Assumptions and scenarios a, b and c for the preliminary estimation of the energy generation needs

	Total Demand (kWh/yr)	**Effective Hours of Solar Generation (h/y)**	**Energy Generated with Solar PV (kWh/yr)**	**Installed Capacity Solar PV (kW)**	**Energy Generated with Gasifier (kWh/yr)**	**Installed Capacity Gasifier (kW)**	**Gasifier Operating Hours (h/day)**	**Biomass Consumption (kg/yr/house)**
a	73,000	1626.8	73,000	45	-	-	4	-
b	73,000	1626.8	36,500	23	36,500	25	4	515.08
c	73,000	1626.8	46,720	29	26,280	18	4	370.14

7.2. INPUT DATA

HOMER requires input data in order to perform the simulation. The variables to introduce include the energy demand characterization, the components or technologies of the system, the available energy resources of the area and the system's restrictions.

7.2.1. Demand Characterization

The demand characterisation consists on the introduction of the daily load curve of the community in HOMER. The average daily load profile for the 24 hours of the day has been introduced in HOMER, considering it constant for the whole year, i.e. without distinguishing between weekday/weekend, month or season. An hourly random variability of 10% for considering more uncertainty in the input values has been considered. From the data, HOMER generates the 8760 hourly values for the year.

As stated previously, the load curve obtained with both methodologies is tested. HOMER allows the graphical representation of the demand in different forms presented as follows for both load profiles.

7.2.1.1. Estimated Load Curve with Methodology 1: Coincidence Factors

Although the load curve has been assumed constant for the whole year, the uncertainty of 10% introduced in HOMER creates a certain monthly variability. Fig. 35 shows the monthly average load values.

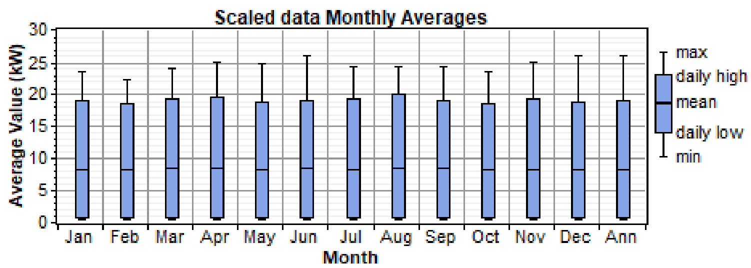


Figure 35. Methodology 1. Monthly average load curve values

Fig. 36 shows what is known as DMAP. This type of graphical plot allows to identify both months and hours of critical demand during the year. It can be observed that the evening hours of the day are the most critical, and when the load peaks are more likely to appear.

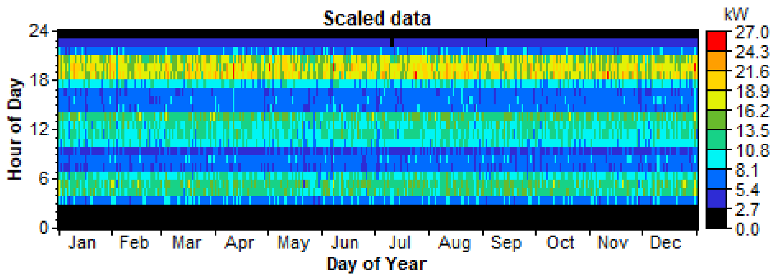


Figure 36. DMAP annual load curve for Methodology 1

In Fig. 37 it is represented the "Partial Distribution of Frequency", which shows the frequency in % of occurrence for the load values. The most frequent load values are below 1 kW and from 5 to 15 kW. Values higher than 20 kW are infrequent. This fact is shown as well in Fig. 38, which shows the "Cumulative Distribution of Frequency" regarding the 8760 hours in a year. Similarly, in Fig. 39 it is represented the "Duration Curve" or hours during the year that a determined load value must be covered. Loads higher of 20 kW must be covered few hours a year, whereas loads lower than 10 kW, and specially around 1 and 2 kW, must be covered more than 6,000 hours during the year. The high frequency of occurrence of values around 1 kW might be due to the low power requirements during the sleeping hours.

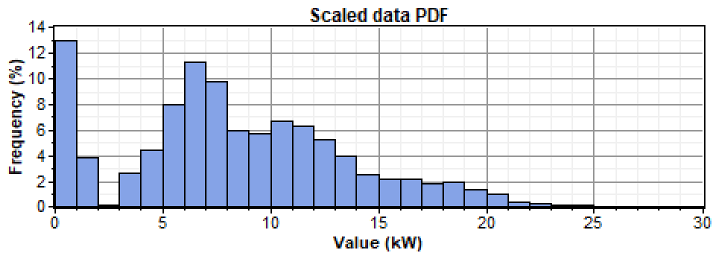


Figure 37. Methodology 1. Partial Distribution Frequency

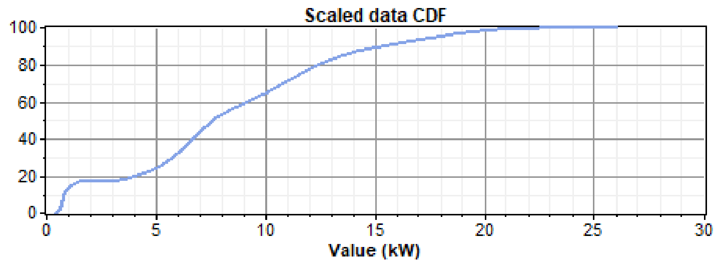


Figure 38. Methodology 1. Cumulative Distribution Frequency

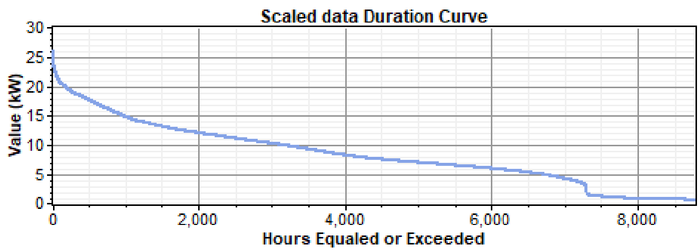


Figure 39. Methodology 1. Duration Curve

7.2.1.2. Estimated Load Curve with Methodology 2: LoadProGen2.0

Fig. 40 shows the monthly average load values for the load curve obtained with LoadProGen2.0. It can be observed that whereas the mean value is around 8 for both methodologies, for Methodology 2 the maximum average values are lower during the whole year.

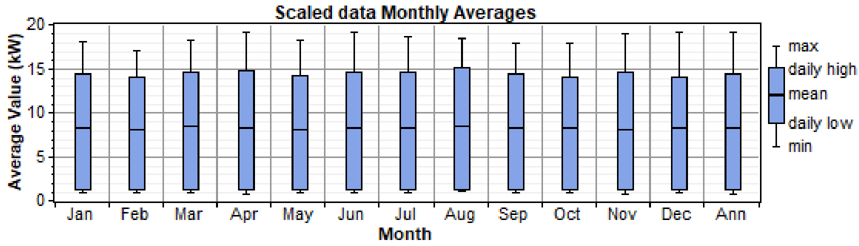


Figure 40. LoadProGen2.0. Monthly average load curve values

Regarding the DMAP it is shown that not only the last hours of the day are the most critical, but also the first hours in the morning (Fig. 41).

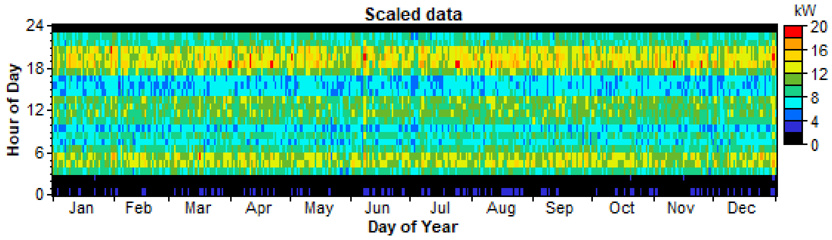


Figure 41. LoadProGen2.0. DMAP annual load curve

Fig. 42, Fig. 43 and Fig. 44 show that the most frequent load values are between 1 and 2 kW and 5 and 10 kW, whereas values around 15 kW must be covered few hours a day. Intermediate values between 2 and 5 kW are infrequent, what is in line with the typical daily schedule of the inhabitants. That means that the sleeping hours match for all the inhabitants, hence the load demanded is low, likewise happens with the waking-up hours and end of the working time, when the inhabitants spend more time at home and thus the load demanded is high.

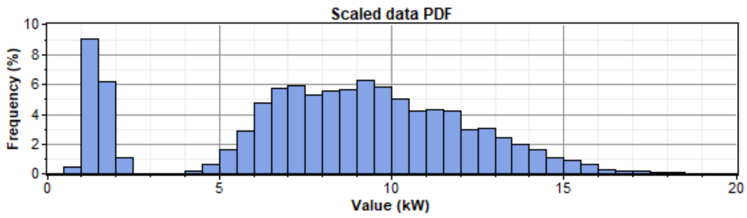


Figure 42. LoadProGen2.0. Partial Distribution Frequency.

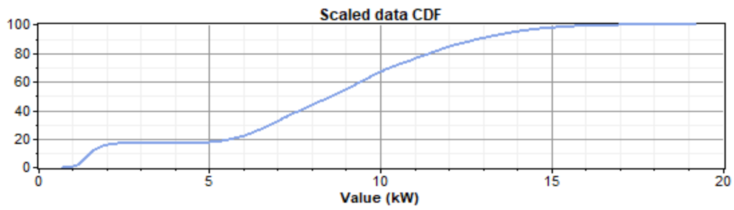


Figure 43. LoadProGen2.0. Cumulative Distribution Frequency

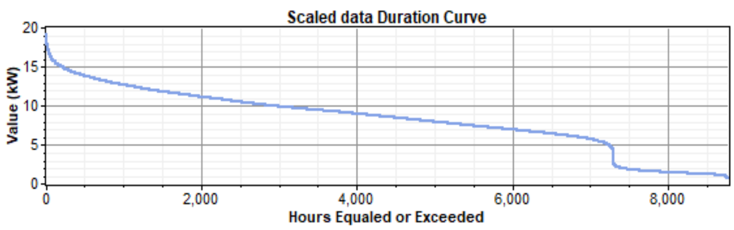


Figure 44. LoadProGen2.0. Duration Curve

7.2.2. Components

The system has as energy generation technologies solar photovoltaic panels and a biomass gasifier. Other required components include inverter/charger and batteries. The technical and economic parameters of the components introduced in HOMER have been selected from HOMER´s catalogue database, considering those suppliers that normally allow the purchasing in Central America. If it is not possible to purchase these specific components, similar ones must be acquired in order to meet the project specifications. The catalogues of all the components are given in the Annexes.

7.2.2.1. Solar Photovoltaic

The photovoltaic modules selected are the REC260P from the Scandinavian company *REC*, composed by 60 polycrystalline cells. The dimensions per module are 1665 x 991 x 38 mm, with an area of 1.65 m^2 and 18 kg of weight. The frame is made of anodized aluminum, and the cover is made of tempered glass with low transmission and low iron quantity. Thus, they ensure strength and durability, as well as good efficiency and nominal power appropriated for the system. Table 12 summarizes the electrical parameters of the modules.

Table 12. Electrical parameters at STC Conditions (1.5 Air Mass and 25ºC cell temperature) for REC260P Solar Photovoltaic Module. Source: REC Catalog.

ELECTRICAL PARAMETERS STC - REC260P	
Nominal Power (P_{MPP})	260 W
Nominal Voltage (V_{MPP})	30.7 V
Nominal Current (I_{MPP})	8.50 A
Open Circuit Voltage (V_{OC})	37.8 V
Short Circuit Current (I_{SC})	9.01 A
Module Efficiency	15.8 %
Power Tolerance	0/+5 W
Maximum System Voltage	DC 1000 V
Maximum Series Fuse Rating	15 A
Operating Module Temperature	45.5 ± 2

The manufacturer guarantees 10 years of manufacturing faults and 25 years of efficiency at least for the 84% of power output.

The price of every unit of 260 Wp is around 224 €/unit. The capital costs have been considered approximately a 40% higher than the selling price, as the installation costs should be included; The replacement cost as been considered as 10% lower than the capital cost; and the operation and maintenance costs are assumed as a 2% of the capital costs. The life time considered is 25 years, and the slope as 15º, value close to the latitude.

7.2.2.2. Biomass Gasifier

Two models of biomass gasifier together with the generating set are selected: model PP20 and PP30 from *All Power Labs*. The devices are configurable to single, split or three phases, at 120/208/240 Vac, 60 Hz or 50 Hz, and allows to generate reliable synchronized power when operating in mini grids. The technical characteristics of the models are summarized in Table 13.

Table 13. Technical Parameters for PP20 and PP30 models from All Power Labs. Source: All Power Labs

	TECHNICAL PARAMETERS PP20	TECHNICAL PARAMETERS PP30
Maximum Power	15 kW @50 Hz / 18 kW @60Hz	25 kW @ 50/60 Hz
Nominal Voltage	240 - 480 V AC	240 - 480 V AC
Biomass Consumption	1.2 kg/kWh (dry biomass)	0.9-1.2 kg/kWh (dry biomass)
Biomass Moisture Content	5 - 30 %	5 - 30 %
Max. Continuous Operation	>12 hours	>12 hours
Startup Time	10-20 min	10-15 min
Hopper Capacity	333 liters	333 liters
Dimensions	1.45 x 1.45 x 1.40 m	1.83x1.47x1.40 m
Weight	791 kg	1441 kg

For the PP20 the cost is 1.5USD per watt of equipment, thus making 27,000 USD per the 18 kW gasifier; whereas for the PP30 the cost is 2USD per watt of equipment, then 50,000 USD for the 25 kW gasifier. As well as for the photovoltaic modules, the replacement costs have been considered an 10% lower than the capital costs; and the operation and maintenance costs a 2% of the capital costs.

It is important to highlight that HOMER does not allow to introduce a biomass gasifier itself but a generator with biogas as fuel used. However, the gasifier uses as fuel the syngas, and there are differences between both gases. Syngas is obtained from the gasification of dry biomass and is composed by a combination of CO, H_2, CH_4, CO_2, N_2 with proportions that vary depending on the type of biomass and carbonating agent (H_2O steam, O_2 or air). Biogas is generated from the anaerobic digestion of organic components, thus significant proportion of its composition, a 50-70%, is CH_4. This makes the properties of both gases different, mainly low calorific value for the syngas.

Therefore, when introducing the gasifier in HOMER, the operational parameters of fuel consumption and output power of the generator to determine the operation efficiency of the device must be defined according to the type of fuel used. This fact presents the disadvantage of needing to determine not only the biomass properties (% of moisture, % of ashes, density in g/m^3, dry and wet Higher Heating Value) but also of the gas produced and the performance of the generator when introducing the gas.

In order to simplify this fact, the parameters of the fuel curve have been estimated based on a similar off-grid renewable hybrid mini grid designed for a laboratory in the Democratic Republic of Congo (DRC) in which the properties of wooden biomass species and the operation of the gasifier where analysed (Hurtado *et al.*, 2018). Along this study, the properties of typical wooden biomass species in DRC were analysed, as well as the operational parameters of the gasifier, obtaining:

-Gas generation per kg of biomass: 2.1 Nm^3/kg

-Electrical generation per kg of biomass: 0.9 kW/kg

-Input air per air produced: 0.7 Nm^3/Nm^3

-Maximum gas Low Heating Value: 6,600 kJ/Nm^3

-Efficiency of the conversion biomass-gas: 79%

-Efficiency of the conversion gas-electricity using an internal combustion engine: 22%

These results are among the average values of the parameters found on the scientific literature.

Regarding the gasifier usage schedule, HOMER has as default option the “Optimized” operation, i.e. HOMER decides whether the generator is started or not following the economic criteria. It has been fixed to stop (“Forced-off” option) during central hours of the day, when more solar resource is available, and during the resting hours at night, as the demand is very low. Moreover, a minimum load ratio of 50% has been fixed as operational requirement, which the inhabitants of the community would have to maintain in order to ensure the correct operation of the device.

7.2.2.3. Batteries

Batteries have been selected as storage system. Between the batteries´ types widely used in energy systems (Lithium-Ion and Lead-Acid), Lead-Acid batteries have been selected as a better cost-effective solution, although they reach less power and energy values. The model of batteries has been selected from HOMER catalog: 2V HOPPECKE Power VL 2-1150. These batteries work at 2V per cell at 20ºC and ensure more than 20 years failure-free operation at 25°C. Moreover, efficiency and reliability are high for solar photovoltaic installations, with 1,000 Ah (2 kWh) of capacity for 10 hours of discharge. The technical parameters are described in Table 14.

Table 14. Technical Parameters for 2V HOPPECKE Power VL 2-1150 model from HOPPECHE. Source: HOPPECHE

2V HOPPECKE Power VL 2-1150	
Nominal Voltage per cell	2 V
Nominal Capacity	1000 Ah (2 kWh)
Weight	76.4 kg
Max. Charge Current	202 A
Min. State of Charge	30 %
Optimum temperature operation range	20°C ± 10°C

According to the manufacturer, the life cycles to failure of the batteries 2V HOPPECKE Power VL 2-1150 will be:

- 8000 cycles with Depth of Discharge (DoD) of 20%, and 21.9 years of useful life.

- 3000 cycles with Depth of Discharge (DoD) of 50%, and 8.2 years of useful life.
- 1500 cycles with Depth of Discharge (DoD) of more than 50%, and 4.1 years of useful life.

For the model introduced in HOMER, 24 batteries of 2 V per string have been considered (48V in total). The cost of the batteries is 400 USD, 350 USD for replacement and 2USD/year for operation and maintenance costs.

7.2.2.4. Converter

HOMER considers the converter as the component that can act as inverter, transforming DC current to AC to feed the loads, or rectifier, to transform AC current to DC in order to charge the batteries. The inverter/charger has been selected following the optimal size according to the system´s capacity requirement resulted from the simulations with HOMER, as will be described further below in the document.

For the parameters introduced in HOMER, a reference model of inverter of 6 kW has been used, with a purchase and replacement cost of 4,000 USD, 85 USD/year of operation and maintenance costs, and efficiency of 92%. The option "Inverter can operate simultaneously with an AC generator" has been selected, in order to ensure the synchronism with the generator of the gasifier.

The technical parameters of the selected model, Sunny Tripower 25000TL, are described in Table 15.

Table 15. Technical Parameters for 25000TL model from SUNNY TRIPOWER. Source: SUNNY TRIPOWER

TECHNICAL PARAMETERS SUNNY TRIPOWER 25000TL	
Maximum Power Input	45,000 Wp
Nominal Power Output	25,000 W
Nominal Voltage Output	380 – 415 V
Max. Current Output	36.2 A
Power Factor	1
MPPT Voltage Range	390 – 800 V
Max. Voltage Input	1000 V
Max. Current Input	33 A
Phases	3
Max. Efficiency	98.3 %
Dimensions	661 x 682 x264 mm
Weight	61 kg

7.2.3. Energy resources

The renewable energy resources to be introduced include those that will feed the technologies for energy generation: global horizontal irradiation and dry biomass.

7.2.3.1. Solar resource

The solar resource has been introduced in HOMER by entering the monthly average values of daily global horizontal irradiation in kWh/m^2/day. The global horizontal irradiation data is obtained from the simulations with the Software PVSYST of meteorological data from the municipality of San Ramon de Arriba, located few kilometres far from the community. The coordinates for the area introduced in HOMER are 13° 19’ North, 87° 10’ West, and the time zone is GMT-4.

Fig. 45 shows the global horizontal radiation and the Clearness Index. The value of the index is obtained by HOMER from the daily radiation data and the coordinates of the location, representing the amount of days that the sky is clear. For the case study is 0.58, a significant value that ensures the harnessing of the solar energy installation.

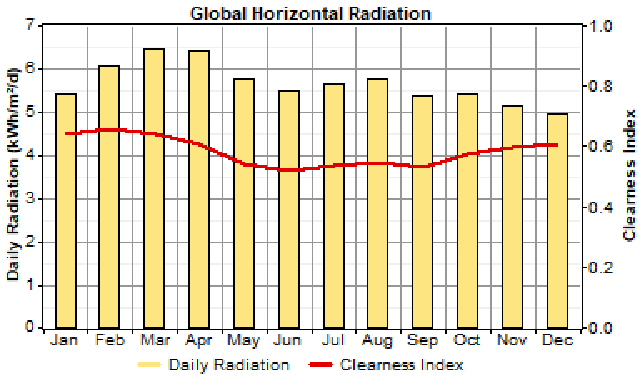


Figure 45. Global Horizontal Radiation in El Santuario

7.2.3.2. Biomass resource

The amount of dry biomass available in El Santuario was determined from the data gathered in the surveys. Approximately, the community has a consumption of 35kg/day and household. The biomass resource in kg/day to introduce in HOMER has been assumed constant for the whole year and proportional to the gasifier generation in a ratio 1:1, i.e. for producing 1kWh of electricity, 1 kg of wood fuel would be required. Therefore, assuming 10 hours/day of gasifier operation, for the 25-kW gasifier a total of 250 kWh could be generated in a day, for what 0.25 t/day of biomass would be required. Similarly, for the 18-kW gasifier, 180 kWh/day could be generated, requiring 0.18 t/day of wood fuel.

For the “Carbon Content” and “Biogas Lower Heating” parameters the default values have been considered, being 5% and 5.5 MJ/kg respectively. Although currently the community owns the forest from which the biomass is obtained, it has been considered a certain “Average price” of the biomass. This will allow to include it among the costs and prevent future needs of purchasing. According to FAO (2018) the commercialization price of wood was 425 USD/m^3 in 2017, and the ratio kg/m^3 reached a value of 725. With that, the average commercialization price of biomass is estimated in approximately 300 USD/ton. For the community, the price has been fixed in a lower value of 100 $/ton.

In Fig. 46 it is shown the biomass resource introduced in HOMER for the 25-kW gasifier as an example.

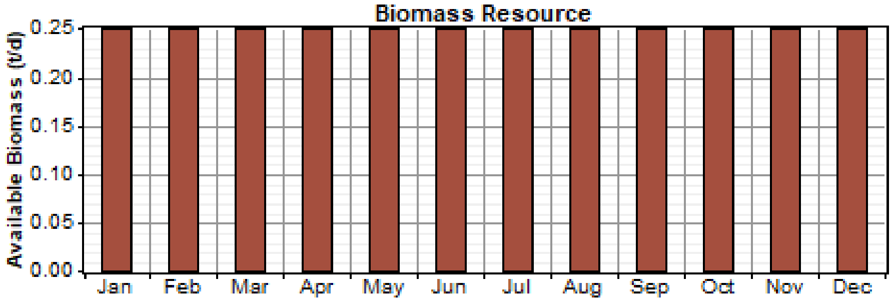


Figure 46. Biomass Resource in El Santuario

7.2.4. System restrictions

7.2.4.1. Economic Inputs

As economic inputs, it has been introduced the annual interest rate of Honduras, 5.75 % in May 2019[13] for the calculation of annualized costs. The project has been simulated for 25 years. Fixed capital and operation and maintenance costs, as well as penalty for capacity shortage are not expected.

7.2.4.2. System Control Inputs

This section includes the operation regulations for covering the demand for the battery bank and the generator. The selected "Dispatch Strategy" is cycle charging, whenever a generator must operate, it operates at full capacity with surplus power going to charge the battery bank. The setpoint state of charge indicates the percentage of battery bank charge that the generator must reach once the generator is started, in this case is fixed in 100%.

7.2.4.3. Emissions

HOMER allows to introduce economic costs associated to emissions as penalties, as well as yearly limits for emissions, ruling out all the alternatives that exceed the limits. For this case, no penalties nor limits have been considered for the simulation.

7.2.4.4. Constraints

The mini grid is designed in order to ensure power supply continuity, thus the maximum annual capacity shortage must be 0%. Moreover, HOMER considers the possibility of occasional increase of the demand and decrease of the renewable generation, thus allowing a power operating reserve that always must be lower than the available.

[13] https://tradingeconomics.com/honduras/interest-rate

7.3. RESULTS

Once the inputs have been introduced, HOMER performs the simulation of the different possible system´s configurations that meet the energy demand and the defined restrictions. The software orders the optimized results according to the lowest Levelized Cost of Electricity (LCoE).

For the first simulations and pre-design of the system the load curve obtained with the Methodology 1 has been taken as reference. This configuration will be optimized by introducing the more accurate load curve obtained with the LoadProGen2.0 in the Methodology 2. The results of the two solutions will be analysed and compared.

For the simulations different configurations of equipment were tested:

- Solar panels with installed power variations of 1 kWp;
- Batteries with accumulation capacity variations of 1kWh, ensuring a minimum Sate of Charge of 30% and maximizing the time they are above the 60% of charge.
- Inverter/charger with installed power variations of 5 kW;
- and two commercial models of gasifiers with 18 kW and 25 kW of power.

In order to identify the optimal solution, several techno-economic parameters for the alternatives proposed by HOMER are analysed.

The technical variables to analyse include:

- **Excess of electricity:** Is the amount of energy that the system generates but it is not possible to be used to feed the loads or charge the batteries, because the energy demand is lower than the energy produced, or the batteries are already charged and not able to storage more energy. This energy can be fed into the grid when on-grid connections and countries where the regulatory framework allows it or can be used to feed other devices.

- **Unmet electric load:** Is the electric load that the system is not able to cover because the energy demanded is higher than the generated by the system.

- **Maximum capacity shortage**: It is a shortfall that occurs because the required operating capacity is higher than the one that the system can provide.

As has been pointed out previously, the system is configurated in order to meet the electric load without shortfalls along the year, therefore these values must be close to 0.

The following economic parameters will be considered:

- **Initial Capital:** Is the total cost for the installation of the components at the beginning of the project implementation.

- **Total Net Present Cost:** It represents the actualization to the present of the costs of the system over its lifetime. The costs include capital costs, replacement costs, operation & maintenance costs, penalties, etc. The incomes include the sales of energy to the grid and salvage value of the components at the end of the project lifetime.

- **Levelized Cost of Electricity:** It is the average cost of producing each kWh of useful electrical energy. It is the result of dividing the annualized cost of the system, in terms of electricity generation, by the total load covered.

7.3.1. Load Curve of Methodology 1 for Simulation and Pre-design of the system

The first simulations of the configurations have been carried out in different iterative stages, i.e. the solution of each stage has been used as starting point for the following stage until arriving to the optimized solution for the preliminary design of the mini-grid.

Trough the HOMER, up to 41 different configurations were analyzed in terms of the described techno-economic parameters. As a result, the optimized configuration obtained in the first simulations for the pre-design of the system is composed by: 52 kWp of solar photovoltaic, 25kW gasifier, 144 units of batteries with 288 kWh storage capacity and two inverter/chargers of 25 kW each.

Table 16 summarizes the main techno-economic parameters analysed for the proposed solution.

Table 16. Techno-economic parameters of the proposed solution obtained with the load curve estimated with Methodology 1.

	Excess Electricity (kWh/yr)	Unmet Load (kWh/yr)	Capacity Shortage (kWh/yr)	Initial Capital (USD)	Total NPC (USD)	LCoE (USD/kWh)
PROPOSED SOLUTION FOR METHODOLOGY 1	14,961	0.0000456	0.00	203,333	293,283	0.285

7.3.1.1. Results discussion

Fig. 47 shows the monthly average electricity production from photovoltaic and the gasifier. It can be observed that the gasifier is only needed from May to September, due to the lower solar resource during the wet season. In total, the photovoltaic generates the 94% of the energy and the gasifier only the 6%.

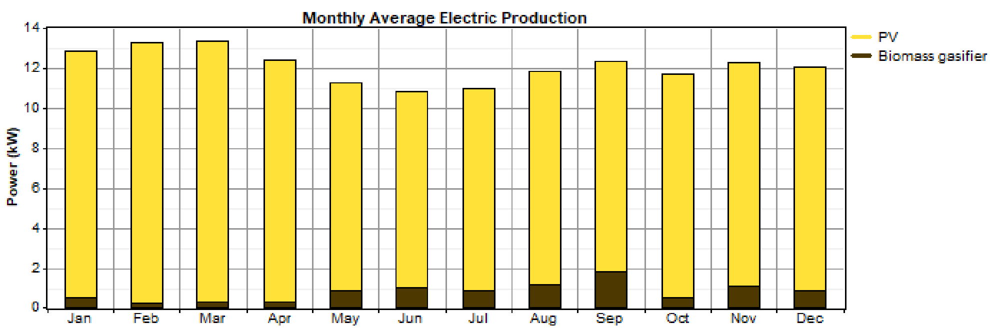


Figure 47. Monthly Average Electric Production per technology.

Indeed, Fig. 48 shows the lower power output of photovoltaic during the wet season. The total energy produced from photovoltaic reaches the 99,147 kWh/year.

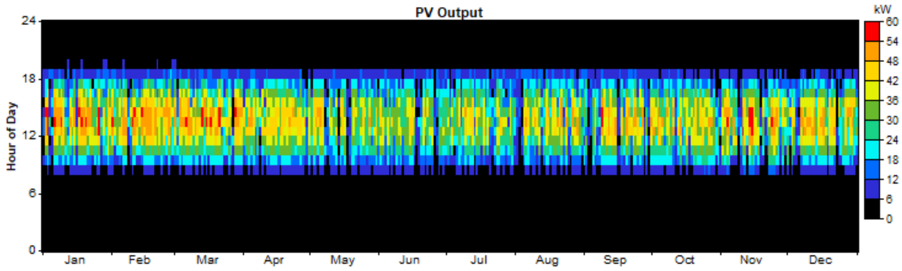


Figure 48. Photovoltaic power output in kW.

Regarding the gasifier, it can be observed in Fig. 49 how it is not needed in most part of the months. However, during the critical months, from May to September, the gasifier is crucial to ensure the continuity of the energy supply, reaching its maximum power output of 25 kW.

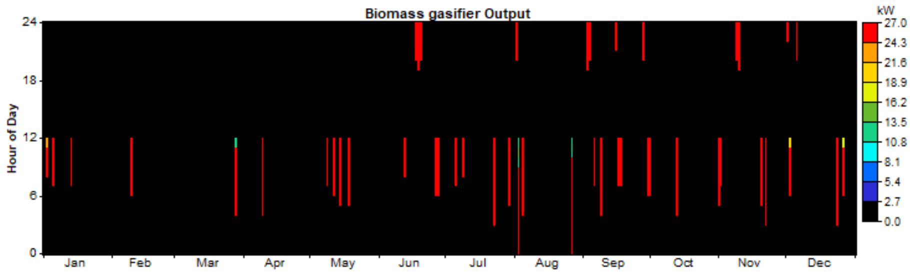


Figure 49. Biomass gasifier power output in kW.

The total energy produced from the biomass gasifier is 6,768 kWh/year, which means approximately a dry biomass consumption of 8,500 kg/year. This quantity represents 0.33 kg of dry biomass per day and family, more than one hundred times below from the 35 kg per family and day that currently is consumed in the community.

Fig. 50 represents the frequency histogram in which is shown that the batteries maintain a state of charge above the 60% the most part of the time, and that the minimum state of charge of 30%. As huge and frequent discharge of batteries exponentially reduce their life time and being one of the most expensive elements of the installation, they must be used the minimum possible.

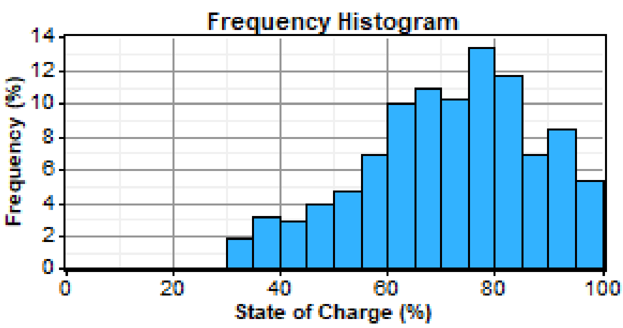


Figure 50. Frequency Histogram of batteries' state of charge.

As is it shown in Fig. 51, the critical hours for the batteries, i.e. when the batteries have a state of charge close to 30%, appear early in the morning due to the lack of solar resource during the night. During the sun hours along day the batteries accumulate energy, reaching a state of charge of almost 100% by the end of the day. During no sun hours along the night, the batteries supply the energy accumulated during the day until the sun rises again. If the accumulated energy of the batteries is not enough to cover the demand, the gasifier must operate. These are critical moments during which the inhabitants of the community have ensure the fuel supply for the biomass gasifier.

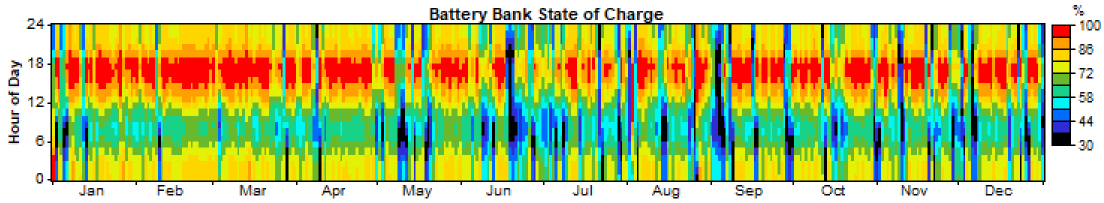


Figure 51. Battery bank hourly state of charge for each month in %

Fig. 52 and Fig. 53 show the operation of the inverter/charger daily for each hour during the year. As expected, during the no-sun hours the system acts as inverter, thus feeding the grid, whereas during sun hours it acts as charger, thus charging the batteries while feeding the grid. As can be seen in the figures below, an inverter of 25 kW is enough most part of the operation time despite the maximum consumption hours during the evening. However, a rectifier of 50 kW is needed for covering the maximum power output. Therefore, 2 inverter/chargers of 25 kW each appear as the optimal and more efficient configuration.

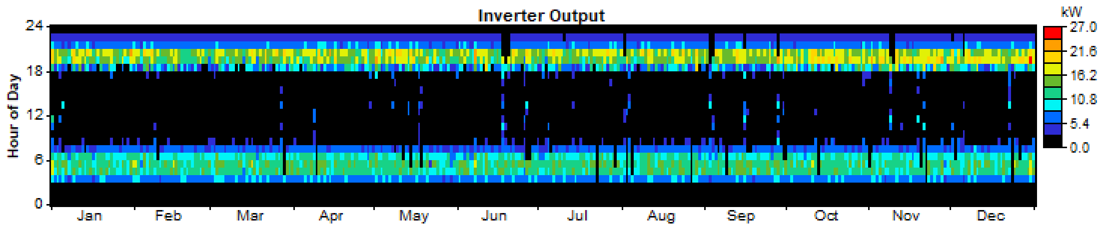


Figure 52.Inverter power output hourly for a year in kW.

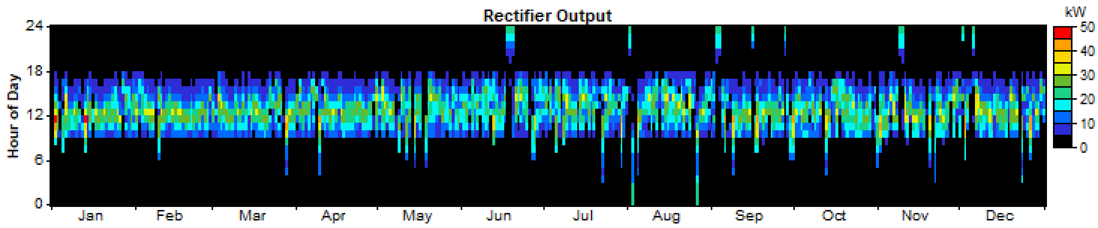


Figure 53. Rectifier power output hourly for a year in kW.

Finally, Fig. 54 shows an example of the grid operation for a typical week in June in when HOMER predicts the need of operation of the gasifier. According to the statistics, the horizontal solar radiation for this month was limited. Therefore, the PV Power is limited (yellow line) and the batteries should be used (red line). When the batteries' state of charge is close to the minimum value of 30% the gasifier is activated (green line), thus covering the demand of the community while charging the batteries.

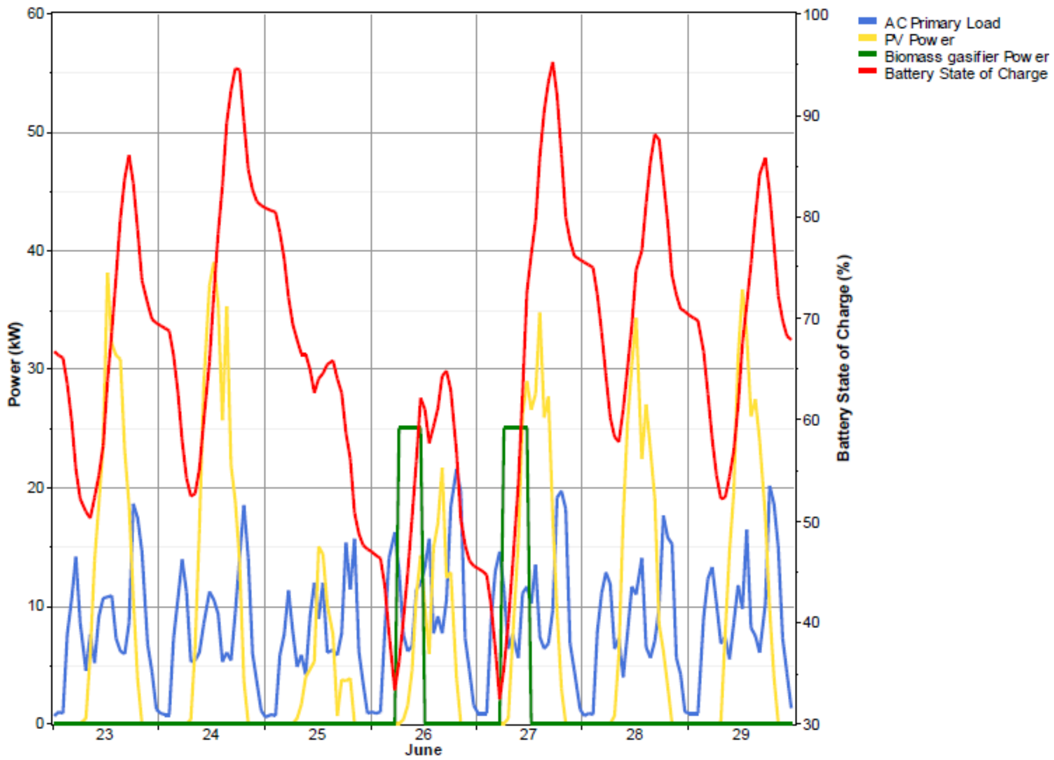


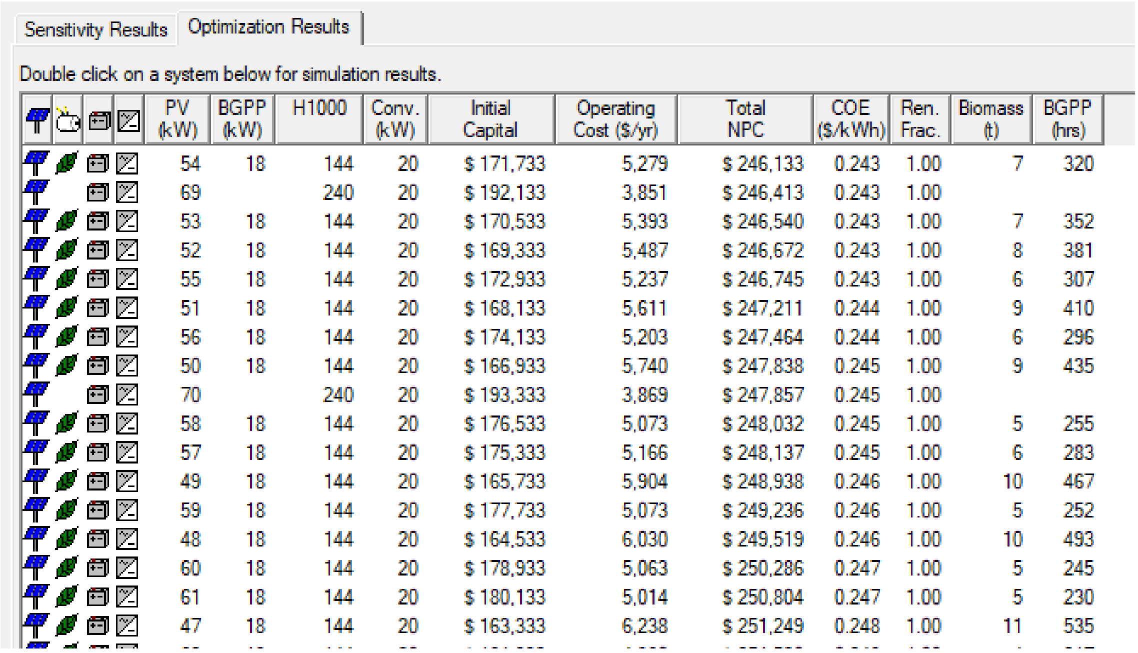
Figure 54. Hourly operation according to HOMER results of the grid for a typical week of June.

7.3.2. Optimization and design of the system with Methodology 2 (LoadProGen2.0) Load Curve

In order to optimize the pre-designed configuration of the mini grid, the more accurate load curve obtained by means of LoadProGen2.0 will be used along the simulations in HOMER. The results obtained in the simulations with the load curve obtained with Methodology 1 serve as a reference for ensuring coherence in the results.

The simulations in HOMER were performed in line with the procedure followed for the first simulations in the preliminary design, i.e. different configurations of the components are tested and analysed in iterative stages.

HOMER performed 19,170 simulations and displayed 200 optimal configurations. As can be seen in Fig. 55, the most representative solutions are the first two ones, whereas the rest of solutions represent slight variations of the previous ones. Therefore, a techno-economic analysis of the two first solutions will be performed.



Sensitivity Results | Optimization Results

Double click on a system below for simulation results.

PV (kW)	BGPP (kW)	H1000	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Biomass (t)	BGPP (hrs)
54	18	144	20	$ 171,733	5,279	$ 246,133	0.243	1.00	7	320
69		240	20	$ 192,133	3,851	$ 246,413	0.243	1.00		
53	18	144	20	$ 170,533	5,393	$ 246,540	0.243	1.00	7	352
52	18	144	20	$ 169,333	5,487	$ 246,672	0.243	1.00	8	381
55	18	144	20	$ 172,933	5,237	$ 246,745	0.243	1.00	6	307
51	18	144	20	$ 168,133	5,611	$ 247,211	0.244	1.00	9	410
56	18	144	20	$ 174,133	5,203	$ 247,464	0.244	1.00	6	296
50	18	144	20	$ 166,933	5,740	$ 247,838	0.245	1.00	9	435
70		240	20	$ 193,333	3,869	$ 247,857	0.245	1.00		
58	18	144	20	$ 176,533	5,073	$ 248,032	0.245	1.00	5	255
57	18	144	20	$ 175,333	5,166	$ 248,137	0.245	1.00	6	283
49	18	144	20	$ 165,733	5,904	$ 248,938	0.246	1.00	10	467
59	18	144	20	$ 177,733	5,073	$ 249,236	0.246	1.00	5	252
48	18	144	20	$ 164,533	6,030	$ 249,519	0.246	1.00	10	493
60	18	144	20	$ 178,933	5,063	$ 250,286	0.247	1.00	5	245
61	18	144	20	$ 180,133	5,014	$ 250,804	0.247	1.00	5	230
47	18	144	20	$ 163,333	6,238	$ 251,249	0.248	1.00	11	535

Figure 55. Optimization results from HOMER simulations.

In order to identify the optimal solution, a techno-economic analysis of the two first alternatives is performed. Configuration 1 is composed by 54 kWp of solar photovoltaic, 18 kW gasifier, 144 units of batteries with 288 kWh storage capacity and inverter/charger of 20 kW. Configuration 2 does not include the gasifier but increases the installed solar capacity to 69 kWp and the units of batteries to 240 with storage capacity of 480 kWh.

Table 17 summarizes both economic and technical parameters obtained in HOMER simulation of Configuration 1 and Configuration 2 to be analysed.

Table 17. Summary of results according to economic and technical parameters to be analysed for Configuration 1 and Configuration 2. Source: Own elaboration from HOMER outputs

	Excess Electricity (kWh/yr)	Unmet Load (kWh/yr)	Capacity Shortage (kWh/yr)	Initial Capital (USD)	Total NPC (USD)	LCoE (USD/kWh)
CONFIGURATION 1 PV + Gasifier + Batteries	18,841	1.26	1.35	171,733	246,133	0.243
CONFIGURATION 2 PV + Batteries	42,321	57.5	66.1	192,133	246,431	0.243

Regarding the technical parameters, it can be observed that Configuration 1 is more suitable for the system´s design according to the requirements, as the Unmet Load and Capacity Shortage are closed to 0, thus the system will be able to meet the energy demand without shortfalls. Moreover, the Excess of Electricity is lower than for the Configuration 2. This fact is positive as in this case there is no possibility of selling electricity to the national grid.

When analyzing the economic parameters, the total NPC and the LCoE have the same value for both configurations. However, the Initial Capital costs are lower for the Configuration 1, thus making it desirable from the economic point of view.

Overall, Configuration 1 appears as the optimal solution to meet the requirements. In addition, the gasifier provides more reliability to the system in the long term as it acts as a backup when neither the solar resource nor the energy accumulated in the batteries are enough to cover the energy demand, events that might increase along the years.

7.3.2.1 Sensitivity Analysis

In order to reach a more accurate solution, a sensitivity analysis has been performed. As the mini-grid is designed in order to ensure continuity in the energy supply, through the sensitivity analysis, the variation of the installed capacity of the equipment with the Unmet Load and Maximum Capacity Shortage is studied.

As starting case for performing the simulations Configuration 1 has been used, which includes 54 kWp of solar photovoltaic, 18 kW gasifier, 144 units of batteries with 288 kWh storage capacity and inverter/charger of 20 kW.

Batteries

The **number of batteries has not been modified**, as in the optimization phase it was shown that **144 units** are enough for the alternatives that consider photovoltaic and gasifier. The need of 240 units appeared for the alternative that did not consider gasification, thus the installed photovoltaic capacity increased and consequently also the number of batteries to storage solar the energy generated.

Converter

HOMER results show that whereas the inverter output is always below 20 kW, the rectifier operates most of the time at 20 kW. As a result, the rectifier would be subjected to overloading, thus increasing the risk of failure as shown in Fig. 56.

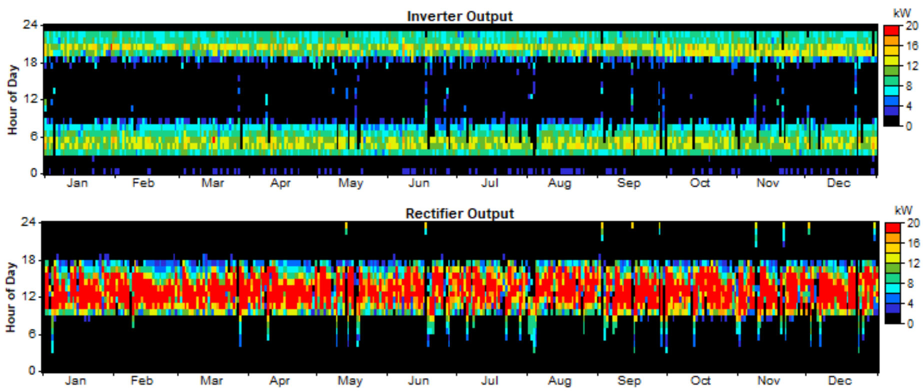


Figure 56. Configuration of 20 kW. Outputs for Inverter and Rectifier.

In order to avoid this, the simulation of different configurations of inverter/charger with variations of 5kW are performed. Fig. 57, Fig. 58, Fig. 59 and Fig. 60 show the results obtained for the case of 25, 30, 35 and 40 kW of inverter/charger installed power. It is shown that the degree of overloading decreases as the size of the converter increases

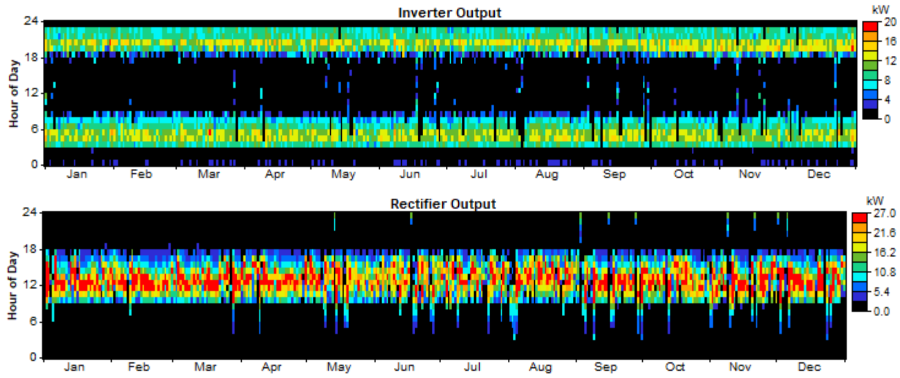


Figure 57. Configuration of 25 kW. Outputs for Inverter and Rectifier.

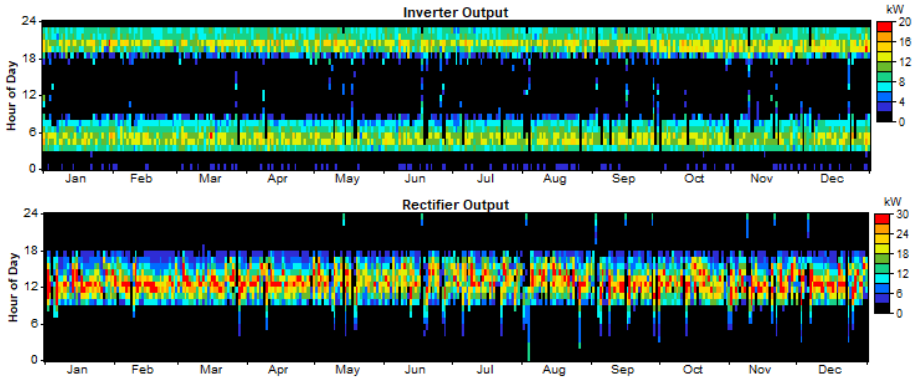


Figure 58. Configuration of 30 kW. Outputs for Inverter and Rectifier.

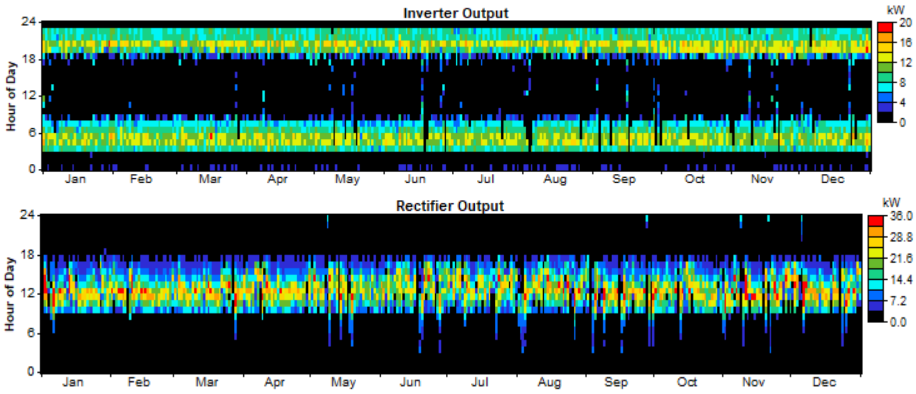


Figure 59. Configuration of 35 kW. Outputs for Inverter and Rectifier.

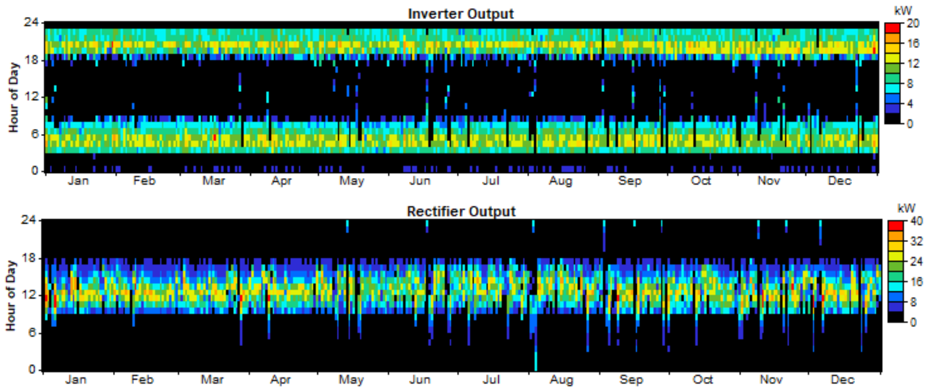


Figure 60. Configuration of 40 kW. Outputs for Inverter and Rectifier.

Fig. 61 illustrates the evolution of the output in kW, the capacity factor in % and the total cost in USD for the different variations of installed capacity for the rectifier.

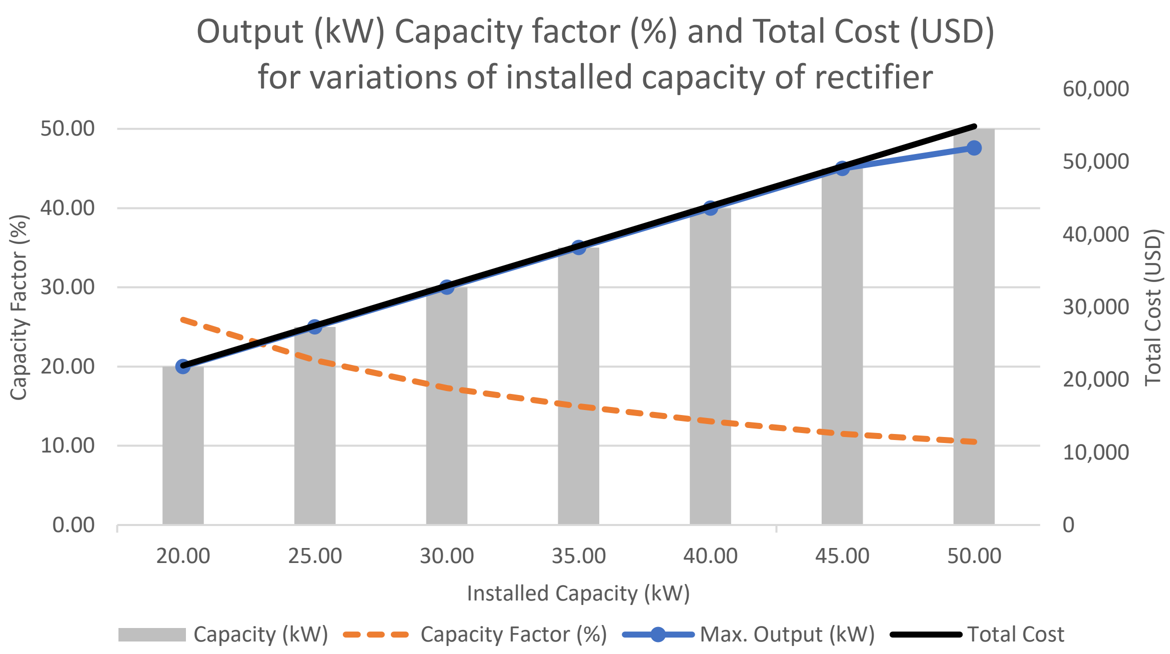


Figure 61. Evolution of Output (kW) Capacity Factor (%) and Total Cost (USD) for 20, 25, 30 35, 40, 45 and 50 kW of installed capacity of Rectifier. Source: Own elaboration from HOMER results.

Overall, it is observed that as the installed capacity of converter increases, the capacity factor of the rectifier in % decreases, thus minimizing the risk of overloading. However, the total cost of the converter increases. Regarding the maximum power output of the rectifier, it can be noticed that it is only below the installed capacity for the 50-kW configuration.

In order to maximize the useful life of the converter and prevent possible size enlargement due to energy demand growing in the future, the **configuration of 50 kW for the converter** has been selected. In practice, two devices of 25 kW will be selected, thus allowing the operation of one device as inverter and the other as rectifier when the required operating capacity is higher.

Solar Photovoltaic and Gasifier

In order to determine the iteration procedure for the installed capacity of solar PV and the gasifier, a sensitivity case has been analysed in HOMER. The variation of the capacity of solar and gasifier with the max. annual capacity shortage is studied. It is shown in Fig. 62 below that for power installed higher than 54 kWp for solar PV and lower than 18 kW for the biomass gasifier, the max. annual capacity shortage value exceeds the 1.1%. Therefore, these configurations will not be analysed to reach the optimal solution.

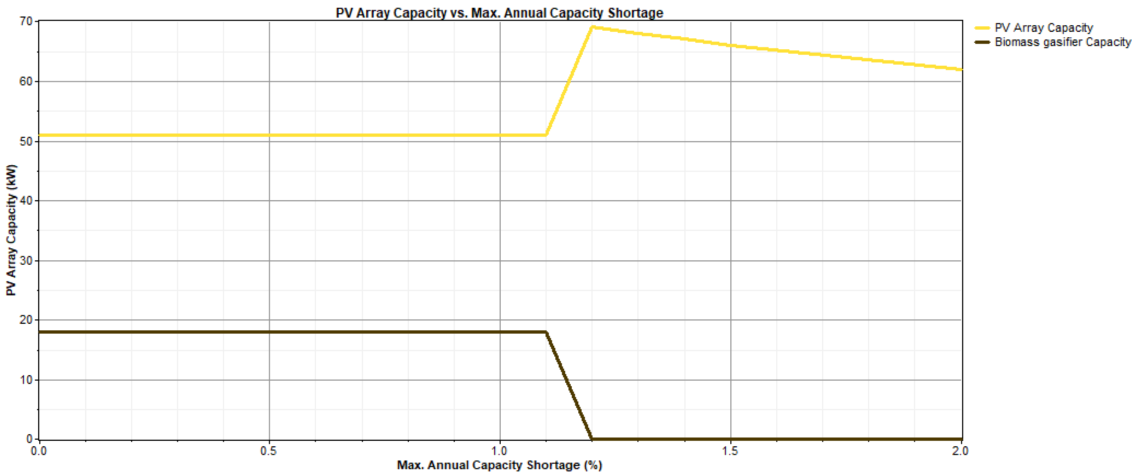


Figure 62. Sensitivity results of PV Array Capacity and Biomass gasifier Capacity vs. Max. Capacity Shortage. Source: HOMER.

The iteration procedure includes variations of solar PV installed capacity from 46 to 54 kWp analysed for configurations of 18 kW and 25 kW of biomass gasifier. For the different alternatives the following factors were evaluated:

- **Capacity Shortage and Unmet Electric Load:** As mentioned, it is expected that the value of these parameters is as close as possible to zero. This will be the key criteria for the selection of the alternatives.
- **Levelized Cost of Electricity (LCoE):** Optimal solutions will be the ones with lower LCoE.
- **Gasifier Usage:** The number of hours that the gasifier must operate is expected to be the lowest possible in order to prolong the useful life of the device and reduce wood consumption.

Table 18 and Table 19 show the mentioned parameters for the different alternatives:

Table 18. HOMER outputs for different alternatives with Gasifier installed capacity of 18 kW and variations of 1 kWp from 46 to 54 kWp of Solar PV. Source: Own elaboration from HOMER results.

ALTERNATIVES A					
Gasifier Installed Capacity (kW)	**Solar Photovoltaic Installed Capacity (kWp)**	**Unmet Load (kWh/year)**	**Capacity Shortage (kWh/year)**	**LCoE (USD/kWh)**	**Gasifier usage (hrs)**
18	46	23.9	36.5	0.275	470
	47	3.53	3.79	0.274	434
	48	0.0000261	0	0.273	405
	49	7.9	8.38	0.273	377
	50	7.76	9.61	0.272	345
	51	0.0000247	0	0.272	318
	52	5.51	5.88	0.273	305
	53	0.552	0.627	0.273	281
	54	4.44	4.68	0.273	257

Table 19. HOMER outputs for different alternatives with Gasifier installed capacity of 25 kW and variations of 1 kWp from 46 to 54 kWp of Solar PV. Source: Own elaboration from HOMER results.

ALTERNATIVES B					
Gasifier Installed Capacity (kW)	**Solar Photovoltaic Installed Capacity (kWp)**	**Unmet Load (kWh/year)**	**Capacity Shortage (kWh/year)**	**LCoE (USD/kWh)**	**Gasifier usage (hrs)**
25	46	20.8	33.2	0.288	372
	47	3.53	3.79	0.288	350
	48	1.83	1.97	0.287	327
	49	3	3.23	0.287	310
	50	1.87	3.23	0.286	282
	51	4.94	5.19	0.286	265
	52	2.66	2.81	0.287	257
	53	4.65	4.93	0.287	240
	54	4.44	4.68	0.285	205

From the results it is observed that the optimal configurations that meet the load without shortfalls appear for 18 kW of gasifier and both 48 and 51 kWp of solar PV. The alternative with less solar power installed presents higher LCoE and gasifier usage hours. Moreover, it is observed that none of the alternatives that include the 25-kW gasifier meet the requirements. This fact is due to the imposed restriction of ensuring a minimum load ratio of the 50% in the gasifier: although the gasifier would be able to generate enough energy to feed the loads it is not able to operate until the load ratio reaches the 50%.

In conclusion, after performing the optimization and sensitivity analysis of the different alternatives simulated by means of HOMER the selected alternative is the one including 51 kWp of solar photovoltaic and 18 kW biomass gasifier.

7.3.2.2. Results discussion

Overall, the proposed mini-grid solution is composed by 18 kW of biomass gasifier, 51 kWp of solar photovoltaic, 144 units of batteries with accumulation capacity of 288 kWh and two inverter/chargers of 25 kW each.

The following image shows the monthly average electricity production from photovoltaic and the gasifier. It can be observed that the gasifier is only needed from May to September, due to the lower solar resource during the wet season. In total, the photovoltaic generates the 94% of the energy and the gasifier only the 6%.

In Fig. 63 it is represented the monthly average electric production. It can be observed that solar photovoltaic covers most part of the energy generation, whereas the gasifier acts as support system. Indeed the electric production of the gasifier is higher form May to September, during the wet season.

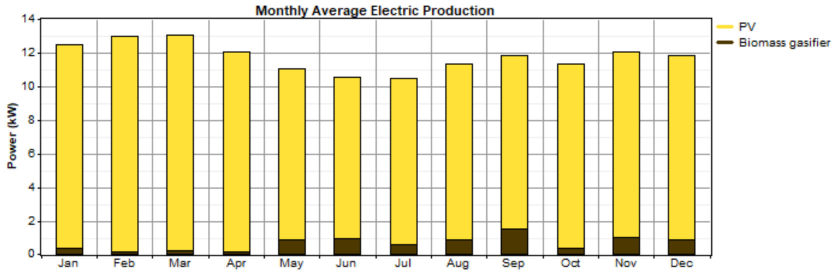


Figure 63. Monthly Average Electric Production per technology.

From the total energy produced by the system, 102,964 kWh/year, solar photovoltaic cover the 94% and the gasifier the 6%. The excess of electricity produced is 13,564 kWh/year, approximately 1,000 kWh/year lower than for the solution obtained with Methodology 1.

Fig. 64 shows the lower power output during the wet season.

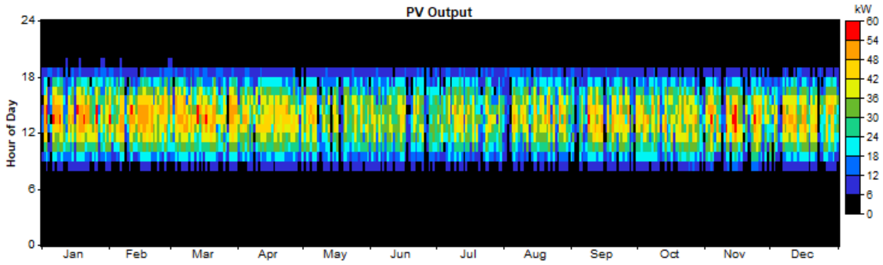


Figure 64. Photovoltaic power output in kW.

Regarding the gasifier output power, it can also be observed in Fig. 65 that the production is higher when the solar resource is reduced. The device operates at its installed capacity of 18 kW for the whole year, and presents a biomass consumption of 7.15 ton/year.

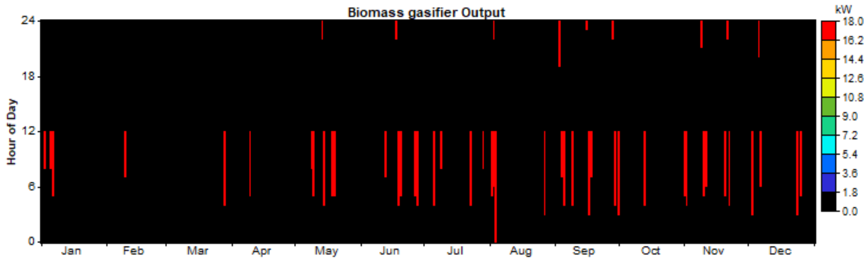


Figure 65. Biomass gasifier power output in kW.

As it is shown in Fig. 66 below, batteries never reach a state of charge below the 30%, as was stablished in the operation conditions. Moreover, they maintain a state of charge between 60 and 80% for most part of the operation time.

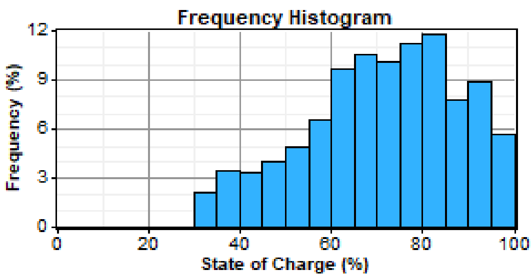


Figure 66. Frequency Histogram of batteries' state of charge.

Fig. 67 shows the monthly state of charge of the batteries during the year. It is observed that the bank reaches the 100% of state of charge at the end of the day, as batteries have been charged with the solar energy production along the day. Critical hours of the day, when the state of charge is close to the 30%, appear early in the morning, as they have been discharging during the night the accumulated energy of the day in order to feed the loads. This fact is especially notable during the wet season, as the low solar resource limits the charging of batteries to the biomass gasifier.

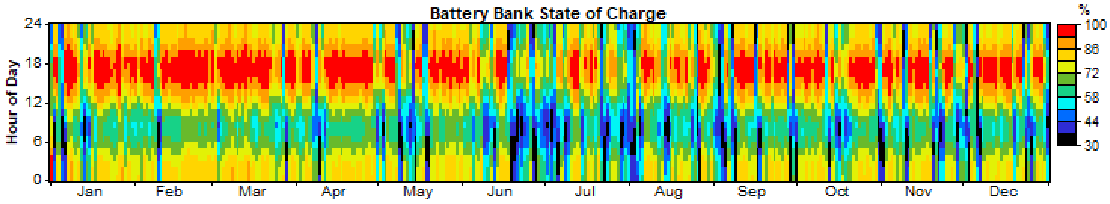


Figure 67. Battery bank hourly state of charge for each month in %

As in the results of the solution obtained with the load curve of Methodology 1, it is observed that although the inverter outputs reach values of less than 20 kW (Fig. 68), the rectifier requires outputs up to 47.6 kW (Fig. 69). Therefore, a converter of 50 kW is required.

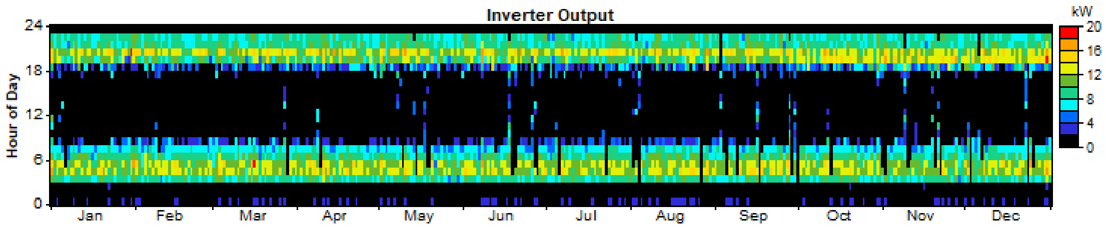


Figure 68. Inverter power output hourly for a year in kW.

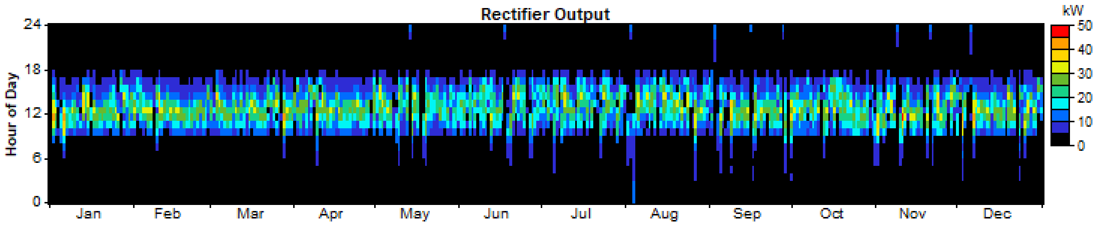


Figure 69. Rectifier power output hourly for a year in kW.

The operation of the grid for a typical week in June, during the wet season, is similar to the obtained with the solution of the pre-design stage as it is represented in the figure below.

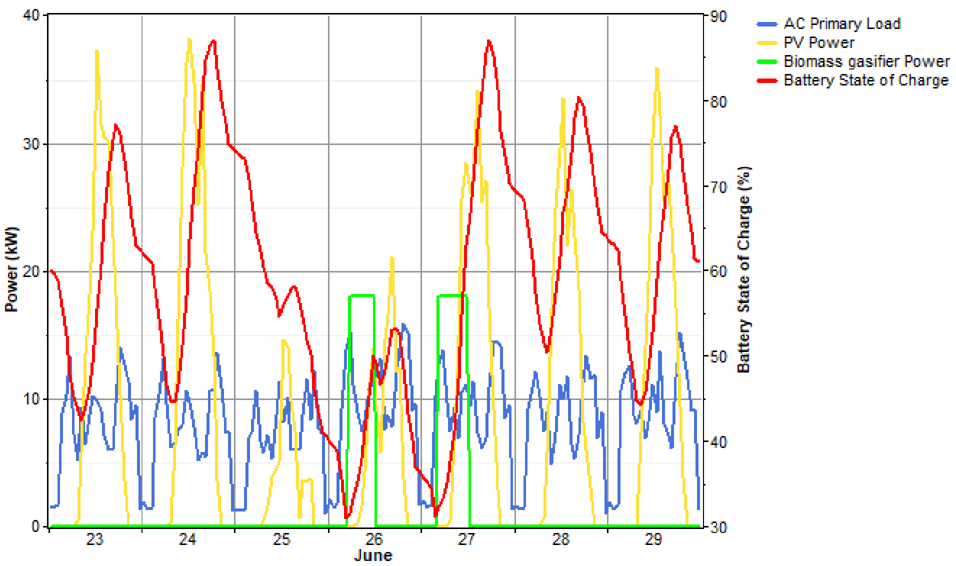


Figure 70. Hourly operation according to HOMER results of the grid for a typical week of June.

7.3.3. Comparison of methodologies

The proposed solutions obtained from the simulations in HOMER of both load profiles estimated following Methodology 1, of building up coincidence factors, and Methodology 2, by means of the software LoadProGen2.0 present slight differences in the results, and basically differ in the amount of installed capacity of solar photovoltaic and biomass gasifier:

-Proposed Solution 1: 25 kW of biomass gasifier, 52 kWp of solar photovoltaic, 144 units of batteries with accumulation capacity of 288 kWh and two inverter/chargers of 25 kW each.

-Proposed Solution 2: 18 kW of biomass gasifier, 51 kWp of solar photovoltaic, 144 units of batteries with accumulation capacity of 288 kWh and two inverter/chargers of 25 kW each.

However, when designing hybrid mini-grid for isolated areas, these variations gain significance as they present impacts on the technical, economic and environmental factors.

7.3.3.1. Economic Analysis

Table 20 summarizes the main economic parameters of both proposed solutions. Overall, it is observed that the costs increased for the Solution 1, as the installed capacity of solar photovoltaic and the gasifier is higher. Indeed, the total NPC is approximately 20,000 USD higher for the 25-kW gasifier than for the 18-kW one; the difference in the solar photovoltaic is about 1,000 USD. Solution 2 is hence the optimal one from the economic point of view.

Table 20. Economic parameters of Solution 1 and 2 from HOMER results

	Initial Capital (USD)	**Operating Cost (USD/year)**	**Total NPC (USD)**	**LCoE (USD/kWh)**
SOLUTION 1	203,333	6,396	293,483	0.285
SOLUTION 2	188,133	6,209	275,636	0.272

7.3.3.2. Technical Analysis

Regarding the electrical parameters, it is observed in Table 21 below that the total electricity produced, and the excess of electricity are higher for the Solution 1, because the value of the energy demand estimated was higher as well. Therefore, Solution 2 would be more accurate and allows to generate less energy.

Table 21. Technical parameters of Solution 1 and 2 from HOMER results

	Load Electric Consumption (kWh/year)	Total Electric Production (kWh/year)	Excess of Electricity (kWh/year)	Unmet Electric Load (%)	Capacity Shortage (%)
SOLUTION 1	73,000	105,915	14,961	0	0
SOLUTION 2	71,905	102,964	13,564	0	0

Solar photovoltaic operational parameters as shown in Table 22 do not present significant differences between the two solutions, as the installed capacity only varies on 1 kWp. However, it can be highlighted that the mean and maximum power output is higher for the Solution 1, as the load profile estimated presents higher load peak values that the one obtained with LoadProGen2.0.

Table 22. Operational parameters solar PV of Solution 1 and 2 from HOMER results

SOLAR PHOTOVOLTAIC				
	Mean Output (kW)	**Max. Output (kW)**	**Capacity Factor (%)**	**Hours of Operation (h/yr)**
SOLUTION 1	11.3	58.2	21.8	4,354
SOLUTION 2	11.1	57.1	21.8	4,354

Differences are observed in Table 23 between the two solutions for the gasifier as the installed capacity for Solution 1 is 18-kW whereas for Solution 2 is 25 kW. On the one hand, the mean power output shows that the 25-kW gasifier does not operate at its maximum capacity during the year, as the mean output is 24.80 kW, in contrast with the 18-kW one. On the other hand, the hours of operation per year are lower for the Solution 1, thus the hours of operation required decrease. This fact might be due to the higher installed capacity. However, biomass consumption is more than 1 ton/year higher for Solution 1, due to the operational restriction of maintaining a minimum load ratio of 50%.

Table 23. Operational parameters biomass gasifier of Solution 1 and 2 from HOMER results

BIOMASS GASIFIER				
	Mean Output (kW)	**Hours of Operation (h/year)**	**Operational Life (years)**	**Biomass Feedstock Consumption (ton/year)**
SOLUTION 1	24.70	274	36.50	8.50
SOLUTION 2	18.00	318	31.40	7.15

Table 24 shows the operational parameters of the battery ban for the two solutions. As the amount of energy demanded and generated by the system is lower for the Solution 2, all the parameters of batteries are improved. This fact is positive as it is one of the most expensive elements of the installation.

Table 24. Operational parameters battery bank of Solution 1 and 2 from HOMER results

BATTERY BANK			
	Losses (kWh/year)	**Useful Life (years)**	**Hours of Autonomy (h)**
SOLUTION 1	6,227	11.3	24.2
SOLUTION 2	6,072	11.6	24.6

Regarding the 50 kW converter, it is observed in Table 25 that maximum value of the power output for the Solution 1 is equal to the capacity of the converter, what limits the output range of the device. As for the batteries´ case, the energy flux is lower for Solution 2, thus the losses and capacity factor are reduced.

Table 25. Operational parameters converter of Solution 1 and 2 from HOMER results

CONVERTER						
	Inverter Max. Output (kW)	**Rectifier Max. Output (kW)**	**Inverter Capacity Factor (%)**	**Rectifier Capacity Factor (%)**	**Inverter Losses (kWh/year)**	**Rectifier Losses (kWh/year)**
SOLUTION 1	26	50	8.5	10.7	3,252	8,303
SOLUTION 2	19.1	47.6	8.3	10.5	3,169	8,090

7.3.3.3. Environmental Analysis

Normally, it is considered that both alternatives consider the energy generation trough renewable energy sources, thus the CO_2 equivalent emissions are equal to zero. However, the gasifier presents certain dry biomass consumption that can be analysed as an environmental impact.

Table 26 shows the emissions for both solutions according to HOMER results.

Table 26. Pollutants Emissions in kg/yr for Solution 1 and 2 from HOMER results

POLLUTANTS EMISSIONS (kg/yr)						
	Carbon Dioxide (CO_2)	**Carbon Monoxide (CO)**	**Unburned Hydrocarbons (HC)**	**Particulate Matter (PM)**	**Sulphur Dioxide (SO_2)**	**Nitrogen Oxides (NO_X)**
SOLUTION 1	1.47	0.0552	0.00612	0.00416	0	0.493
SOLUTION 2	1.24	0.0465	0.00515	0.00351	0	0.415

Due to the higher wood consumption of the 25-kW gasifier (8.5 ton/year) compared with the 18-kW one (7.15 ton/year), the emissions in kg/year are lower for the Solution 2 for all the type of pollutants.

Overall, from the comparison, it can be concluded that the alternative proposed for the configuration of the hybrid mini-grid in the rural community that meets all the requirements and presents the optimal technical, economic and environmental impacts is the Solution 2 composed by 18 kW of biomass gasifier, 51 kWp of solar photovoltaic, 144 units of batteries with accumulation capacity of 288 kWh and two inverter/chargers of 25 kW each.

7.4. ESTIMATION OF AVOIDED EMISSIONS

For the estimation of avoided Green House Gases (GHG) emissions with the mini-grid installation, two different scenarios can be considered: Business as Usual (BAU) scenarios or alternative generation scenarios.

- **BAU Scenarios.** BAU scenarios are based on considering that the situation evolves following the current trends. For rural isolated communities of developing countries, the BAU scenarios consider that in the future the energy consumption would be limited to the existing one, due to the limited access to external sources of energy.

  Therefore, the emissions of a BAU scenario would be obtained as the sum of the amount of energy consumed from each energy source multiplied by the emission factor associated to each type of energy source (Eq. 17). The emissions factors are expressed in units of grams or kilograms of emitted pollutant per kWh, GJ or g/kg of fuel consumed.

$$BAU\ Scenario\ Emissions = \sum_{i=Energy\ sources} Current\ Energy\ Consumtion_i \times Emission\ Factor_i \tag{17}$$

- **Alternative Scenarios.** The alternative scenarios are based on assuming that the energy demand is supplied by other energy sources. Normally, it is considered either that in the future the community is able to be connected to the national electric grid, or that the energy demand is supplied by a Diesel generator, as has been happening in similar rural areas.
  Therefore, the emissions of the alternative scenarios would be obtained as the energy demand that is covered by each energy source multiplied by the associated emission factor (Eq. 18). It is considered also the possibility that part of the demand is covered with the national grid whereas the rest is covered by the generator, or other type of energy sources are used for covering the demand.

$$Alternative\ Scenarios\ Emissions = \sum_{i=Energy\ Sources} Energy\ Demand\ Covered\ by\ Source_i \times Emission\ Factor\ of\ Source_i \tag{18}$$

When applied to the practical case of the rural community of El Santuario, for the BAU scenario it is consider that the community maintains the current energy consumption in batteries, kerosene and candles, as no other relevant energy generation sources where identified. For the alternative scenarios, both the electrification with the national electric grid and Diesel generator where considered in the analysis.

7.4.1. Batteries, kerosene and candles

According to the data base of the American Environmental Protection Agency (EPA15[14]), a candle has an emission factor per hour of 7 gCO_2eq. Assuming 5 candles per household, lighted 4 hours per day the current CO_2 equivalent emissions from the consumption of candles is given by Eq. 19 as follows:

$$\boldsymbol{Candles\ CO_2eq\ emissions} = 7\ \frac{\text{gCO2eq}}{h} \times 4\,\frac{h}{candle * day} \times 5\,\frac{candle}{houses} \times 71\ houses \times 365\ \frac{day}{yr} = \mathbf{3.63}\,\frac{\boldsymbol{ton}\mathbf{CO2eq}}{\mathbf{year}} \tag{19}$$

Based on data from the Intergovernmental Panel on Climate Change (IPCC), alkaline batteries on average emit 70.2 gCO_2[15] during their lifecycle. Assuming 3 alkaline batteries per week and household, the current CO_2 equivalent emissions associates to the consumption of alkaline batteries can be obtained as in Eq. 20:

$$\boldsymbol{Alkaline\ Batteries\ CO_2eq\ emissions} = 70.2\ \frac{\text{gCO2}}{battery} \times 3\,\frac{battery}{house * week} \times 52\,\frac{weeks}{yr} \times 71\ houses = \mathbf{0.78}\,\frac{\boldsymbol{ton}\mathbf{CO2eq}}{\mathbf{year}} \tag{20}$$

Finally, if every week 5 litres of kerosene are consumed in the community, and that according to the IPCC the burning of kerosene to generate electricity produces 2,600 gCO_2 per liter of kerosene, the current CO_2 equivalent emissions from the burning of kerosene is given by Eq. 21:

$$\boldsymbol{Kerosene\ CO_2eq\ emissions} = 5\ \frac{\text{litres}}{week} \times 2600\,\frac{\text{gCO2}}{liter} \times 52\,\frac{weeks}{yr} = \mathbf{0.67}\,\frac{\boldsymbol{ton}\mathbf{CO2eq}}{\mathbf{year}} \tag{21}$$

The mini grid will supply enough energy to eliminate this consumption. Therefore, the **avoided emissions** will be **5.09 tonCO2eq/year**.

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[14] http://www.ehso.com/ehshome/candles2.htm

[15] Emissions Factors from IPCC database developed by National Greenhouse Gas Inventories Programme (NGGIP)

7.4.2. Alternative scenario with Diesel Generator

An alternative for the electrification of the community are the generator sets powered by Diesel. The emissions of a Diesel generator set, the usual fuel of the electric mini grids in Latin America, can vary depending on many factors: fuel quality, operation mode of the installation, temperature, quality of installation equipment, etc. If the latest-generation technology is chosen, and an adequate operation, the estimation of the greenhouse gas emissions per kWh of electricity generated could be: 840 gCO_2eq[16]. Considering that the demand of the community is around the 73,000 kWh/year, that the Diesel Generator would have to generate, and applying the formula below, there is a reduction in emissions of 61.32 tons of CO_2eq/year (Eq. 22).

$$\boldsymbol{Diesel\ Generator\ CO_2eq\ emissions} = 200\frac{kWh}{day}\times 365\frac{d}{yr}\times 840\frac{gCO_2eq}{kWh} = \mathbf{61.32}\frac{\boldsymbol{ton}\mathbf{CO2eq}}{\mathbf{year}} \tag{22}$$

7.4.3. Alternative scenario with connection to national electric grid

Similarly, if the same amount of energy would be provided by the Honduran electric grid, which has an emissions conversion factor of 353 gCO_2eq/kWh[17], the reduction of emissions reaches 25.91 **tons of CO_2eq/year** (Eq. 23).

$$National\ Electric\ Grid\ CO_2eq\ emissions = 200\frac{kWh}{day}\times 365\frac{d}{yr}\times 353\frac{gCO_2eq}{kWh} = \mathbf{21.92}\frac{\boldsymbol{ton}\mathbf{CO2eq}}{\mathbf{year}} \tag{23}$$

Overall, considering the avoided emissions of batteries, kerosene and candles, besides the alternative scenario with Diesel Generator, as it is the most common in rural communities of Central America, the avoided emissions with the renewable mini grid would reach approximately **62 tons of CO_2eq/year**.

Table 27 summarizes the estimated avoided emissions with the mini-grid.

Table 27. Summary of avoided emissions with the mini-grid in $tonCO_2eq$/year

AVOIDED EMISSIONS WITH THE MINI-GRID ($tonCO_2eq$/year)

BAU Scenario			**Alternative Scenarios**	
Batteries	Kerosene	Candles	Diesel Generator	National Electric Grid
0.78	0.67	3.63	61.32	21.92

[16] Emissions Factors from IPCC database developed by National Greenhouse Gas Inventories Programme (NGGIP)

[17] Emission Factor from CEPAL (2016)

CHAPTER 8. DISCUSSION AND WAY FORWARD

8.1. PROPOSED METHODOLOGY FOR THE DESIGN OF MINI-GRIDS

As stated and justified in the practical case of the rural community of El Santuario, the energy demand assessment process is a key element that directly influences the size and design of mini-grids, thus the costs and the operation of the system. However, a common standardised methodology for assessing the energy demand has not been developed yet.

A methodology for assessing the energy demand of rural isolated areas of developing countries should be generic and comprehensive. Therefore, it has to be applicable to different practical cases regardless the specific characteristics; and at the same time include all the methods and guidelines required in order to reduce uncertainty and provide accurate and reliable results. Due to the intrinsic uncertainty in the data, it should include both quantitative and qualitative approaches, including experts' criteria throughout the procedure.

Therefore, a methodology based on a combination of approaches and methods already used for demand forecasting is proposed. The methodology includes the findings in the reviewed scientific literature and technical implementations, besides the outcomes obtained from the application of two demand assessment-methods to the practical case of the mini-grid designed for the rural community of El Santuario.

The proposed actions and steps to follow in order to obtain the estimated energy demand and load profile of an area are described as follows:

0. **Data Collection:** Visits to the area in order to gather data trough measurements and surveys.
1. **Initial Energy Demand Assessment:** To obtain a preliminary estimation of the energy needs of the area based on the data collected.
   1.1. **Load Profile Characterization:** To distribute the identified energy needs during a typical day. To build-up coincidence behavior among users and appliances.
2. **Effective Demand Calculation:** The application of socio-economic correlation factors specific of the area or country based on consumers´ ability and willingness to pay for energy services (GIZ, 2016).
3. **Future Demand Forecasting:** To apply probabilistic models implemented in computational tools in order to obtain more accurate energy demand estimation and load profile formulation. As justified, the proposed software is LoadProGen2.0.

Consequently, the mini-grid is designed based on the energy demand estimated.

4. **Preliminary Mathematical Modeling:** The use of mathematical expressions to obtain a preliminary overview of the energy generation needs and components' size.

5. **Simulation and Pre-design:** To introduce the inputs in computational tools in order to analyze the response of the parameters and possible system's configurations. The proposed and widely used software for mini grids' design is HOMER.
6. **Optimization and Sensitivity Analysis:** To simulate and evaluate different alternatives in order to obtain the optimized one that meets the design requirements at the minimum cost.

As a result, the mini grid model is designed. Next steps include the detailed design of the components and interconnections of the solution as well as the layout and implementation in the available land.

Fig. 71 shows a flow chart as a graphical overview of the proposed methodology.

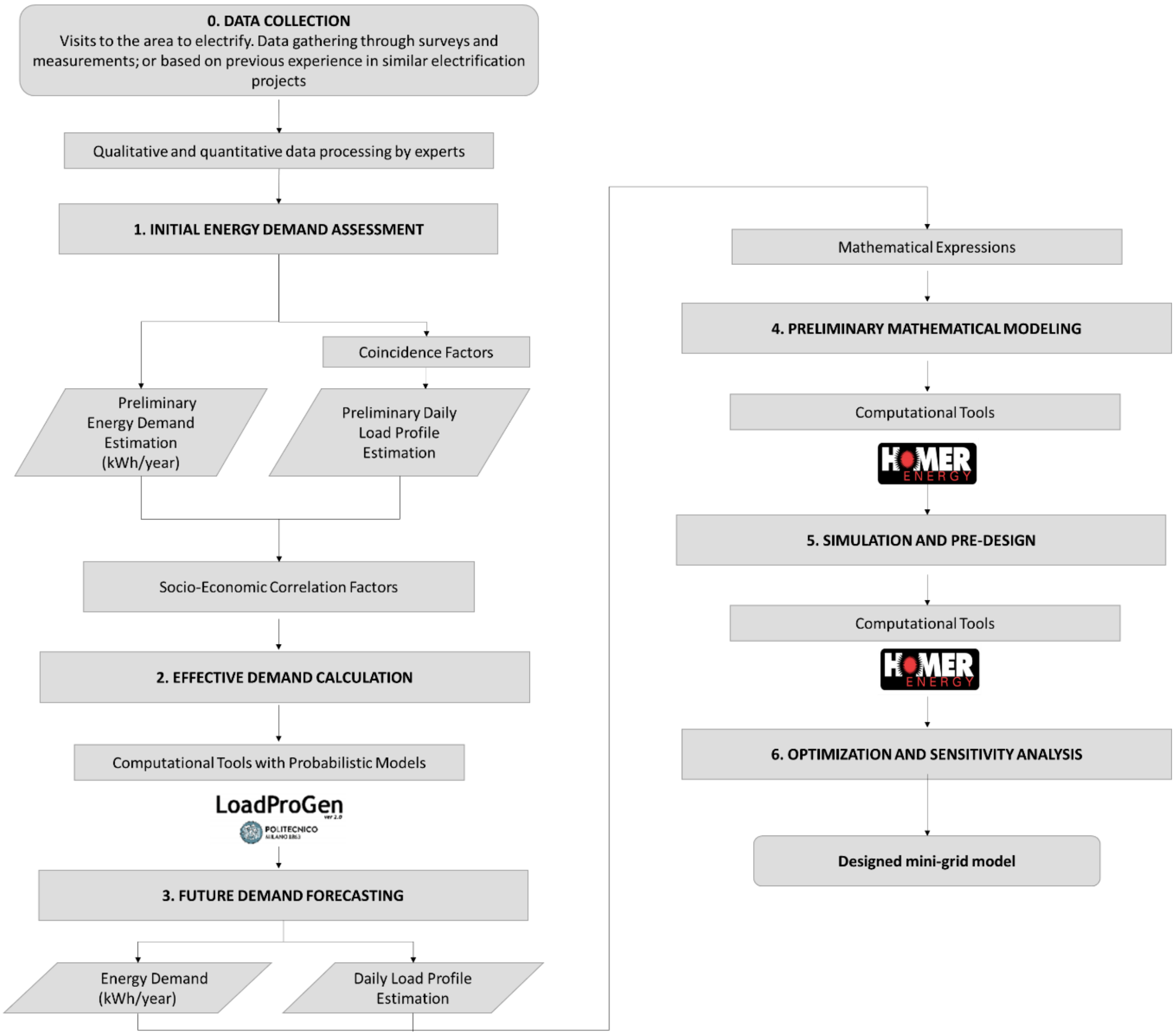

Figure 71. Proposed methodology for the design of mini grids. Source: Own elaboration

Additionally, the avoided Green House Gases (GHG) emissions in terms of CO_2 equivalent with the mini grid can be estimated. As proposed for non-electrified rural areas of developing countries, the analysis can be carried out considering Business as Usual (BAU) scenarios or alternative generation scenarios with Diesel generator or national electric grid.

8.2. RECOMMENDATIONS TO MINI GRIDS' DESIGNERS

Overall, the estimation of the energy demand in rural isolated communities of developing countries is a complex process. Therefore, some guidelines for designers based on the lessons learned in this analysis are proposed:

1. **To ensure correct baseline.** Ensuring accuracy in the input data is crucial as it directly influences in the mini grid design. Therefore, the model and questions of the survey must be properly defined and combined with measurements and designer's expertise in order to reduce uncertainty in the data and inaccurate results.
2. **To validate the data** by comparing the obtained one with other similar electrification projects and energy consumption standards.
3. **Viability of the project.** The first observations should be oriented to identify information such as the availability and adequacy of renewable energy sources or the availability of a land where to install the mini-grid, as well as ensuring the proactivity and involvement of the customers in the decision-making process.
4. **To process the gathered data** and translate it into useful data for performing the energy demand assessment. The demand estimation and load profile formulation must be in line with the requirements of the customers. However, expertise is crucial in order to formulate the load profiles. For instance, some appliances present more flexible usage schedules that the designers can readapt in order to distribute and equilibrate the energy consumption during the day. This will allow to maximize the use of energy sources and the correct operation of the system.
5. **To implement software tools based on probability scenarios.** As justified, formulating one single profile is not enough to provide accurate results due to the uncertainty in the input data. Therefore, models based on probability should be used. The implementation in computational tools will provide confidence and speed in the analysis.
6. **The LoadProGen2.0 software** is proposed as stochastic procedure to formulate load profiles in rural isolated areas. Some recommendations to obtain more accurate results include:
   - **6.1.** Minimum experience in energy demand assessment processes is required in order to make use of the software.
   - **6.2.** The data obtained in the preliminary energy assessment must be adapted to the specific parameters of the software.
   - **6.3.** The parameters of functioning time and functioning windows, and specially the percentage of random variation applied, strongly influence in the results. That means that the more percentage of random variation introduced, the more possible load profiles would be analyzed and the more time it will take to the software to perform the simulations, but the results obtained would be more accurate. In that regard, introducing low random percentages of variations is more recommendable for those devices in which the usage schedule is fixed, such as the fridge or hospital appliances.
   - **6.4.** If some devices present different consumption patterns along the day the functioning window has to be wider to avoid wrong results. A recommendation is to create different categories for a same device in which the parameter of functioning time is adapted to the functioning windows. For instance, the lights might present a total functioning time of 4 hours during the functioning window from 6 p.m. to 23 p.m., but a total functioning

time of 2 hours for the rest of the day. In that way the software would properly distribute the possible consumption scenarios along the day.

6.5. The uncertainty band of the software represents the maximum and minimum values between which the software has performed the simulations. That means that these scenarios are possible but not probable and considering them in the mini grid's design would result in over or under-dimensioned systems.

7. **Complement the analysis with mathematical expressions.** A preliminary estimation of the energy generation needs and components of the system by means of mathematical expressions would simplify the analysis as it would provide a reference point to start the simulations with a computational tool.
8. **The use of computational tools for the design of mini grids** such as **HOMER software** is highly recommended as it makes easier the process by allowing the simulation and optimization of different configurations based on certain parameters. Recommendations for the use of HOMER include:

8.1. Expertise in mini-grids design is required to use the software.

8.2. Parameters of the components might be introduced from HOMER database or external catalogs. However, some components as the gasifier need specific data such as biomass' specific characteristics like moisture or carbon content and operation behavior in terms of efficiency with the biogas introduced. This data can be difficult to obtain precisely without a biomass characterization laboratory, especially for rural isolated areas where the biomass resource is variable. If the laboratory test is not possible, a recommendation is to use data from other similar electrification projects in which the type of biomass used is similar.

8.3. HOMER provides different alternatives ordered according to the lowest Levelized Cost of Electricity. However, in order to reach an optimized solution, these alternatives should be analyzed in terms of other technical, economic and environmental parameters.

8.4. One disadvantage of HOMER is that it only performs the simulations with variations of capacity installed that the designer sets. The alternative to obtain more accurate solutions is to start by studying configurations with small power variations of 1 to 5 kW.

8.5. In order to obtain more accurate results, a sensitivity analysis in which different cases are analyzed should be performed. In that regard, for instance, when fixing the maximum capacity shortage to zero in order to ensure continuity in the supply, HOMER does not provide at first exact results but approximate ones, thus a sensitivity analysis must be carried out.

Applying the proposed methodology and following these recommendations would allow to obtain more accurate designs of mini-grids, thus minimizing the costs and ensuring the proper operation of the system.

Finally, regarding the estimation of GHG emissions, it has to be considered that in the case of rural communities already electrified with non-renewable sources, the analysed scenarios would be comparative, i.e. comparing the emissions before and after the installation of the mini-grid. In this case, the result obtained would be "reduced" emissions with regard to the baseline scenario.

8.3. REPLICATION AND SCALABILITY

The proposed methodology has potential to be replicable and scalable to other electrification projects in developing countries. As described, along the area of the Mesoamerican Dry Corridor (MDC) in Central America more than 3.5 billion are in need of humanitarian aid, the 40% of them located in Honduras. Half of the population live in rural areas with limited access to electricity. The case of the rural community of El Santuario is just one example of those rural communities in which providing access to electricity will improve resilience and livelihoods. Moreover, it might serve as a basis for gaining insights of results and best practices to replicate these interventions in other communities.

As an example of potential of scalability, Fig. 72 shows the electrification rate per department in 2016 in the area of the MDC of Honduras.

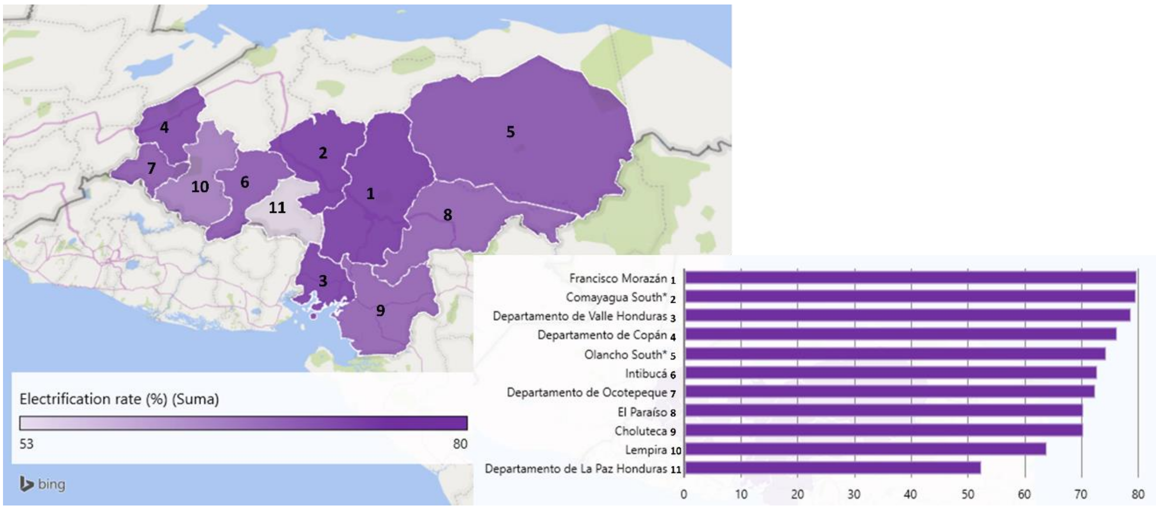

Figure 72. Electrification rate in % per Department in the MDC area of Honduras in 2016. Source: Own elaboration based on data from ENEE (2016)

8.3.1. Mitigation potential

The estimated avoided emissions for the case study of the rural community of El Santuario were approximately of 62 ton of CO_2eq per year. If these emissions are certified, it would enhance to the community the access to voluntary carbon markets where selling the avoided emissions. There is an opportunity for the community to obtain additional profits that can be estimated in 1,574.8 USD/year, according to the European Emissions Allowance (EUA)[18] prices.

Therefore, the project has potential to generate additional incomes for the inhabitants of rural communities, which will improve their livelihoods as well as contributing to ensure the operation and maintenance of the energy services in the long term.

[18]Secondary Market EUA: 25.4 USD/tonCO2 consulted 28/05/2019 https://www.eex.com/en/market-data/environmentalmarkets/spot-market/european-emission-allowances#!/2019/05/28

CHAPTER 9. CONCLUSIONS

The importance of the demand assessment step for designing mini grids and its impact in the cost and reliability of the system has been justified, although currently there is no common methodology for assessing the energy demand.

The state of the art performed shows that the most common approaches used for estimating the energy demand of rural areas are based on building up coincidence factors among users and appliances during the day. However, these approaches do not fully deal with the uncertainty in the input data, as only one single daily demand profile is formulated, and it is bound to designers' subjectivity.

In order to minimize subjectivity in the input data visits to the community are required so as to carry out measurements and surveys as well as expertise and comparison with similar electrification projects. Specific correlation factors would provide more accurate results. Moreover, computational tools based on probability provide more accurate and reliable results in short time.

The software LoadProGen2.0 has been identified as the most complete and functional tool for forecasting the demand of rural isolated communities in developing countries, especially for those off-grid areas without previous access to electricity, because is based on data easily obtained through surveys conducted to a specific group of customers and minimize the designer influence on the load profile shape. The software builds up the coincidence behaviour and formulates several realistic profiles given the input data. However, expertise for processing and introducing the data in the software is required in order to avoid non-realistic results.

Based on that, two methodologies for assessing the energy demand are described and applied to the design of a hybrid renewable energy mini grid in the rural community of El Santuario, Honduras. Methodology 1 is based on building up the coincidence factor whereas Methodology 2 considers the implementation of the stochastic procedure of LoadProGen2.0.

Although no significant differences in the energy demand in kWh/year estimated by the two methodologies are observed, the load profile obtained with LoadProGen2.0 is flatter, thus reducing load peaks. The estimated load peak occurs around 6 p.m. for both methodologies but has a value of 18.13 kW for Methodology 1 and 13.76 kW for the obtained with the LoadProGen2.0.

Regarding the design of the mini-grid, HOMER has been identified as the most widely used computational tool specially for hybrid mini-grids as it allows to simulate different technologies and configurations to reach the optimal solution, besides detecting errors and allowing changes in short time. However, expertise is required to introduce and analyse the proposed alternatives. The software only considers among the suitable configurations the combinations of installed capacity that the user has previously introduced, thus more accurate analysis that include sensitivity cases should be performed. Moreover, the limitation on the introduction of the gasifier as it requires to characterize not only the biomass resource but also the biogas has been found as a disadvantage, being bioenergy one of the most used technologies in rural electrification projects.

The load curves estimated with both methodologies were introduced in HOMER together with components' characteristics and available energy resources. The optimal solution that meet the economic, technical and environmental conditions is obtained for the more accurate curve obtained with the LoadProGen2.0 in Methodology 2.

The proposed solution is composed by 18 kW of biomass gasifier, 51 kWp of solar photovoltaic, 144 units of batteries with accumulation capacity of 288 kWh and two inverter/chargers of 25 kW each. It presents an initial investment cost of 188,133 USD, a total NPC of 275,636 USD and a LCoE of 0.727 USD/kWh.

The mini grid presents a mitigation potential estimated in 62 ton of CO_2eq avoided per year. These avoided emissions if certified would allow the access to voluntary markets and provide additional incomes valued in 1,574.8 USD/year.

A methodology for assessing the energy demand in rural isolated communities of developing countries that includes the insights from the literature review and the practical case application has been proposed. It includes designers' recommendations and find outs obtained from the application to the rural community of El Santuario.

The proposed methodology has potential to be replicable and scalable not only along the Mesoamerican Dry Corridor but also in other communities worldwide.

Finally, ensuring an enabling framework in terms of regulatory framework, private sector investment or technology transfer, among others, is crucial for the promotion of electrification projects in rural isolated communities of developing countries.

CHAPTER 10. BIBLIOGRAPHY

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ANNEXES

1. SURVEY MODEL

<table>
<tr><th colspan="6">CURRENT ENERGY DEMAND</th></tr>
<tr><td>TYPE OF USER</td><td colspan="5">Household Business Other</td></tr>
<tr><td>REFERENCE DATA</td><td>Address:</td><td colspan="4"></td></tr>
<tr><td rowspan="5">CUSTOMER INFORMATION</td><td>Name:</td><td colspan="4"></td></tr>
<tr><td>Contact:</td><td colspan="4"></td></tr>
<tr><td colspan="3">Number of people in the household:</td><td colspan="2"></td></tr>
<tr><td colspan="3">Number of rooms per household:</td><td colspan="2"></td></tr>
<tr><td colspan="3">Internal power grid</td><td colspan="2">Yes No</td></tr>
<tr><td rowspan="14">CURRENT ENERGY SOURCES AND EXPENSES</td><td colspan="2">Type of source</td><td colspan="2">Weekly expenditure</td><td>Unit price</td></tr>
<tr><td colspan="2">Diesel</td><td colspan="2"></td><td></td></tr>
<tr><td colspan="2">Kerosene</td><td colspan="2"></td><td></td></tr>
<tr><td colspan="2">Candles</td><td colspan="2"></td><td></td></tr>
<tr><td colspan="2">Batteries</td><td colspan="2"></td><td></td></tr>
<tr><td colspan="2">Charge of batteries</td><td colspan="2"></td><td></td></tr>
<tr><td colspan="2">Wood</td><td colspan="2"></td><td></td></tr>
<tr><td colspan="2">Coal</td><td colspan="2"></td><td></td></tr>
<tr><td colspan="2">Wood fuel</td><td colspan="2"></td><td></td></tr>
<tr><td colspan="2">Pellets</td><td colspan="2"></td><td></td></tr>
<tr><td colspan="2">Low pressure gas</td><td colspan="2"></td><td></td></tr>
<tr><td colspan="2">Oil fuel</td><td colspan="2"></td><td></td></tr>
<tr><td colspan="2">Natural Gas</td><td colspan="2"></td><td></td></tr>
<tr><td colspan="2">Total</td><td colspan="2"></td><td></td></tr>
<tr><td rowspan="18">CURRENT ENERGY NEEDS</td><td>Appliances</td><td>Power (W)</td><td>Units</td><td>Daily schedule (hours)</td><td>Usage hours</td></tr>
<tr><td>Light bulbs (8-20)</td><td></td><td></td><td></td><td></td></tr>
<tr><td>TV (45-120)</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Radio (20-60)</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Iron</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Cooking pot</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Microwave</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Laundry machine 5kg</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Electric boiler</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Phone</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Fan</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Fridge</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Computer</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Irrigation</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Food processing</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Other:</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Total:</td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="5"></td></tr>
<tr><td>ELECTRICITY CONSUMPTION PER ACTIVITY</td><td>Activity</td><td>Total Power Installed (W)</td><td>Daily schedule (hours)</td><td colspan="2">Electricity Consumption (kWh)</td></tr>
</table>

	Construction			
	Shop			
	Hairdressing			
	Small-scale Industry			
	Bar			
	Restaurant			
	Other:			
SOURCES OF INCOMES	**Source**	**Amount (low season)**		**Amount (High Season)**
	1			
	2			
	3			
	4			
	5			
	Total			
EXPRESSED ABILITY TO PAY	**Monthly Amount (low season)**		**Monthly Amount (High Season)**	

PRELIMINARY ESTIMATION OF LOADS AND DEMAND

Expected Appliances	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**
Light bulbs (8-20)					
TV (45-120)					
Radio (20-60)					
Iron					
Cooking pot					
Microwave					
Laundry machine 5kg					
Electric boiler					
Phone					
Fan					
Fridge					
Computer					
Irrigation					
Food processing					
Other:					
Total:					

WILLINGNESS TO PAY

Which factor is more important for you regarding to the electrical service?	Cost	Quality	Access time

What would encourage your connection to the grid?	Neighbours with access	Own need		Low price of connection	
Would electricity access enhance your life or business in any way?	Yes	No		Don't know	
How do you think electricity should be provided?	Free			Commercially	
Who decides the payment for electricity?	Myself	My supervisor		Family	
Do you possess any single-user electricity generation system?	Yes	No		Under consideration	
Are you satisfied with your current electric system?	Yes	No		Neutral	
Is your current electric system able to cover your electricity needs?	Yes	No		Percentage	
Would you be interested on using electricity for agricultural activities?	Yes	No			
If the answer is yes, in which agricultural activities are you interested?	Irrigation	Cold chain	Drying	Packaging	Other

REFERENCE DATA

Crops			
Type of crop	**Area**	**Annual Production (kg)**	**Collection period**
Corn			
Bean			
Sorghum			
Fruit Trees			
Forest - Total forested area			
Wood fuel production			
Wood in roll production			
Other:			
Total:			
Livestock			
Type	**Units**	**Location**	**Productive Usage**
Beef			
Ovine			
Porcine			
Goat			
Mules			
Poultry			
Waste			
Type of Waste	**Source location**	**Annual production (kg)**	**Collection period**
Households			
Fertilizers			
Manure			
Water			
Other:			
Total:			

2. COINCIDENCE FACTORS

HOUSEHOLDS																
	Lights		**Fridge**		**TV**		**Radio**		**Phone**		**Fan**		**Computer**		**Other appliances**	
Hour	CF	Power (kW)	CF	Power (kW)	CF	Power (kW)	CF	Power (kW)	CF	Power (kW)	CF	Power (kW)	CF	Power (kW)	CF	Power (kW)
0:00	-	-	0.01	80	-	-	0	0	0.5	195	0	0	0	0	0	0
1:00	-	-	0.01	80	-	-	0	0	0.5	195	0	0	0	0	0	0
2:00	-	-	0.01	80	-	-	0	0	0.5	195	0	0	0	0	0	0
3:00	-	-	0.05	400	0.25	1,500	0.5	430	0.5	195	0	0	0.1	20	0.2	3800
4:00	0.50	2,003	0.10	800	0.50	3,000	1	860	0.5	195	0.25	425	0.25	50	0.2	3800
5:00	1.00	4,005	0.10	800	0.25	1,500	1	860	0.5	195	0.25	425	0.25	50	0.2	3800
6:00	1.00	4,005	0.10	800	-	-	0.5	430	0	0	0.25	425	0.25	50	0.2	3800
7:00	0.75	3,004	0.05	400	-	-	0.5	430	0	0	0.25	425	0	0		0
8:00	0.50	2,003	0.01	80	-	-	0.5	430	0	0	0.25	425	0	0	0	0
9:00	0.05	200	0.01	80	-	-	0.5	430	0	0	0.25	425	0	0		0
10:00	0.05	200	0.05	400	-	-	0.5	430	0	0	0.25	425	0	0	0.2	3800
11:00	0.05	200	0.10	800	0.10	600	0.5	430	0	0	0.25	425	0.1	20	0.2	3800
12:00	0.05	200	0.10	800	0.10	600	1	860	0	0	0.25	425	0.1	20	0.2	3800
13:00	0.05	200	0.05	400	0.10	600	1	860	0	0	0.25	425	0.1	20	0.2	3800
14:00	0.05	200	0.01	80	0.10	600	1	860	0	0	0.25	425	0.1	20	0	0
15:00	0.05	200	0.01	80	0.10	600	1	860	0	0	0.25	425	0.1	20	0	0
16:00	0.05	200	0.05	400	0.10	600	0.5	430	0	0	0.25	425	0.1	20		0
17:00	0.50	2,003	0.10	800	0.10	600	0.5	430	0	0	0.25	425	0.1	20	0.2	3800
18:00	1.00	4,005	0.10	800	1.00	6,000	1	860	0.5	195	0.25	425	0.75	150	0.2	3800
19:00	1.00	4,005	0.10	800	1.00	6,000	1	860	0.5	195	0	0	0.75	150	0.2	3800
20:00	1.00	4,005	0.05	400	0.75	4,500	1	860	0.5	195	0	0	0.75	150	0.2	3800
21:00	0.50	2,003	0.05	400	0.50	3,000	0.5	430	0.5	195	0	0	0.25	50	0	0
22:00	0.25	1,001	0.01	80	0.25	1,500	0	0	0.5	195	0	0	0.25	50	0	0
23:00	0.10	401	0.01	80	-	-	0	0	0.5	195	0	0	0	0	0	0
Total	8.50	34,043	1	9,920	5	31,200	14	12,040	6	2,340	3.75	6,375	4.3	860	2.4	45,600

	COMMUNITARIAN SERVICES											
	Water Pump		Chipper		Street Lights		IT Services		Lights		Fan	
Hour	CF	Power (kW)	CF	Power (kW)	CF	Power (kW)	CF	Power (kW)	CF	Power (kW)	CF	Power (kW)
0:00	-	-	-	-	0.50	500	-	-	-	-	-	-
1:00	-	-	-	-	0.50	500	-	-	-	-	-	-
2:00	-	-	-	-	0.50	500	-	-	-	-	-	-
3:00	-	-	-	-	1.00	1,000	-	-	-	-	-	-
4:00	-	-	-	-	1.00	1,000	-	-	-	-	-	-
5:00	-	-	-	-	1.00	1,000	-	-	-	-	-	-
6:00		-	-	-	1.00	1,000	-	-	-	-	-	-
7:00		-		-	-	-	0.50	450	0.75	878	0.50	400
8:00	-	-	0.25	1,875	-	-	0.50	450	0.75	878	1.00	800
9:00	-	-	0.25	1,875	-	-	0.50	450	0.75	878	1.00	800
10:00	-	-	0.25	1,875	-	-	1.00	900	0.75	878	1.00	800
11:00	-	-	0.25	1,875	-	-	1.00	900	0.75	878	1.00	800
12:00	-	-	0.25	1,875	-	-	1.00	900	0.75	878	1.00	800
13:00	1.00	2,000	0.25	1,875	-	-	1.00	900	0.75	878	1.00	800
14:00	1.00	2,000	-	-	-	-	1.00	900	0.75	878	1.00	800
15:00	1.00	2,000	-	-	-	-	1.00	900	0.75	878	1.00	800
16:00	1.00	2,000	-	-	-	-	1.00	900	0.50	585	1.00	800
17:00	-	-	-	-	-	-	1.00	900	0.25	293	0.25	200
18:00	-	-	-	-	0.50	500	1.00	900	0.25	293	0.25	200
19:00	-	-	-	-	1.00	1,000	1.00	900	0.25	293	-	-
20:00	-	-	-	-	1.00	1,000	1.00	900	0.25	293	-	-
21:00	-	-	-	-	1.00	1,000	-	-	-	-	-	-
22:00	-	-	-	-	1.00	1,000	-	-	-	-	-	-
23:00	-	-	-	-	0.50	500	-	-	-	-	-	-
Total	4.00	8,000	1.50	11,250	10.50	10,500	12.50	11,250	8.25	9,653	10.00	8,000

3. DATA SHEETS SELECTED EQUIPMENT

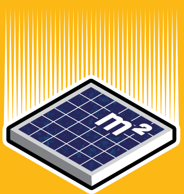
ENERGIZING LIFE TOGETHER

REC

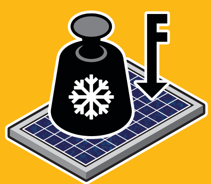
HIGH PERFORMANCE SOLAR MODULES

REC PEAK ENERGY SERIES

REC Peak Energy Series modules are the perfect choice for building solar systems that combine long lasting product quality with reliable power output. REC combines high quality design and manufacturing standards to produce high-performance solar modules with uncompromising quality.



MORE POWER PER M²

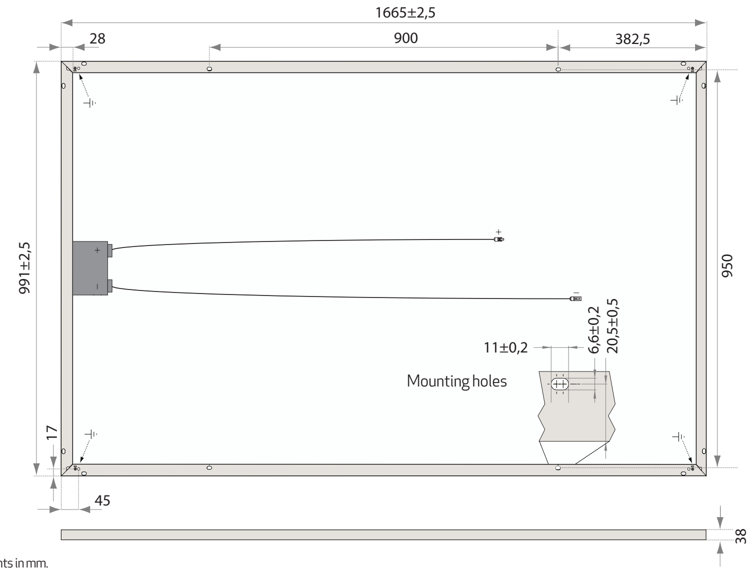


ROBUST AND DURABLE DESIGN

ENERGY PAYBACK TIME OF ONE YEAR

OPTIMIZED FOR ALL SUNLIGHT CONDITIONS

REC PEAK ENERGY SERIES



Measurements in mm.

15.8% EFFICIENCY

10 YEAR PRODUCT WARRANTY

25 YEAR LINEAR POWER OUTPUT WARRANTY

ELECTRICAL DATA @ STC	REC235PE	REC240PE	REC245PE	REC250PE	REC255PE	REC260PE
Nominal Power - P_{MPP} (Wp)	235	240	245	250	255	260
Watt Class Sorting - (W)	0/+5	0/+5	0/+5	0/+5	0/+5	0/+5
Nominal Power Voltage - V_{MPP} (V)	29.5	29.7	30.1	30.2	30.5	30.7
Nominal Power Current - I_{MPP} (A)	8.06	8.17	8.23	8.30	8.42	8.50
Open Circuit Voltage - V_{OC} (V)	36.6	36.8	37.1	37.4	37.6	37.8
Short Circuit Current - I_{SC} (A)	8.66	8.75	8.80	8.86	8.95	9.01
Module Efficiency (%)	14.2	14.5	14.8	15.1	15.5	15.8

Analysed data demonstrates that 99.7% of modules produced have current and voltage tolerance of ±3% from nominal values.
Values at standard test conditions STC (airmass AM 1.5, irradiance 1000 W/m², cell temperature 25°C).
At low irradiance of 200 W/m² (AM 1.5 and cell temperature 25°C) at least 97% of the STC module efficiency will be achieved.

ELECTRICAL DATA @ NOCT	REC235PE	REC240PE	REC245PE	REC250PE	REC255PE	REC260PE
Nominal Power - P_{MPP} (Wp)	179	183	187	189	193	197
Nominal Power Voltage - V_{MPP} (V)	27.5	27.7	28.1	28.3	28.5	29.0
Nominal Power Current - I_{MPP} (A)	6.51	6.58	6.64	6.68	6.77	6.81
Open Circuit Voltage - V_{OC} (V)	34.2	34.4	34.7	35.0	35.3	35.7
Short Circuit Current - I_{SC} (A)	6.96	7.03	7.08	7.12	7.21	7.24

Nominal operating cell temperature NOCT (800 W/m², AM 1.5, windspeed 1 m/s, ambient temperature 20°C).

CERTIFICATIONS

IEC 61215 & IEC 61730, IEC 62716 (ammonia resistance) & IEC 61701 (salt mist - severity level 6).

Member of PV Cycle

WARRANTY

10 year product warranty
25 year linear power output warranty
(max. degression in performance of 0.7% p.a.)
See warranty conditions for further details.

TEMPERATURE RATINGS	
Nominal operating cell temperature (NOCT)	45.7°C (±2°C)
Temperature coefficient of P_{MPP}	-0.40 %/°C
Temperature coefficient of V_{OC}	-0.27 %/°C
Temperature coefficient of I_{SC}	0.024 %/°C

GENERAL DATA	
Cell type:	60 REC PE multi-crystalline 3 strings of 20 cells with bypass diodes
Glass:	3.2 mm solar glass with anti-reflection surface treatment
Back sheet:	Double layer highly resistant polyester
Frame:	Anodized aluminium (silver)
Junction box:	IP67 rated 4 mm² solar cable, 0.9 m + 1.2 m
Connectors:	Multi-Contact MC4 (4 mm²)
Origin	Made in Singapore

MAXIMUM RATINGS	
Operational temperature:	-40 ... +85°C
Maximum system voltage:	1000 V
Maximum snow load:	550 kg/m² (5400 Pa)
Maximum wind load:	244 kg/m² (2400 Pa)
Max series fuse rating:	25 A
Max reverse current:	25 A

MECHANICAL DATA	
Dimensions:	1665 x 991 x 38 mm
Area:	1.65 m²
Weight:	18 kg

Note! Specifications subject to change without notice.

Rev Q - 10.2013. This datasheet is EN 50380 compliant

REC is a leading global provider of solar electricity solutions. With nearly two decades of expertise, we offer sustainable, high-performing products, services and investment opportunities for the solar and electronics industries. Together with our partners, we create value by providing solutions that better meet the world's growing electricity needs. Our 2,300 employees worldwide generated revenues of more than NOK 7 billion in 2012, approximately EUR 1 billion.

REC

www.recgroup.com

HOPPECKE
POWER FROM INNOVATION

Similar to the illustration

grid | power V L

Series OPzS/power.bloc OPzS

Vented lead-acid battery

www.hoppecke.com

grid | power V L Series OPzS

Typical applications:

- Telecommunications
  - Mobile phone stations
  - BTS-stations
  - Off-grid/on-grid solutions
- Power Supply
- Security lighting

Your benefits:

- Very high expected service life – due to optimized low-antimony selenium alloy
- Excellent cycle stability – due to tubular plate design
- Maximum compatibility – design according to DIN 40736-1
- Higher short-circuit safety even during the installation – based on HOPPECKE system connectors
- Extremely extended water refill intervals up to maintenance-free – optional use of AquaGen® recombination system minimizes emission of gas and aerosols[1]

grid | power V L Series power.bloc OPzS

Typical applications:

- Telecommunications
  - Mobile phone stations
  - BTS-stations
  - Off-grid/on-grid solutions
- Power Supply systems
- Security lighting

Your benefits:

- High expected service life – due to optimized low-antimony selenium alloy
- Excellent cycle stability – due to tubular plate design
- Maximum compatibility – dimensions according to DIN 40737-3
- Easy assembly and installation – battery lid with integral handle
- Higher short-circuit safety even during the installation – based on HOPPECKE system connectors
- Extremely extended water refill intervals up to maintenance-free – optional use of AquaGen® recombination system minimizes emission of gas and aerosols[1]

[1] Similar to sealed lead-acid batteries

Capacities dimensions and weights

Series OPzS	DIN Type	C_{10}/1.80 V Ah	C_5/1.77 V Ah	C_3/1.75 V Ah	C_1/1.67 V Ah	max.* Weight kg	Weight electrolyte kg (1.24 kg/l)	max.* Length L mm	max.* Width W mm	max.* Height H mm	Fig.
grid | power VL 2-215	4 OPzS 200	213	182	161	118	17.3	4.5	105	208	420	A
grid | power VL 2-270	5 OPzS 250	266	227	201	147	21.0	5.6	126	208	420	A
grid | power VL 2-325	6 OPzS 300	320	273	241	177	24.9	6.7	147	208	420	A
grid | power VL 2-390	5 OPzS 350	390	345	303	217	29.3	8.5	126	208	535	A
grid | power VL 2-470	6 OPzS 420	468	414	363	261	34.4	10.1	147	208	535	A
grid | power VL 2-550	7 OPzS 490	546	483	426	304	39.5	11.7	168	208	535	A
grid | power VL 2-690	6 OPzS 600	686	590	510	353	46.1	13.3	147	208	710	A
grid | power VL 2-805	7 OPzS 700	801	691	596	411	59.1	16.7	215	193	710	B
grid | power VL 2-920	8 OPzS 800	915	790	681	470	63.1	17.3	215	193	710	B
grid | power VL 2-1035	9 OPzS 900	1026	887	767	529	72.4	20.5	215	235	710	B
grid | power VL 2-1150	10 OPzS 1000	1140	985	852	588	76.4	21.1	215	235	710	B
grid | power VL 2-1265	11 OPzS 1100	1256	1086	938	647	86.6	25.2	215	277	710	B
grid | power VL 2-1380	12 OPzS 1200	1370	1185	1023	706	90.6	25.8	215	277	710	B
grid | power VL 2-1610	12 OPzS 1500	1610	1400	1197	784	110.4	32.7	215	277	855	B
grid | power VL 2-1880	14 OPzS 1750	1881	1632	1397	914	142.3	46.2	215	400	815	C
grid | power VL 2-2015	15 OPzS 1875	2016	1748	1496	980	146.6	46.7	215	400	815	C
grid | power VL 2-2150	16 OPzS 2000	2150	1865	1596	1045	150.9	45.9	215	400	815	C
grid | power VL 2-2420	18 OPzS 2250	2412	2097	1796	1176	179.1	56.4	215	490	815	D
grid | power VL 2-2555	19 OPzS 2375	2546	2213	1895	1242	182.9	55.6	215	490	815	D
grid | power VL 2-2690	20 OPzS 2500	2680	2330	1995	1307	187.3	55.7	215	490	815	D
grid | power VL 2-2960	22 OPzS 2750	2952	2562	2195	1437	212.5	67.0	215	580	815	D
grid | power VL 2-3095	23 OPzS 2875	3086	2678	2294	1503	216.8	65.9	215	580	815	D
grid | power VL 2-3230	24 OPzS 3000	3220	2795	2394	1568	221.2	66.4	215	580	815	D
grid | power VL 2-3500	26 OPzS 3250	3488	3028	2594	1699	229.6	65.4	215	580	815	D

C_{10}, C_5, C_3 and C_1 = Capacity at 10 h, 5 h, 3 h and 1 h discharge

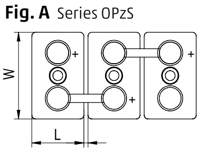
* according to DIN 40736-1 data to be understood as maximum values

Series power.bloc OPzS	DIN Type	C_{10}/1.80 V Ah	C_5/1.77 V Ah	C_3/1.75 V Ah	C_1/1.67 V Ah	max.* Weight kg	Weight electrolyte kg (1.24 kg/l)	max.* Length L mm	max.* Width W mm	max.* Height H mm	Fig.
grid | power VL 12-50	12 V 1 power.bloc OPzS 50	50	44	39	28	37.0	15.0	272	205	383	A
grid | power VL 12-100	12 V 2 power.bloc OPzS 100	101	88	78	57	48.0	13.0	272	205	383	A
grid | power VL 12-150	12 V 3 power.bloc OPzS 150	151	132	117	85	67.0	18.0	380	205	383	A
grid | power VL 6-200	6 V 4 power.bloc OPzS 200	202	176	155	114	47.0	13.0	272	205	383	B
grid | power VL 6-250	6 V 5 power.bloc OPzS 250	252	220	194	142	60.0	20.0	380	205	383	B
grid | power VL 6-300	6 V 6 power.bloc OPzS 300	302	264	233	171	67.0	18.0	380	205	383	B

C_{10}, C_5, C_3 and C_1 = Capacity at 10 h, 5 h, 3 h and 1 h discharge

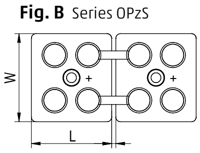
* according to DIN 40737-3 data to be unterstood as maximum values

Fig. A Series OPzS



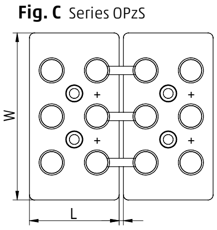
grid | power VL 2-215 -
grid | power VL 2-690

Fig. B Series OPzS



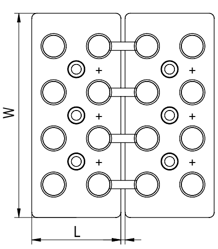
grid | power VL 2-805 -
grid | power VL 2-1610

Fig. C Series OPzS



grid | power VL 2-1880-
grid | power VL 2-2150

Fig. D Series OPzS



grid | power VL 2-2420 -
grid | power VL 2-3500

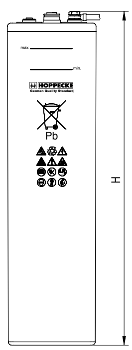
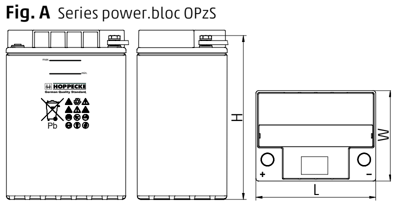
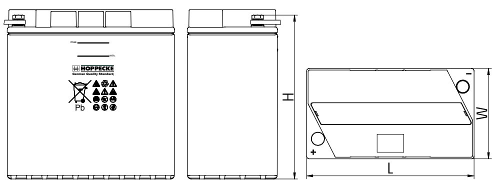


Fig. A Series power.bloc OPzS



grid | power VL 12-50 -
grid | power VL 12-150

Fig. B Series power.bloc OPzS



grid | power VL 6-200 -
grid | power VL 6-300

Design life: up to 20 years

Optimal environmental compatibility – closed loop for recovery of materials in an accredited recycling system

Design life: up to 18 years

Optimal environmental compatibility – closed loop for recovery of materials in an accredited recycling system

HOPPECKE
POWER FROM INNOVATION

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Bontkirchener Str. 1
D - 59929 Brilon
Tel: +49 (0) 2963 61-374
Fax: +49 (0) 2963 61-270
E-Mail: reservepower@hoppecke.com

01/2018 EN grid | power VL All details in this brochure are based on state-of-the-art technology. Our products are subject to constant development. We therefore reserve the right to make changes.

SUNNY TRIPOWER 15000TL / 20000TL / 25000TL

Rentable

- Rendimiento máximo del 98,4 %

Seguro

- Descargador de sobretensión de CC integrable (DPS tipo II)

Flexible

- Tensión de entrada de CC hasta 1000 V
- Diseño de plantas perfecto gracias al concepto de multistring
- Pantalla opcional

Innovador

- Innovadoras funciones de gestión de red gracias a Integrated Plant Control
- Suministro de potencia reactiva las 24 horas del día (Q on Demand 24/7)

SUNNY TRIPOWER 15000TL / 20000TL / 25000TL

El especialista flexible para plantas comerciales y centrales fotovoltaicas de gran tamaño

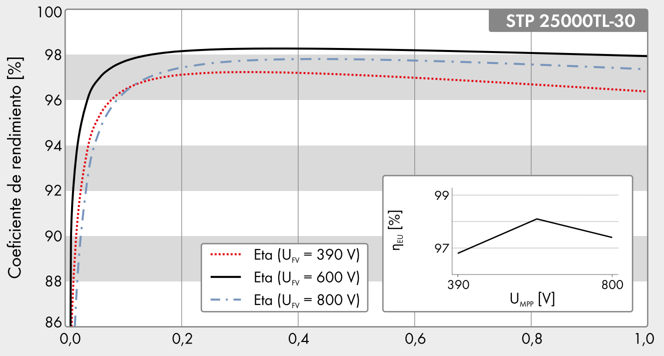
El Sunny Tripower es el inversor ideal para plantas de gran tamaño en el sector comercial e industrial. Gracias a su rendimiento del 98,4 %, no solo garantiza unas ganancias excepcionalmente elevadas, sino que a través de su concepto de multistring combinado con un amplio rango de tensión de entrada también ofrece una alta flexibilidad de diseño y compatibilidad con muchos módulos fotovoltaicos disponibles.

La integración de nuevas funciones de gestión de energía como, por ejemplo, Integrated Plant Control, que permite regular la potencia reactiva en el punto de conexión a la red tan solo por medio del inversor, es una firme apuesta de futuro. Esto permite prescindir de unidades de control de orden superior y reducir los costes del sistema. El suministro de potencia reactiva las 24 horas del día (Q on Demand 24/7) es otra de las novedades que ofrece.

SUNNY TRIPOWER
15000TL / 20000TL / 25000TL

Datos técnicos	**Sunny Tripower 15000TL**
Entrada (CC)	
Potencia máx. del generador fotovoltaico	27000 Wp
Potencia asignada de CC	15330 W
Tensión de entrada máx.	1000 V
Rango de tensión MPP/tensión asignada de entrada	240 V a 800 V/600 V
Tensión de entrada mín./de inicio	150 V/188 V
Corriente máx. de entrada, entradas: A/B	33 A/33 A
Número de entradas de MPP independientes/strings por entrada de MPP	2/A:3; B:3
Salida (CA)	
Potencia asignada (a 230 V, 50 Hz)	15000 W
Potencia máx. aparente de CA	15000 VA
Tensión nominal de CA	3 / N / PE; 220 V / 380 V 3 / N / PE; 230 V / 400 V 3 / N / PE; 240 V / 415 V
Rango de tensión de CA	180 V a 280 V
Frecuencia de red de CA/rango	50 Hz/44 Hz a 55 Hz 60 Hz/54 Hz a 65 Hz
Frecuencia asignada de red/tensión asignada de red	50 Hz/230 V
Corriente máx. de salida/corriente asignada de salida	29 A/21,7 A
Factor de potencia a potencia asignada/Factor de desfase ajustable	1/0 inductivo a 0 capacitivo
THD	≤ 3%
Fases de inyección/conexión	3/3
Rendimiento	
Rendimiento máx./europeo	98,4%/98,0%
Dispositivos de protección	
Punto de desconexión en el lado de entrada	●
Monitorización de toma a tierra/de red	● / ●
Descargador de sobretensión de CC: DPS tipo II	○
Protección contra polarización inversa de CC/resistencia al cortocircuito de CA/con separación galvánica	● / ● / –
Unidad de seguimiento de la corriente residual sensible a la corriente universal	●
Clase de protección (según IEC 62109-1)/categoría de sobretensión (según IEC 62109-1)	I / AC: III; DC: II
Datos generales	
Dimensiones (ancho/alto/fondo)	661/682/264 mm (26,0/26,9/10,4 in)
Peso	61 kg (134,48 lb)
Rango de temperatura de servicio	−25 °C a +60 °C (−13 °F a +140 °F)
Emisión sonora, típica	51 dB(A)
Autoconsumo nocturno	1 W
Topología/principio de refrigeración	Sin transformador/OptiCool
Tipo de protección (según IEC 60529)	IP65
Clase climática (según IEC 60721-3-4)	4K4H
Valor máximo permitido para la humedad relativa (sin condensación)	100%
Equipamiento / función / accesorios	
Conexión de CC/CA	SUNCLIX/Borne de conexión por resorte
Pantalla	○
Interfaz: RS485, Speedwire/Webconnect	○ / ●
Interfaz de datos: SMA Modbus / SunSpec Modbus	● / ●
Relé multifunción/Power Control Module	○ / ○
OptiTrac Global Peak/Integrated Plant Control/Q on Demand 24/7	● / ● / ●
Compatible con redes aisladas/con SMA Fuel Save Controller	● / ●
Garantía: 5/10/15/20 años	● / ○ / ○ / ○
Certificados y autorizaciones previstos * No es válido para todas las ediciones nacionales de la norma EN 50438	ANRE 30, AS 4777, BDEW 2008, C10/11:2012, CE, CEI 0-16, CEI 0-21, DEWA 2.0, EN 50438:2013*, G59/3, IEC 60068-2-x, IEC 61727, IEC 62109-1/2, IEC 62116, MEA 2013, NBR 16149, NEN EN 50438, NRS 097-2-1, PEA 2013, PPC, RD 1699/413, RD 661/2007, Res. n°7:2013, SI4777, TOR D4, TR 3.2.2, UTE C15-712-1, VDE 0126-1-1, VDE-AR-N 4105, VFR 2014
Modelo comercial	STP 15000TL-30

Curva de rendimiento



Accesorios


Interfaz RS485
DM-485CB-10


Power Control Module
PWCMOD-10


Descargador de sobretensión de CC tipo II, entradas A y B
DCSPD KIT3-10


Relé multifunción
MFR01-10

● De serie ○ Opcional – No disponible
Datos en condiciones nominales
Actualizado: octubre de 2017

Datos técnicos	Sunny Tripower 20000TL	Sunny Tripower 25000TL
Entrada (CC)		
Potencia máx. del generador fotovoltaico	36000 Wp	45000 Wp
Potencia asignada de CC	20440 W	25550 W
Tensión de entrada máx.	1000 V	1000 V
Rango de tensión MPP/tensión asignada de entrada	320 V a 800 V/600 V	390 V a 800 V/600 V
Tensión de entrada mín./de inicio	150 V/188 V	150 V/188 V
Corriente máx. de entrada, entradas: A/B	33 A/33 A	33 A/33 A
Número de entradas de MPP independientes/strings por entrada de MPP	2/A:3; B:3	2/A:3; B:3
Salida (CA)		
Potencia asignada (a 230 V, 50 Hz)	20000 W	25000 W
Potencia máx. aparente de CA	20000 VA	25000 VA
Tensión nominal de CA	3 / N / PE; 220 V / 380 V 3 / N / PE; 230 V / 400 V 3 / N / PE; 240 V / 415 V	
Rango de tensión de CA	180 V a 280 V	
Frecuencia de red de CA/rango	50 Hz/44 Hz a 55 Hz 60 Hz/54 Hz a 65 Hz	
Frecuencia asignada de red/tensión asignada de red	50 Hz/230 V	
Corriente máx. de salida/corriente asignada de salida	29 A/29 A	36,2 A/36,2 A
Factor de potencia a potencia asignada/Factor de desfase ajustable	1/0 inductivo a 0 capacitivo	
THD	≤ 3%	
Fases de inyección/conexión	3/3	
Rendimiento		
Rendimiento máx./europeo	98,4%/98,0%	98,3%/98,1%
Dispositivos de protección		
Punto de desconexión en el lado de entrada	●	
Monitorización de toma a tierra/de red	● / ●	
Descargador de sobretensión de CC: DPS tipo II	○	
Protección contra polarización inversa de CC/resistencia al cortocircuito de CA/con separación galvánica	● / ● / –	
Unidad de seguimiento de la corriente residual sensible a la corriente universal	●	
Clase de protección (según IEC 62109-1)/categoría de sobretensión (según IEC 62109-1)	I / AC: III; DC: II	
Datos generales		
Dimensiones (ancho/alto/fondo)	661/682/264 mm (26,0/26,9/10,4 in)	
Peso	61 kg (134,48 lb)	
Rango de temperatura de servicio	−25 °C a +60 °C (−13 °F a +140 °F)	
Emisión sonora, típica	51 dB(A)	
Autoconsumo nocturno	1 W	
Topología/principio de refrigeración	Sin transformador/OptiCool	
Tipo de protección (según IEC 60529)	IP65	
Clase climática (según IEC 60721-3-4)	4K4H	
Valor máximo permitido para la humedad relativa (sin condensación)	100%	
Equipamiento / función / accesorios		
Conexión de CC/CA	SUNCLIX/Borne de conexión por resorte	
Pantalla	○	
Interfaz: RS485, Speedwire/Webconnect	○ / ●	
Interfaz de datos: SMA Modbus / SunSpec Modbus	● / ●	
Relé multifunción/Power Control Module	○ / ○	
OptiTrac Global Peak/Integrated Plant Control/Q on Demand 24/7	● / ● / ●	
Compatible con redes aisladas/con SMA Fuel Save Controller	● / ●	
Garantía: 5/10/15/20 años	● / ○ / ○ / ○	
Certificados y autorizaciones (otros a petición) * No es válido para todas las ediciones nacionales de la norma EN 50438	ANRE 30, AS 4777, BDEW 2008, C10/11:2012, CE, CEI 0-16, CEI 0-21, DEWA 2.0, EN 50438:2013*, G59/3, IEC 60068-2-x, IEC 61727, IEC 62109-1/2, IEC 62116, MEA 2013, NBR 16149, NEN EN 50438, NRS 097-2-1, PEA 2013, PPC, RD 1699/413, RD 661/2007, Res. n.°7:2013, SI4777, TOR D4, TR 3.2.2, UTE C15-712-1, VDE 0126-1-1, VDE-AR-N 4105, VFR 2014	
Modelo comercial	STP 20000TL-30	STP 25000TL-30

www.SunnyPortal.com

Monitorización, gestión y presentación profesionales de plantas fotovoltaicas

www.SMA-Iberica.com

SMA Solar Technology

ALL POWER LABS

Carbon Negative Power & Products

POWER PALLET - PP20

RENEWABLE
AFFORDABLE
ON-DEMAND
POWER

PP20 - Basic Configuration

The **Power Pallet** is a renewable power solution that is a sensible answer to a critical global problem. It meets the expectations for portable on-demand generators, is proudly made in California and available now at an affordable price.

APL's unique patented multi-stage gasification architecture, in combination with our innovative gasifier-engine thermal integration, our electronic control system and waste-heat recycling, gives the Power Pallet unprecedented biomass fuel flexibility and efficiency.

The Power Pallet uses agricultural and forestry waste materials that can be readily sourced very near the point of generation. It is compact and portable, easily transported in the bed of a pickup truck to where the fuel is and where the power is needed. Unlike diesel fuel or gasoline, this fuel is often available at little or no cost, and most importantly, depending on feedstock selection and use details, the Power Pallet is capable of the carbon negative operation.

PERFORMANCE

Continuous Power Rating:	15 kW@50 Hz/18 kW@60 Hz
Sound Level @ 30 feet:	85 dB(A)
Biomass Consumption:	1.2 kg/kWh, 2.5 lbs/kWh
Run Time per Hopper Fill: approximate @ 250 kg/m³ fuel density	5 kW: 10 hrs 10 kW: 5 hrs 15 kW: 3 hrs
Max. Continuous Operation:	>12 hours
Start Up Time:	10-20 min.

OPERATING CONDITIONS

Ambient Temperature:	5-40°C/40-100°F
Humidity:	5-95% RH
Installed Footprint: without ash vessel or grid tie	1.36 x 1.36 m 53.5 x 53.5 inches
Site Requirements:	Well-Ventilated protected from rain & direct sun

FEEDSTOCK BIOMASS

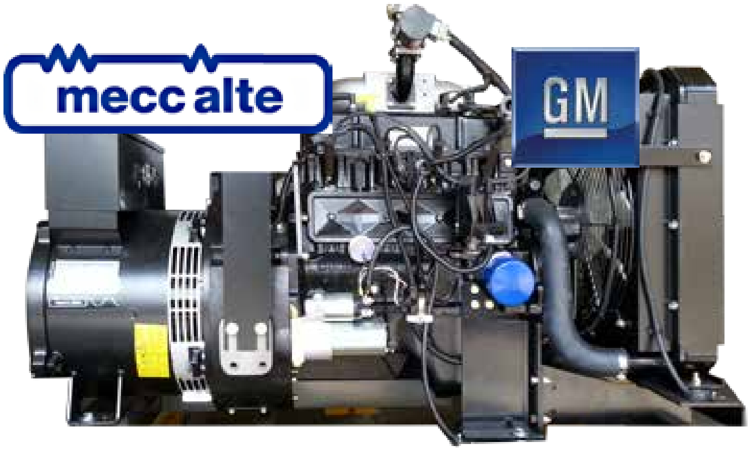
Size:	12-40 mm/0.5-1.5 in.
Moisture Content:	5-30% dry basis
Approved and Tested w/ normal operating procedures	Nut Shells (e.g. Walnut, Hazelnut) Softwood Chips (e.g. Fir, Pine) Hardwood Chips (e.g. Oak, Ash)
Approved and Tested w/ increased operating effort	Corn Cobs Coconut Shells Palm Kernel Shells
Not Approved dangerous & voids warranty	Coal Tires Plastic Municipal Solid Waste

SHIPPING

Dimensions:	PP20 - Crated Hopper - Crated	145 x 145 x 140 cm/57 x 57 x 54 in. 83 x 83 x 114 cm/33 x 33 x 45 in.
Weight:	PP20 - Crated Hopper - Crated	700 kg/1550 lbs. 91 kg/200 lbs.

FUEL COST COMPARISON (VARIES by REGION)

FUEL	PRICE RANGE
Diesel/LPG	$0.40 - $0.75/kWh
Gasoline	$0.50 - $1.00/kWh
Gasified Biomass	***$0.00 - $0.20/kWh***



Mecc Alte NPE32 Genhead GM Vortec 3.0 I.C. Engine

ALL Power Labs

APL is the global leader in small-scale gasification technology. We make biomass-fueled power generators that are ready for everyday work, to serve real-world, distributed-energy needs. Our compact gasifiers are now at work in over thirty countries, and support research at more than fifty universities around the world.

Our APL team is an unusual combination of hands-on fabricators and university-trained scientists and engineers. The result is a powerful combination of technical ability and physical know-how for developing innovative energy solutions.

We are deeply committed to supporting and developing biomass energy conversion by curating and disseminating comprehensive information and data on gasification science and technology—online, in work-shops, and free open house events.

Our facility is in Berkeley, CA. Please contact us to arrange a visit the next time you are in the Bay Area. We would love to show you around.

WARRANTY

ALL Power Labs products are covered by a 100% money back guarantee. If you buy something & find yourself unimpressed with the value of the product or company, we'll refund all your money (minus shipping costs) within 30 days of delivery. APL directly warrants all parts we manufacture (i.e. gasifiers, electronics, & related components) for two years or 4000 hours, & passes along the OEM warranty for parts we source & configure into our end products (e.g. engines & genheads). See **http://allpowerlabs.com** for full details.

GASIFIER

Type:	APL v5 Patented Thermally Integrated Downdraft
Materials:	304 SS/310 SS/ 321 SS/mild steel
Hearth:	Coated Ceramic
Ash Removal:	Automated 12 hour batch vessel
Fuel Feed:	Automated
Hopper Capacity:	0.33 m^3/88 gallons
Hopper Filling:	Batch - refill while operating
Min. Maintenance Cycle:	~ 12 hours
Control System:	On-Board Automation

ENGINE

Type:	GM Vortec
Displacement:	3.0 liter
Compression Ratio:	10.25:1
RPM:	1500@50 Hz 1800@60 Hz
Valve Configuration:	Overhead, Pushrod
Engine Block/Cyl. Head:	Cast Iron w/ exh. valve inserts
Ignition:	Solidstate Distributor
Spark Timing:	Fixed
Lube Oil Capacity:	5 quarts - including filter
Coolant Capacity:	11.4 L, 12 qts - incl. radiator
Auto Shutdown:	Low Oil Pressure High Coolant Temperature
Starter:	Reduction Gear PG-260L
Charging System:	Delco-Remy 7-SI (70 A)
System Voltage:	12 V DC
Recommended Battery:	75Ah, 880 CCA Marine
Battery Footprint:	250 x 300 mm/10 x 12 in.
Speed Control:	Electronic Governor Woodward L-Series
Oxygen Sensor:	Bosch Wide Band

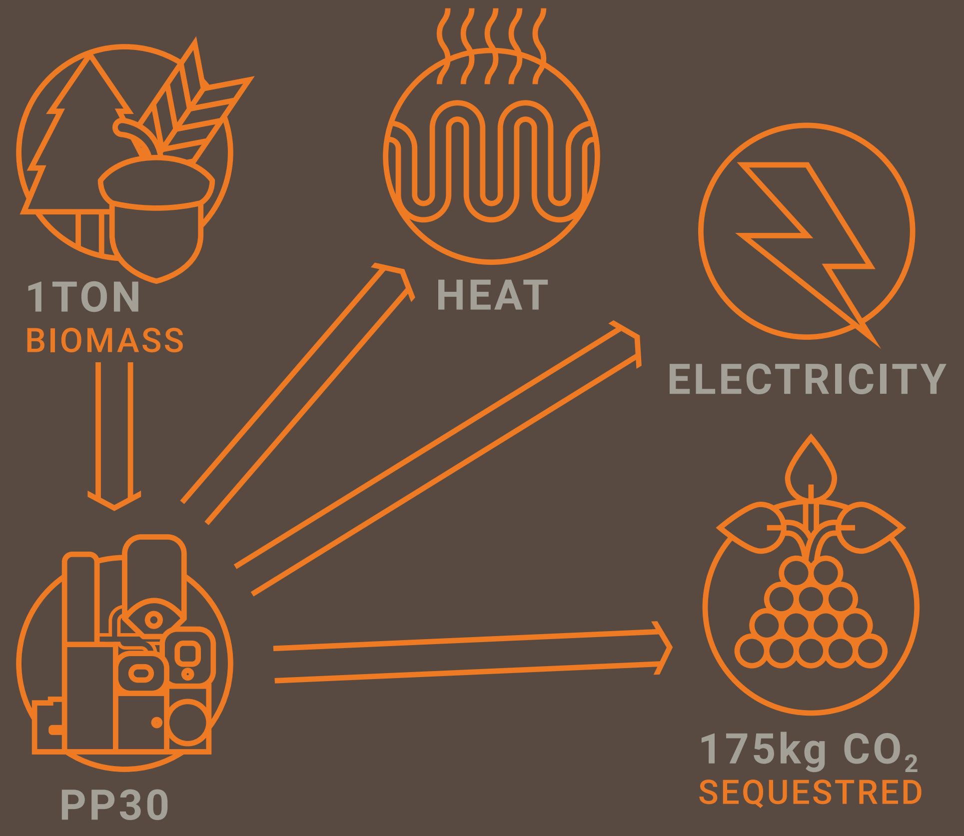
GENERATOR

Type:	Mecc Alte NPE32-E/4 12 wire
AVR:	Mecc Alte DSR
Available Voltages:	190-277, 380-480 V AC
Available Topologies:	Series Delta/Star, Parallel Delta
Total Harmonic Distortion:	<5%
Genset Starting:	Manual Handover
Maximum Step Load:	50% of rated power

All specifications are subject to change without notice

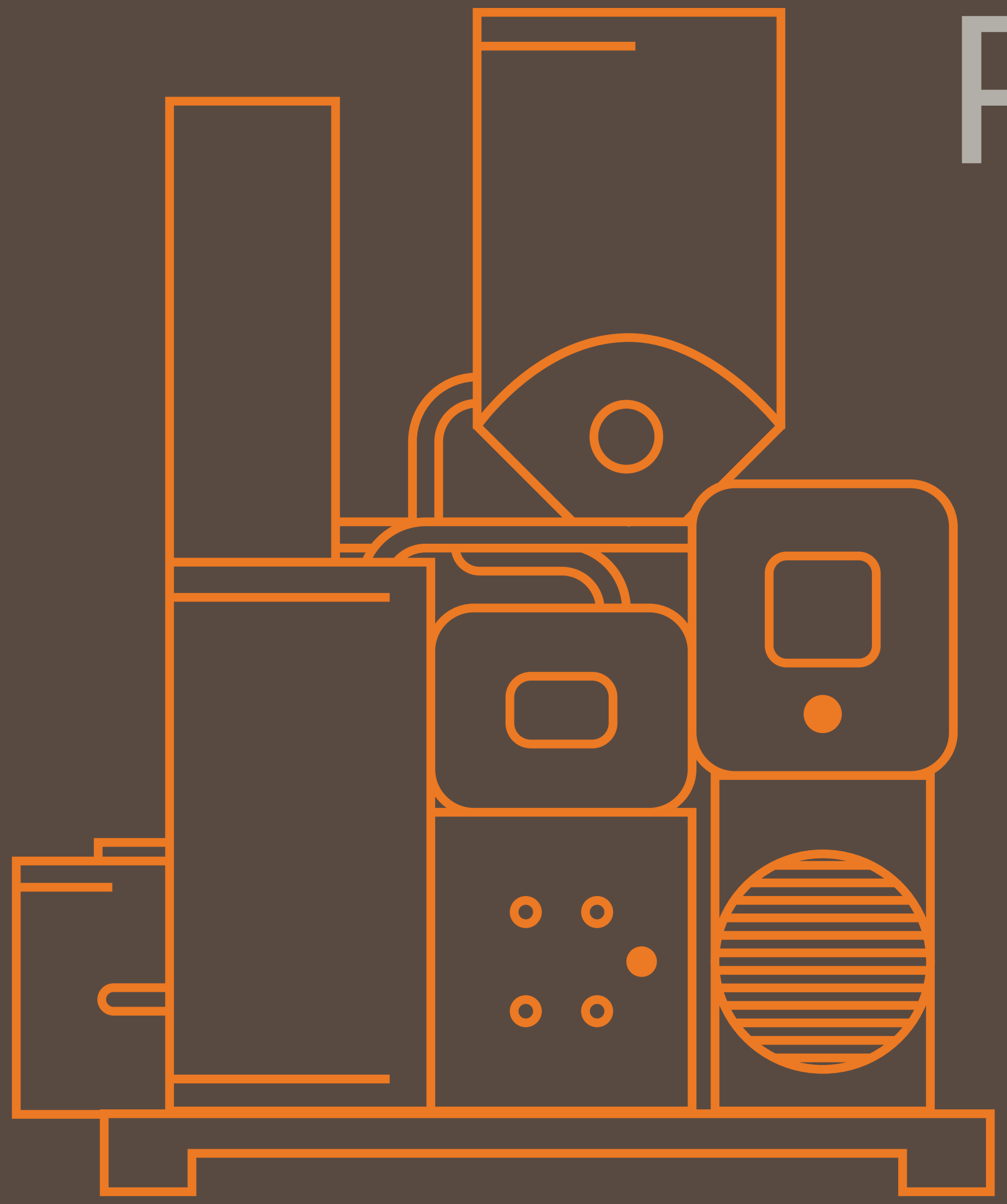
ALL Power Labs - 1010 Murray Street Berkeley, CA 94710 U.S.A.
+1-510-845-1500 Email: sales@allpowerlabs.com Web: allpowerlabs.com

PP30



Solving Global Warming

Biomass-based solutions to climate change are of unique interest in that the hardest problem —the capture and storage of atmospheric CO_2—is already solved and globally installed at scale in the form of plant photosynthesis. We don't have to start from scratch, as with expensive direct capture of atmospheric CO_2; we only have to process the biomass in some form that prevents the captured CO_2 from returning to atmosphere. We do this by producing Biochar as part of our gasification process for energy production. When mixed with soil, the carbon in the biochar can be sequestered from the atmosphere for centuries or more, making the Power Pallet one of the only carbon-negative technologies currently ready for global deployment.



ALL POWER LABS

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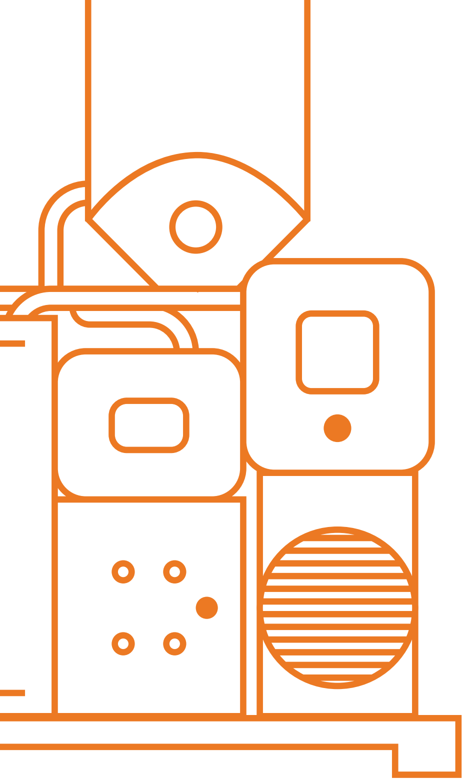
ALL POWER LABS
Carbon Negative Power & Products



PP30
Spec Sheet

SHIPPING

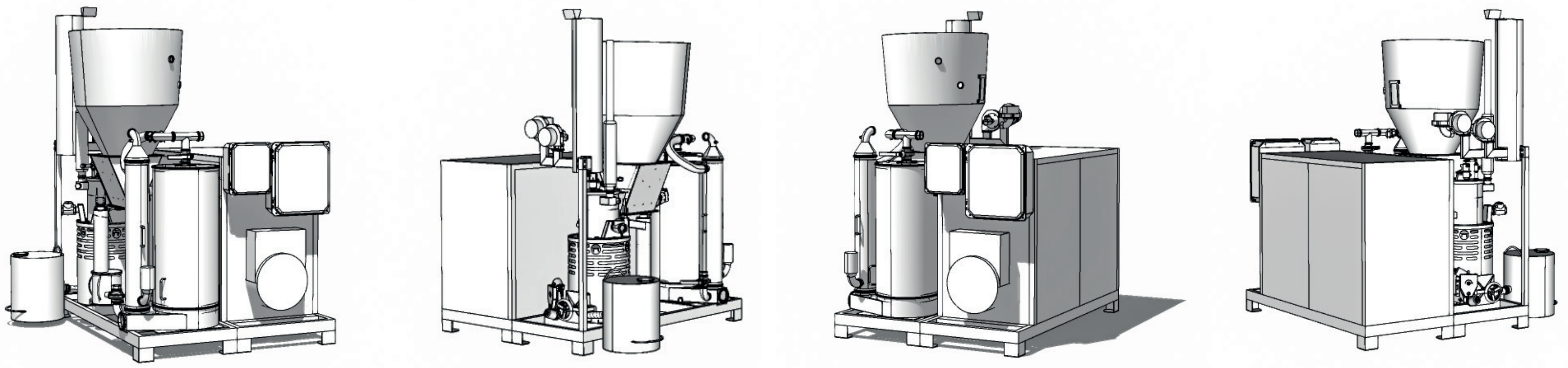
Dimensions	Main crate	1.83 x 1.47 x 1.40 m 72 × 58 × 55 inches
	Hopper crate	83 × 83 × 114 cm 33 × 33 × 45 inches
Weight	Main crate	1,350 kg - 2,976 lbs
	Hopper crate	91 kg - 200 lbs

PERFORMANCE
ELECTRICAL OUTPUT

Continuous Power Rating	25 kW @ 50/60 Hz
Sound Level @ 7 meters	75 db
Biomass Consumption	1.0 kg/kWh (dry biomass)
Runtime per hopper fill: Approximate @ 250kg/m³ feedstock density	**5 kW:** 12 hours **10 kW:** 6 hours **15 kW:** 4 hours **25 kW:** 2.4 hours
Max. continuous operation	>12 hours
Start up time	10-15 minutes

PERFORMANCE
THERMAL ENERGY OUTPUT

Maximum Outlet Temperature	90˚C (190˚F)
Return Temperature Range	40˚C – 90˚C (160˚F – 190˚F)
Standard Temperature Difference	10˚C (50˚F)
Heating Water Volume Flow	Variable
Max Heating Water Volume Flow	50 gpm
Maximum Thermal Output	50 kW



two separate skids for gas making and powertrain

ENGINE

Type	Ashok Leyland /Hino
Cylinder count	4
Displacement	4.0 liter
Compression Ratio	12:1
RPM	1500 @ 50hz, 1800 @ 60Hz
Valve Configuration	Overhead valves, Pushrods
Engine block / Cylinder head	Cast Iron w/ hardened exhaust valve inserts
Ignition	Coil over plug (COP)
Oil capacity	8L 15 W-40
Oil Maintenance Interval	500 hrs
Coolant capacity	15 L
Auto-shutdown	Low oil pressure High coolant temperature
Starter	12 V Starter
Charging system	switch mode power supply from AC genhead
System voltage	12 V DC
Recommended battery	75 Ah, 880 CCA Marine
Battery tray dimensions	20 × 30 cm / 10 × 12 inches
Speed control	Electronic governor Woodward L-series
Mixture control	Automated with Wide Band Oxygen Sensor

GASIFIER

Type	APL v5 Patented Multistage heat recycling downdraft gasifier
Materials	304 Stainless, 310 Stainless, 321 Stainless, 316 Stainless, Mild Steel
Hearth	Coated Ceramic
Char-Ash Removal	Automated removal from reactor to 12-hour batch vessel.
Fuel Feed	Automated from hopper to reactor
Hopper Capacity	333 liters / 88 gallons
Hopper Filling	Batch—manual refilling while operating OPTIONAL CONTINUOUS FEED HOPPER SYSTEM AUTOMATES FILLING
Minimum maintenance cycle	~12 hours
Control system	On-board automation

GENERATOR

Type	Marathon 284CSL1542 wire reconfigurable
AVR	DSE A106 MK II
Available Voltages	120-277, 240-480V AC
Available Topologies	3 phase: Series Star, Parallel Star, Series Delta, Parallel Delta, 1 phase: Double Delta (Base Model)
Total Harmonic Distortion	<5%
Motor Surge Starting Capacity	>300%
Genset Starting	Manual Handover
Maximum step-load	50% of rated power
Generator efficiency	92%