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DE VALENCIA

DOCTORAL THESIS

METHODOLOGY FOR ASSESING AND OPTIMISING RENEWABLE HYBRID SYSTEMS FOR ISOLATED AREAS ELECTRIFICATION

METODOLOGÍA DE EVALUACIÓN Y OPTIMIZACIÓN DE SISTEMAS RENOVABLES HÍBRIDOS PARA ELECTRIFICACIÓN DE ZONAS AISLADAS DE LA RED

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EXECUTIVE SUMMARIES

The objective of this thesis is the definition and development of a comprehensive methodology of energy planning for areas isolated from the mains, considering not only the energy context of the country and its development towards a sustainable scenario, but also studying the potential of renewable generation in the remote area under study, the ability for demand management and the socio-economic aspects involved in the final decision on what renewable energy solution would be the most appropriate in accordance with the characteristics of the location.

The research work is organized into three major phases. The first one defines the algorithm of analysis of the context energy of the country and its evolution towards a future energy scenario based on renewable energies. A second phase which analyses the best configurations of hybrid renewable systems capable of responding to energy needs in the area, sorting them based on their net present value. And a third one introducing the method of multi-criteria analysis which allows to select, from among all possible configurations identified in the previous stage, the most appropriate to the needs and characteristics of the area to study, taking into account not only economic or technical aspects, but also sociological, political, and environmental criteria.

Finally, the developed methodology is applied to a case concrete as example of its potential. An isolated community in the Democratic Republic of the Congo has been selected since 90% of the population living in areas isolated from the mains, and being one of the African countries with the greatest potential for renewable energy generation.

RESUMEN EJECUTIVO

El objetivo de esta tesis es la definición y desarrollo de una metodología integral de planificación energética para zonas aisladas de la red eléctrica que considere no solo el contexto energético del país y su desarrollo hacia un escenario sostenible, sino también el estudio del potencial de generación renovable en la zona remota a estudiar, la capacidad de gestión de la demanda y los aspectos socio-económicos que intervienen en la decisión final sobre qué solución energética renovable sería la más apropiada de acuerdo con las características de la ubicación.

El trabajo de investigación se organiza en tres grandes etapas. La primera donde se define el algoritmo de análisis del contexto energético del país y su evolución hacia un escenario energético futuro basado en energías renovables. Una segunda fase donde se analizan las mejores configuraciones de sistemas renovables híbridos capaces de responder a las necesidades energéticas de la zona, clasificándolas en base a su valor neto actual. Y una tercera donde se describe el método de análisis multi-criterio que permite seleccionar, de entre todas las posibles configuraciones identificadas en la etapa anterior, la más adecuada para las necesidades y características de la zona a estudiar, teniendo en cuenta no solo aspectos económicos o técnicos, sino también criterios sociológicos, políticos y medioambientales.

Finalmente, se aplica la metodología a un caso concreto en la República Democrática del Congo como ejemplo de su aplicación. Para el análisis del caso de estudio, se ha seleccionado una comunidad aislada en la República Democrática del Congo ya que el 90% de la población vive en zonas aisladas de la red eléctrica, y es uno de los países de África con mayor potencial de generación con energías renovables.

RESUMEN EXECUTIU

L'objectiu d'aquesta tesi és la definició i desenvolupament d'una metodologia integral de planificació energètica per a zones aïllades de la xarxa elèctrica que considere no solament el context energètic del país i el seu desenvolupament cap a un escenari sostenible, sinó també l'estudi del potencial de generació renovable en la zona remota a estudiar, la capacitat de gestió de la demanda i els aspectes soci-econòmics que intervenen en la decisió final sobre quina solució energètica renovable seria la més apropiada d'acord amb les característiques de la ubicació.

El treball de recerca s'organitza en tres grans etapes. La primera on es defineix l'algorisme d'anàlisi del context energètic del país i la seua evolució cap a un escenari energètic futur basat en energies renovables. Una segona fase on s'analitzen les millors configuracions de sistemes renovables híbrids capaços de respondre a les necessitats energètiques de la zona, classificant-les sobre la base del seu valor net actual. I una tercera on es descriu el mètode d'anàlisi multi-criteri que permet seleccionar, d'entre totes les possibles configuracions identificades en l'etapa anterior, la més adequada per a les necessitats i característiques de la zona a estudiar, tenint en compte no sol aspectes econòmics o tècnics, sinó també criteris sociològics, polítics i mediambientals.

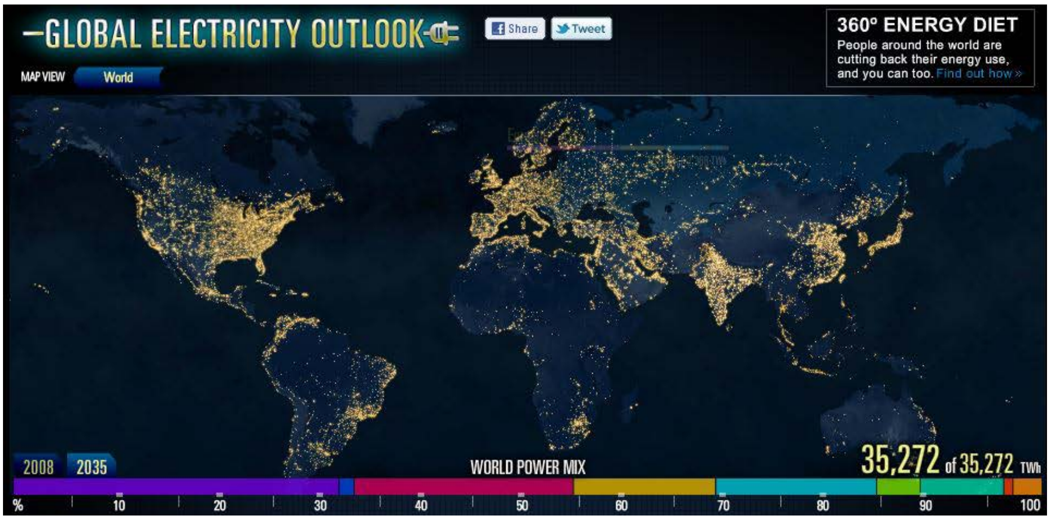
Finalment, s'aplica la metodologia a un cas concret en la República Democràtica del Congo com a exemple de la seua aplicació. Per a l'anàlisi del cas d'estudi, s'ha seleccionat una comunitat aïllada en la República Democràtica del Congo ja que el 90% de la població viu en zones aïllades de la xarxa elèctrica, i és un dels països d'Àfrica amb major potencial de generació amb energies renovable.

CHAPTER 1. INTRODUCTION

Electricity has become one of the main driven forces for development, especially in remote areas where lack of access to modern energy is linked to poverty. One of the main challenges of the international community is to minimize the inequality of energy services between OECD and developing countries. According to many different organizations, such as the United Nations [1.1][1.2], the World Bank [1.3] or the International Energy Agency [1.4], electricity provides the necessary framework for economic, social and human progress with deep effect on productivity, health, education, climate change, food and water security, and communication services.

In 2009, the number of people without access to electricity exceeded 1.3 billion, one-fifth of world's population, where 84% lives in rural areas and 3 billion rely on “traditional biomass” and coal as their main fuel source. According to the International Energy Agency (IEA) approximately 16% of the world population will still lack access to electricity in 2030 if no additional policies are introduced to alleviate energy poverty [1.5]. IEA projections from the universal modern energy access case study for 2010-2030 suggests that 60% of the additional capacity, and 63% of the investment budget, will be directed to mini-grids and off-grid systems [1.4], enhancing off-grid and mini-grid systems as the emerging solution to improve welfare and socio-economic development of small isolated communities, as islands and remote villages.

Figure 1.1 represents the expected world´s electricity map for 2035 in a business as usual (BAU) scenario. It may be easily observed the absence of electricity in many different world areas and the rapid energy development of emerging countries, such India and the east coast of China.



People around the world are cutting back their energy use, and you can too. Find out how »

Figure 1.1. Global Electricity Outlook for 2035 (Courtesy of National Geographic)

Recognizing the importance of energy within a sustainable development, the United Nations concluded during the General Assembly designating the year 2012 as the "International Year of Sustainable Energy for All" in order to raise awareness about the importance of increasing sustainable access to energy, energy efficiency, and renewable energy at the local, national, regional and international levels. This declaration established three main objectives to be accomplished by 2030: i) to ensure universal access to modern energy services; ii) double the global rate of improvement in global energy efficiency, and iii) double the share of renewable energy in the global energy mix.

Furthermore, International Energy Agency (IEA) has also estimated that basic electricity represents 17% of the overall global energy demand and is expected to increase to 23% by 2050 [1.5]. According to the IEA BLUE Map Scenario [1.5], electricity demand is expected to grow between 30% and 37% in OECD member countries from 2007 until 2050 compared to 104% to 509% in non-OECD regions in the same time period. Considering this expected massive growth, it is absolutely necessary to enhance policies and planning to guarantee a responsible and sustainable progress in electricity generation.

Developing countries should be able to learn from developed countries and take advantage of actual methodologies and technologies in order to pursue an environmental friendly future, while developed countries shall continue investigating in how to mitigate their accelerated energy footprint on climate change, basically by improving energy generation, transport, distribution and final use by new and more efficient technologies and processes up to reach in 2050 an scenario where to cover the same energy demand than nowadays with only 50% of primary energy consumption of the currently used resources. Nevertheless, these ambitious objectives could not be accomplished without an appropriate planning.

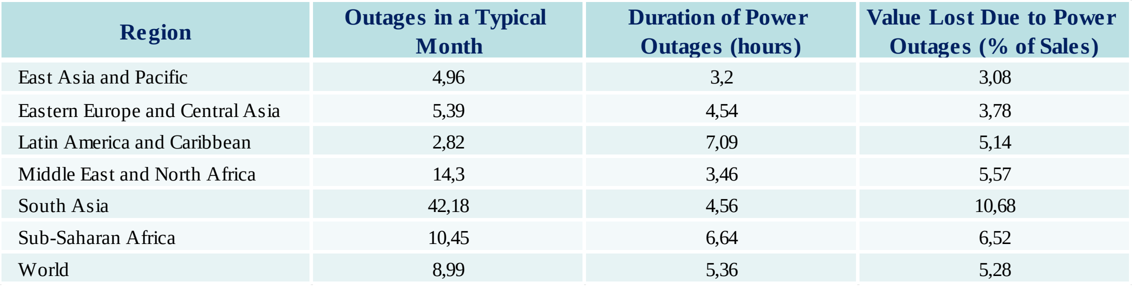
Energy-planning involves finding most convenient alternatives for energy system configuration to meet the energy requirements and demands of different tasks in an optimal manner. This implies analysing the resources available and studying the characteristic load profiles of the area.

An energy planning aiming towards a sustainable future requires a change of paradigm based on two main action lines: reducing, or at least maintaining at the current levels, the energy consumption rates and increasing renewables share in the energy mix. The first goal is mainly achieved by implementing energy efficiency measures and demand side management schemes, while the second one depends on local conditions, due to the necessity to assess the local renewable energy potential for electricity generation and, therefore, it should be tackled locally.

The utilization of renewable sources diversifies the energy supply mix, ensuring both energy security and sustainability. Global concern on climate change also justifies renewable energy utilization since it produces little or no emissions. For large, dispersed countries with vast rural areas, renewable sources can be utilized in a Distributed Generation System to generate electricity. Distributed Generation (DG) refers to the concept of generating electricity near the user, thus DG technology is considered as a promising alternative for electrifying geographically disadvantaged rural and remote areas [1.6].

This Dissertation introduces a novel Energy Planning Methodology for implementing Distributed Generation in non-connected area based on the combination of different renewable sources and demand strategies, such as demand-side management and energy efficiency measures.

Modern energy services are crucial to human well-being and economic development. As stated, approximately 20% of the global population does not have access to electricity and roughly 1 billion have only intermittent access. Frequent power outages are common in emerging and developing countries, lacking continuous electricity supply that reduces significantly the productivity of the local services and industry as it may be observed in Table 1.1.



Region	Outages in a Typical Month	Duration of Power Outages (hours)	Value Lost Due to Power Outages (% of Sales)
East Asia and Pacific	4,96	3,2	3,08
Eastern Europe and Central Asia	5,39	4,54	3,78
Latin America and Caribbean	2,82	7,09	5,14
Middle East and North Africa	14,3	3,46	5,57
South Asia	42,18	4,56	10,68
Sub-Saharan Africa	10,45	6,64	6,52
World	8,99	5,36	5,28

Table 1.1. Economic impact of electrical supply reliability

Electrification facilitates the economic and social development of a region by providing lighting, refrigeration and appliance power that would be difficult to replace with other forms of energy. Despite, electricity is not the only motor for economic development, it represents a key aspect to any society.

Electricity may be supplied throughout different energy sources. However, in contrast with traditional ones, such as fuel or coal, renewables are unlimited and cause limited damage to the environment. In fact, the rapid deployment of renewable energy technologies over the past years, and the wider projection over the near future, raise challenges and opportunities for their integration that should be taken into consideration in the strategies for energy planning and optimization methods.

Results of the methodology presented in this dissertation will demonstrate the economic and environmental benefits associated to combine different renewable technologies and demand side management to cover in a sustainable way the energy needs for isolated areas. This methodology facilitates the process of decision making to regulators, governments and technicians, by facilitating a common ground for Energy Planning of non-connected areas. It will also provide a method for identifying the most promising energy configuration system including the customer capacity to assist in the overall system operation as a way to increase the reliability of the electrical service.

1.1 Objective

The objective of this thesis is the definition and development of an Integral Energy Planning Methodology for isolated areas bringing together macro energy goals, the potential of renewable generation in isolated areas, customer's flexibility and socio-political aspects.

The methodology assesses the potential for energy generation with renewable energies, evaluating possible hybrid configurations, together with demand side management strategies. Besides, it analyses the available resources with potential for demand response actions for distributed generation and energy storage needs. In summary, this methodology optimizes the quality of energy services to non-connected areas from three main approaches: technical, economical, and sustainability.

To reach this general objective, the following specific tasks have been sequentially developed:

- Review of the actual methodologies and tools for Energy Planning applied to rural communities in remote or isolated areas.
- Review of distributed generation systems based on renewable energies.
- Characterization of electrical in non-connected communities and review of demand side management strategies.
- Review of different multi-criteria decision methods.
- Development of an energy planning approach based on scenarios using a bottom-up approach
- Definition of the protocol to evaluate the natural resources of isolated areas in order to determine their renewable energy potential for distributed generation.

- Development of a general procedure for the determination of actual electrical requirements of isolated areas, non-connected to the regional/national grid.
- Analysis of the actual Demand Side Management strategies implemented in non-connected areas.
- Review of Optimization Methods and Tools for minimizing the gap between the electrical requirements and the distributed generation based on renewable energies.
- Integrate a qualitative assessment of social and political aspects of the implementation of Hybrid Renewable Energy Systems (HRES) in a rural community using the Analytic Hierarchy Process (AHP).
- Development of an Integral Energy Planning Methodology bringing together macro energy goals, the potential of renewable generation in isolated areas, customer’s flexibility and socio-political aspects.
- Implementation of the methodology in a case study, representing the characteristics and needs of a specific isolated community.
- Verification of the methodology results in LabDER, the laboratory for Distributed Energy Resources located at the *Universitat Politècnica de Valencia*, by conducting experimental tests with a scalable prototype of a promising hybrid renewable configuration and analysing its operation and response to a simulated demand.

Figure 1.2 includes a diagram with the relations between the different activities that have been developed.

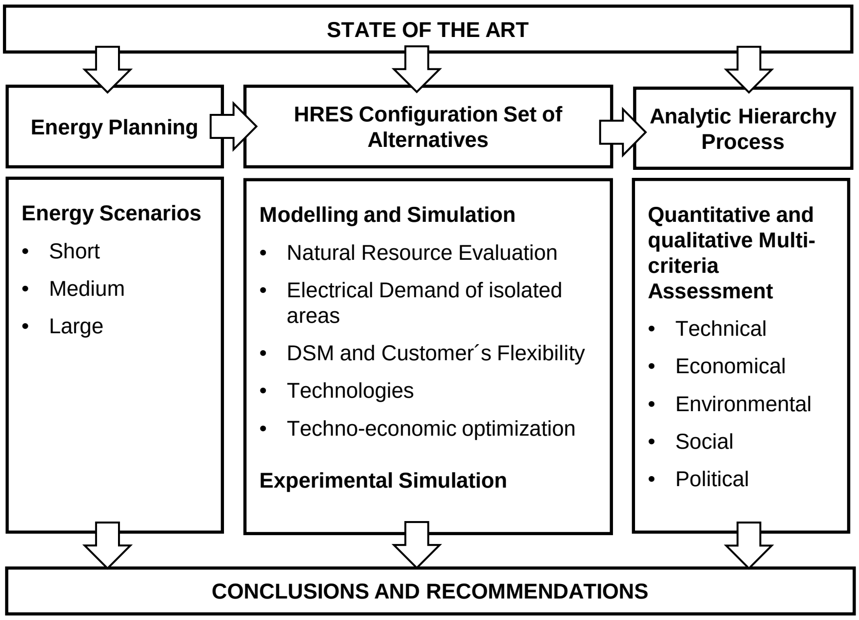


Figure 1.2. Overview of the Activities

1.2 Structure

This research has been achieved in five main stages, which relate to the chapters of this dissertation.

- **Chapter 1. Objective of the research**. This chapter introduces the main objective for the research project justifying its necessity and defining the different tasks to be addressed.
- **Chapter 2. State of the art**. This chapter includes a revision of the relevant bibliography and research work in energy planning, decentralized distributed generation, and multi-criteria decision methods for optimizing the process of decision making when qualitative and quantitative criteria are considered. The chapter also reviews the concept of demand side management and the strategies used in demand flexibility analysis.
- **Chapter 3. Methodology.** In this chapter, it is described the integral methodology for isolated areas electrification. Methodology is based in three main pillars: energy planning, identification of possible Hybrid

Renewable Energy Systems (HRES) configurations for isolated areas, and multi-criteria assessment of the several HRES configurations in order to identify the alternatives that fulfil not just the economic and technical criteria, but also environmental, social and political. In the Energy Planning section, it is described SIMESEN, the developed tool used for energy scenarios analysis. Then, the identification of possible HRES configurations is carried out using the software HOMER, which provides an optimise ranking of solutions according to their Net Present Cost. And finally, Multicriteria Assessment includes a description of the Analytic Hierarchy Process (AHP) and its application to HRES decision making process.

- **Chapter 4. Application to a Case Study.** This chapter provides an example of application of the methodology introduced in the previous chapter. A specific area in Republic Democratic of Congo is selected as a case study in order to validate the methodology. In addition, this chapter includes the experimental validation of the HRES configuration, operating a scalable prototype in LabDER at UPV. Experimental tests conducted in the laboratory are described and main results and conclusions are discussed.

- **Chapter 5. Conclusion and Recommendations.** Finally, this chapter includes main conclusions of this study and recommendations for future works in this area of research.

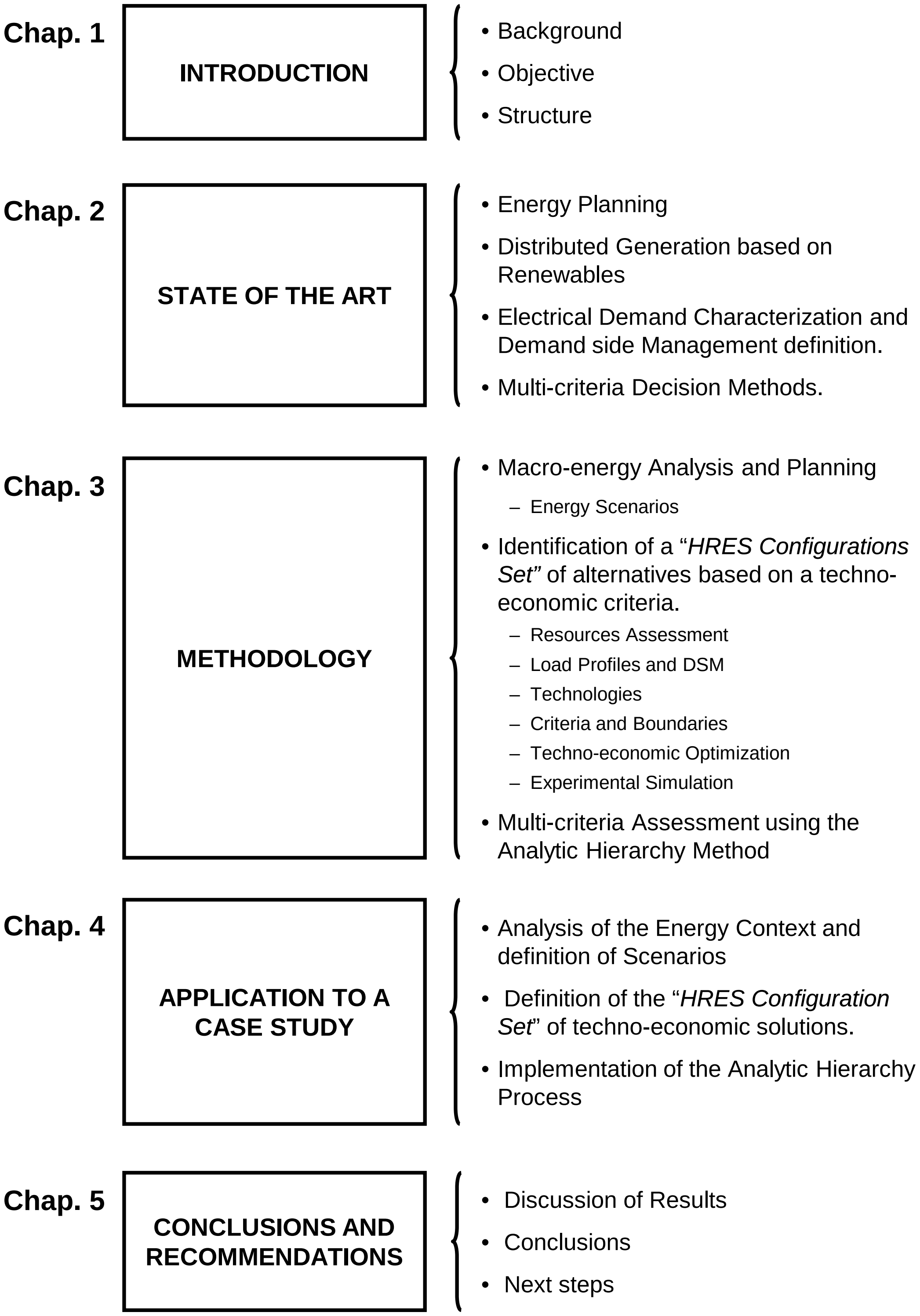


Figure 1.3. Structure of the thesis

1.3 Bibliography

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[1.6] A. Chaurey, M. Ranganathan et al. (2004). "*Electricity access for geographically disadvantaged rural communities: technology and policy insights*". Energy Policy, Vol. 32, pp.1693–1705.

CHAPTER 2. STATE OF THE ART

This chapter includes a revision of the relevant bibliography and research work in electrifying a remote community, revising the background and actual trends in the field. Literature review has focused in energy planning, decentralized distributed generation, demand side management and multi-criteria decision methods for optimizing the process of decision making when qualitative and quantitative criteria are considered. Next sections provide an overview and description of these main aspects related to hybrid renewable energies for non-connected areas.

2.1 Energy Planning

Energy Planning (EP) analyses the alternative paths for energy evolution of a region by studying different energy scenarios in three temporal ranges: short (1 to 10 years), medium (10 to approximately 30 years) and long term analysis (more than 30 years). Generally, it begins examining as a reference the actual scenario, named "*Business As Usual (BAU)*", and its evolution for the time span considered. Then, it compares the results from other different alternative scenarios under the same time span and demand constraints. Each energy scenario involves assessing and matching in an optimal manner the energy sources and their conversion with the energy requirements of different demand sectors (commercial, industrial, residential, etc.). Although, it may seem a simple idea, it becomes a complex problem in which various decisions and criteria converge, together with the existence of complex relationships between the different actors involved in the simulation process: generation, demand, emissions, economics, and technologies [2.1]. Models in energy planning are important in emerging communities and in developed urban areas, since they determine the energy path and goals for the next time period. Precise modelling requires large computational resources, thus a trade-off between exactness and resources needs to be balanced. In order to approximate reality with acceptable computational resources, models are based on certain hypothesis that tackle possible scenarios and casuistry, using estimations and assumptions which may or may not become valid under initial premises but that are unknown at the moment of modelling [2.2].

Traditionally, remote and non-connected areas do not use energy planning in their energy analysis due to their small size. Electrification plans normally follow simple schemes, implementing simple solutions based on one technology, the most suitable one depending on the available natural resource (solar radiation, wind, type of biomass residues, etc.) [2.3]. These schemes are mainly referred to stand-alone systems based on photovoltaic and/or wind configurations, storing the excess of energy in batteries and using private diesel generators as backup. However, this simple approach based on stand-alone systems do not take into consideration important factors, such as: energy needs of the population, potential flexibility of consumers, expected demand's growth and synergies between different renewable generation systems, which invites to analyse more in detail the different variables and relationships involved in energy planning from a new perspective, considering decentralized energy modelling and customer's participation.

2.1.1 Centralized versus Decentralized

Energy planning is normally analysed at a national scale with modelling tools based on a centralised approach. In this case, improving electrical access to remote communities is pursued by initial infrastructure investments in large power plants, such as coal, natural gas, nuclear, hydroelectric, photovoltaic and wind parks, aiming to take advantage of the economy of scale. However, cost reduction of small-scale technologies, such as solar panels or small wind turbines, has encouraged distributed generation. This is particularly attractive for isolated communities with relatively low consumption and difficult accessibility where grid expansion is very costly [2.4]. Furthermore, modern access to electricity involves a wider range of energy mix and demand strategies, enhancing energy valorisation of local resources in a decentralized approach. Along with this, energy planning should introduce decentralized models responding to the following aspects [2.5]:

- Develop novel methodologies for decentralized energy planning considering all environmental aspects.

- Enhance models of energy planning focusing on decentralized strategies.
- Literature's studies and projects in rural environment show that their implementation focuses only in one or two available energy resources.
- Increase the number of models integrating an optimum mix of renewable energies to meet the energy demand of remote areas. The objective of these models should be to explore the optimal matching of demand-supply paradigm with an important share of renewable sources.
- Use bottom–up approach in decentralized planning models to define energy demand and services to be met by supply technologies and energy resources at a regional/national level.
- Decentralized energy models should also be considered at a national level to assess the impact of decentralized planning, and enhance distributed generation based on renewable energies.
- Decentralized models should consider quantitative (i.e.: economic and technical) as well as qualitative (i.e.: social and political issues) aspects in order to guarantee a successful implementation in real cases.

2.1.2 Methods and Tools

Literature reviews show numerous tools for energy planning. The applicability and benefits of software tools in energy planning, which facilitate calculations and reduces processing time, is widely demonstrated. Tools allow comparing different alternatives in order to assess the advantages and disadvantages of each solution, assisting in the evaluation of different energy planning scenarios in a feasible time frame. In 2010, Connolly et al. [2.6] published a review of 37 computer tools for analysing the integration of renewable energy into various energy systems. A list of the revised tools is presented at the table below.

Tools for renewable energy analysis	
AEOLIUS: power-plant dispatch simulation tool	BALMOREL: open source electricity and district heating tool
BCHP Screening Tool: assesses CHP* in buildings	COMPOSE: techno-economic single-project assessments
E4cast: tool for energy projection, production, and trade	EMCAS: creates techno-economic models of the electricity sector
EMINENT: early stage technologies assessment	EMPS: electricity systems with thermal/hydro generators
EnergyPLAN: user friendly analysis of national energy-systems	energyPRO: techno-economic single-project assessments
ENPEP-BALANCE: market-based energy-system tool	GTMax: simulates electricity generation and flows
H2RES: energy balancing models for Island energy-systems	HOMER: techno-economic optimisation for stand-alone systems
HYDROGEMS: renewable and H2 stand-alone systems	IKARUS: bottom-up cost-optimisation tool for national systems
INFORSE: energy balancing models for national energy-systems	Invert: simulates promotion schemes for renewable energy
LEAP: user friendly analysis for national energy-systems	MARKAL/TIMES: energy–economic tools for national energy-systems
MESAP PlaNet: linear network models of national energy-systems	MESSAGE: national or global energy-systems in medium/long-term
MiniCAM: simulates long-term, large-scale global changes	NEMS: simulates the US energy market
ORCED: simulates regional electricity-dispatch	PERSEUS: family of energy and material flow tools
PRIMES: a market equilibrium tool for energy supply and demand	ProdRisk: optimises operation of hydro power
RAMSES: simulates the electricity and district heating sector	RETScreen: renewable analysis for electricity/heat in any size system
SimREN: bottom-up supply and demand for national energy-systems	SIVAEL: electricity and district heating sector tool
STREAM: overview of national energy-systems to create scenarios	TRNSYS16: modular structured models for community energy-systems
UniSyD3.0: national energy-systems scenario tool	WASP: identifies the least-cost expansion of power-plants
WILMAR Planning Tool: increasing wind in national energy-systems	
(CHP*: combined heat and power.)	

Table 2.1. Tools for analysing renewable energies in energy systems

Reviewing actual tools, it is highlighted the use of EnergyPLAN. and LEAP as user friendly software for detailed analysis of national energy systems.

EnergyPLAN [2.7] is a computer tool developed by the Department of Development and Planning at Aalborg University (Denmark). It provides hourly simulation of complete regional or national energy systems including electricity, individual and district heating/cooling, industry and transportation. It facilitates the design and evaluation of sustainable energy systems using a mix of renewable and fossil energy sources [2.8]. General inputs are demands, renewable energy sources, energy plant capacities, costs and a number of optional regulation strategies emphasizing import/export and excess electricity production. Outputs include energy balances and resulting annual production, fuel consumption, import/exports and total costs including income from the exchange of electricity [2.9]. EnergyPlan has been implemented in numerous research publications, analysing different scenarios, such as Jayakrishnan et al. [2.10] who presented in 2008 a comparative analysis of hourly and dynamic power balancing models for validating future energy scenarios based on a feasible technology mix for a higher share of wind power. EnergyPLAN optimizes the operation of a given system during one year rather than tools which optimize the investment and O&M costs, reducing any procedures which would increase the calculation time.

LEAP, (Long range Energy Alternatives Planning system) is a widely-used software tool for energy policy analysis and climate change mitigation assessment. It was developed in 1980 in USA and is currently maintained by the Stockholm Environment Institute [2.11]. It is an integrated modelling tool used to evaluate energy consumption, production and resource extraction in all sectors of an economy in a certain scenario. LEAP has been implemented in many regions with published results, such as California [2.12], Venezuela [2.13], Korea [2.14] and [2.15], Bangkok [2.16], Thailand [2.17] and Lebanon [2.18], among others. On the demand-side, LEAP implements the bottom-up approach in the definition of energy consumption at the different sectors and top-down macroeconomic modelling. On the supply side, it provides a technology database for energy generation modelling and capacity expansion planning, but it does not support optimisation.

2.2 Distributed Generation

Decentralized Distributed Generation (DDG) systems, including small, geographically dispersed sources of electricity generation from Renewable Energy Technologies (RETs), are emerging as viable alternatives to grid supplied electricity for isolated regions. These technologies are particularly suited for areas which have low demand for electricity. DDG systems range from a few kilowatts to tens of megawatts, producing power locally with the goal of providing electricity to the nearby populace. Grid losses, which are intrinsic to centralized power generation, are minimized in this scenario since DDG systems are typically located near the demand. The implementation of DDG systems in areas without electricity has also additional benefits, such as job creation and increased standard of living. DDG may serve reliable power near the demand area, independently from the grid, while reducing environmental impacts [2.19].

Traditionally, DDG electricity has been achieved using Diesel generators, LPG, disposable batteries, paraffin (or kerosene) and biomass technologies. However, actual considerations in sustainability have encouraged emerging countries to focus in energy technologies such as renewables, including cleaner bioenergy applications. Nevertheless, diesel generators remain an attractive technology in rural electrification, mainly used in hybrid systems [2.20] due to its wide implementation.

Two different approaches can be found in the technical literature, these are based, respectively, in the implementation of single systems or of hybrid ones. In the first case, the objective is to provide energy whenever is possible while, in the second case, the system should also guarantee the feasibility of such energy production.

2.2.1 Stand-alone systems

Stand-alone systems are off grid solutions composed by a single energy technology supported by a storage system. The most widely used renewable energy technologies for rural electrification are solar photovoltaic, wind and bioenergy, using as backup batteries storage and/or diesel generator.

Photovoltaic (PV), together with batteries, is the most common configuration use in rural electrification for places located in remote communities. In developing countries, it is estimated that approximately 500.000 to 1 million rural households, lacking access to the grid, are electrified with this type of configuration [2.21]. It is particularly attractive for areas with significant solar radiation and whose rural electricity grid is poorly developed. PV systems can provide decentralized electricity near the demand, which reduces the cost of electrical losses in distribution. The most common systems used in rural areas in developing countries are solar home systems (SHS), which have the potential to power light bulbs and small appliances such as televisions, radios or fans. Generally, the capacity of the units used in rural households ranges from 30 to 100 peak watts, but their size varies [2.22]. However, because of the system limited capacity, mechanisms are often needed to prevent excessive consumption by users. Currently, there is a move towards solar-diesel hybrid-powered mini-grids.

Wind energy has a very high potential for rural electrification, especially in remote and windy areas. However, its intermittency obliges using this resource to supply deferrable demands (i.e.: pumping) or having a battery bank capable to absorb its erratic generation mode and supply electricity when necessary. In rural settings, wind energy does not necessitate large power plants or complex centralised planning for its development as it is fast and simple to install. Successful examples of rural electrification based on wind power are in areas with high wind resource, which makes this renewable energy among the most cost-effective power plants to install and operate.

Bioenergy is still the main source for heating and cooking in developing countries. However, biomass can also generate electricity when crops or forest residues are available at a reasonable distance. Small-scaled biomass systems are based on combustion (heat) and gasification (electrical) for local use. Gasification systems are electric generation systems that can be used as primary source or back-up system in renewable hybrid systems. This is because biomass can be easily stored prior its use, but it requires large area for drying and storing. Besides, small-scaled gasifiers need personnel to be operated, which promotes local employment. In general terms, bioenergy provides local development since it uses nearby biomass residues, activates local employment and promotes an economic development.

2.2.2 Hybrid Renewable Energy Systems

Nowadays, energy demand of a remote area is usually met from locally available renewable energy sources like solar, wind, hydro or biomass micro plants. The solution for electrifying an area in usually single-system based, however an analysis of the synergy between renewables should also be included in order to reduce costs and increase reliability of energy supply. Hybrid Renewable Energy Systems (HRES) provide benefits such as energy efficiency, minimization of energy storage requirement, or/and increment of reliability of power supply and power quality.

In addition, HRES avoid fluctuations in the system’s energy supply, which is the main disadvantage of stand-alone renewable energy technologies such as wind and PV.

HRES provide a relatively constant delivery of energy even when one of the supply devices of the system is unable to generate power (lack of wind in the case of a windmill or of sunlight in the case of a PV) by optimizing the synergy between the different renewable technologies and storage systems. Typical hybrid systems are photovoltaic/wind systems, wind/diesel systems, wind/photovoltaic/micro hydropower systems, wind/small hydropower and so forth. The selection of the energy technology mix to use for isolated electrification depends on the climatic conditions (natural resources availability) and load characteristics, whether the energy produced is required for lighting or cooling purposes in a single household, productive processes (irrigation pumping, water supplies, crop processing, refrigeration, etc.) or commercial businesses, such as small shops, etc.

Combining renewable energy sources with back-up units in renewable hybrid systems may provide an economic, environmental and reliable supply of electricity for power demand at isolated regions. Several research works have demonstrated the suitability of decentralized distributed generation for electric supply of these regions. In 2012, Enric et al. [2.23] provided a detailed literature study of HRES size optimization to extend renewable energy penetration in a developing region. The study concluded that among all possible hybrid system configurations that are optimally dispatched, the configuration with the lowest “Net Present Value (NPV)” is declared as the “optimal configuration” or the “optimal design” [2.24] and [2.25]. During the same year, Bajpai et al. [2.26] presented a comprehensive review on HRES design methods over the past decade, focusing on unit sizing and optimization, modelling of system components and optimal energy flow management strategies. In this literature review, the authors concluded that HRES has an immense potential to meet the load demand of remote, isolated sites while supplying uninterrupted power at zero emission level.

Furthermore, in 2014, Neves et al. [2.27] reviewed several projects developed in different micro-communities, small islands and remote villages, with real implementation and evaluation studies. The study mapped the state of the art of HRES in isolated micro-communities and remarks the increasing interest for HRES in the world, as a way to provide sustainable energy independence for small communities and the use of methodologies to design the energy systems of isolated micro-communities.

The techno-economic analysis of the hybrid system is essential for the efficient utilization of renewable energy resources. Due to multiple generation systems, hybrid system analysis is quite complex and requires a detailed analysis. This requires software tools for the design, analysis, optimization, and economic viability of the systems. Turcotte et al. [2.28] classifies HRES software tools in four categories: pre-feasibility, sizing, simulation and open architecture research tools. According to the authors, the prefeasibility tools are mainly used for initial sizing and a comprehensive financial analysis, such as the tool RETScreen [2.29]. Sizing tools, like HOMER [2.30], facilitate the determination of optimal size of the elements and provide detailed information about energy flows among various components, while in simulation tools the user has to specify the details of each component in order to get the detailed behavior of the system. An example may be the tool HYBRID2 [2.31]. Finally, the authors introduce the open architecture research tool, where the user is allowed to modify the algorithms and interactions of the individual components (for example, TRNSYS [2.32]).

In fact, the application of these tools to specific cases is widespread in the literature. Klise and Stein [2.33] described various PV performance models with battery storage. Arribas et al. [2.34] carried out a survey of ten existing software tools based on the availability, features and applications and presented guidelines and recommendations in an International Energy Agency (IEA) report. Connolly et al. [2.35] surveyed 37 computer tools for integration of energy systems analysis. This study provided information for analysing the integration of renewable energy into different objective based energy-systems. Ibrahim et al. [2.36] described the design and simulation models of hybrid systems composed by wind–diesel systems for remote area electrification. Bernal-Agustin and Dufo-López [2.37] revised the simulation and optimization techniques, as well as the existing tools used for stand-alone hybrid system design. Zhou et al. [2.38] applied HOMER, HYBRID2, HOGA [2.39] and HYBRIDS [2.40] for evaluating hybrid solar–wind systems performance. Finally, Sinha et al. [2.41] carried out a review study of 19 actual software tools for HRES modelling, analysing their main features and applicability.

In summary, there is an extensive research activity in the development of software for HRES simulation, aiming to optimize the design based on efficiency and economical parameters. Along the literature, it has been identified 19 applications, 4 of which are open access, but most popular and used software is HOMER. All systems present limitations based on the selected approach that may restrict its application range. Required improvements are: a) include a wider range of renewable and conventional energy sources and storage systems; b) introduce the possibility of demand-side management strategies; c) incorporate the use or modification of control strategies with full customization; d) improve the usability of applications, and e) perform benchmarking of different applications in a wide range of configurations.

2.2.3 Control Strategies

In addition to modelling HRES's components and behaviour, it is also necessary to define a control strategy in order to supply energy in a reliable manner. Energy system components may be optimized working together as a system, defining how energy flow should be distributed. At any time, the control system may determine which energy of the different generators should be on/off, where the excess of energy should be stored and which element should supply the demand. These aspects are optimized based on the climatic variables (radiation, wind, etc.), load requirements (AC/ DC) and the state of charge of the storage systems (batteries, gas of synthesis tank, water deposit, etc.)

In 1995, Baeley et al.[2.42] proposed several dispatch strategies for remote PV-Diesel hybrid systems with batteries, considering calculations for 1 hour intervals and ideal batteries behaviour (influence of life cycling was not considered). A year later, Baeley et al. [2.43] improved the model considering additional parameters such as the battery's state of charge (SOC) and the critical discharge/charge load (Ld/Lc), refining the initial dispatching approach. These improved control strategies are in used today, being the basis for important studies and tools, such as HYBRID2 or HOMER. Every hour it is checked if the non-dispatchable renewable power sources, which produce power in direct response to the renewable source available and are limited to climate conditions, may supply the required electric load to the customers. This is defined as the net load. If not, it determines the most convenient way to respond the demand with dispatchable components, such as other generator (diesel, gasification plant), storage systems (battery bank, water tank, deposit of hydrogen) or the grid (when available).

Proposed dispatching strategies are Load Following, Full Cycle Charging, Combined Strategy and Predictive Control.

Under the **Load Following** strategy, the diesel generator produces only enough power to serve the load and does not charge the batteries. If the batteries cannot meet the net load, the Diesel generator operates at a rate that produces only enough power to meet the net load. The batteries are then charged whenever the renewable power exceeds the demand, but they are not charged by the Diesel generator.

In the case of **Full** C**ycle Charging**, whenever the generator operates it runs at its maximum rated capacity, follows the load profile and charges the battery bank with the excess. If a SOC set point is applied, the Diesel generator will continue running until the batteries reach this SOC set point.

Next, it is defined the **Combined strategy**, introducing the concept of Critical Charge Load (Lc), which refers to the net load where the cost of generating with Diesel for 1 h is the same as the cost of supplying this load from the batteries, which were previously charged by the Diesel generator. Thus, if the net load is lower than the Critical Charge Load, Lc (kW), the cycle charging strategy is applied, while if the net load is higher than Lc the load following strategy is applied.

Finally, under the **Predictive** strategy, the bank of battery is charged based on the forecasted demand and renewable generation. This strategy reduces energy surplus from renewable sources, however it requires good predictions, which in reality this information always involves certain uncertainty.

Revising related literature, one of the most important factors for optimizing HRES operation is economic. Generally, HRES are optimized based on supplying power economically; however, there exist other objectives such as reliability or renewable contribution to the mix that are also considered. The problem of deciding how power supplies are shared among generators in a system in the most economic manner has been studied extensively and various control strategies have been developed and applied. R. Dufo-Lopez et al. [2.44] and [2.45] introduced a control for stand-alone HRES with battery storage, optimized by genetic algorithm. Then, J. L. Bernal-Agustin and colleagues presented a strategy, optimized by evolutionary algorithm. The design optimized the configuration of the system as well as the control strategy to simultaneously minimize the total cost through the useful life of the installation and the pollutant emissions [2.46]. Vlleberg [2.47] described control strategies of PV-hydrogen based hybrid systems using fuel cell, depending on the value of state of charge (SOC) of batteries. Similarly, Kolhe et al [2.48] analyzed a renewable energy system with hydrogen as a long term energy storage source and a battery bank for a short-term, where the energy management is also controlled through the SOC of the batteries. Gao et al. [2.49] and Jiang et al. [2.50] presented control strategies for hybrid fuel cell/battery system, while Jeong et al. [2.51] introduced a fuzzy logic algorithm for determining the fuel cell output power depending on the external power requirement and the battery state of charge (SOC). However, in this paper power management strategies between power sources have been focused on rule-based strategies.

2.3 Electric Demand in Isolated Areas

2.3.1 Demand Characterization

Isolated areas refer to regions lacking electricity supply. These non-connected communities are normally located at a reasonable distance from national or regional electricity grids (i.e.: remote villages in the Amazon), have difficult geographical access (islands, communities with a difficult terrain such as large rivers or jungles) and/or may suffer severe climatic conditions that limit electrification through grid extension.

Demand characterization of an isolated area depends on various factors: geographical location, population, economic activity, annual demand and demand growth rate, etc. The location is important to determine the electrical demand patterns since they highly relate to geographical site and cultural habits. Population provides information on how demand per capita differs from region to region, while economic structure represents the economic activities of the community, such as farming, fishing and agriculture (primary sector); industry (secondary sector); and tourism and services (tertiary sector).

Isolated communities are generally distinguished between islands and remote villages. Islands normally represent communities with higher energy demand and potential use of natural resources for electrical generation and storage; while remote villages include communities that may or may not be geographically isolated, therefore have the possibility of grid-connection in some cases.

Islands with higher energy demand per capita are generally located in developed countries with an important economic activity based on tourism, whereas islands with lower energy consumption are found in developing countries where primary economic activities are farming, fishing or agriculture. Thus, electricity demand varies by continent. Annual electricity per capita demanded by European islands is in the range of 1000 - 14000 kWh/capita/year, which shows significant differences in energy needs based on its geographical, cultural and economic heterogeneity. Asia and Oceania present smaller electrical demand with a range of 30 - 4000 kWh/capita/year and 200 - 7500 kWh/capita/year, respectively, depending if islands are isolated by the ocean or connected to the main country with access to services and goods. North America’s islands are the ones with highest electrical demand, ranging from 5000 - 8000 kWh/capita/year, depending if they are located in the Caribbean areas or Northern States, mainly depending on their economic activities (i.e.: tourism) [2.27].

Remote villages represent communities with an economic activity destined to subsistence. These communities are normally highly dispersed with a low population density and characterized by a low level of education, low load density generally concentrated at evening peak hours, and low revenues. Adding to these challenges, rural communities without access to electricity either spend relatively large amounts of their scarce financial resources on energy or a disproportionate amount of time collecting firewood. Electrification leads to more productive processes, growth of businesses and farms using electricity, which creates an increment of demanded electricity over the years that needs to be planned in advance in order to maintain a sustainable development. Remote communities are not necessarily geographically isolated as island; therefore, the possibility of grid connection always exits. They normally represent areas with difficult accessibility, where most communities are not connected to electric grid and, when they are, the connection quality and service is very low. Characterization of the electrical needs of these villages is very difficult due to the lack of systematic data collection; information is mainly gathered by specific stationary studies based on surveys. Considering energy demand per household, South America presents an approximate value of 115 kWh/ household /year, while remote communities in Asia demand a range of 365 to 705 kWh/ household /year, except Iran, with a value of 5278 kWh/ household /year due to heating demand in the cold climate close to the mountains. In the case of Africa, previous projects and studies show values oscillating between 79 and 2200 kWh/ household /year. In summary, villages with 100 households or more present a limit of 2200 kWh/ household /year, while villages under 100 households have 1200 kWh/ household /year as upper limit of the range [2.27].

Comparing islands and remote islands, main difference derives from the existing economic activity and the natural resources available, which determines the energy needs and renewable power capacity of supply. Regarding the energy production system used, large islands are mainly supplied by Diesel Power Plant Generators and Photovoltaic - Wind – Diesel configurations, seeking for high reliability. Remote islands with low demand use decentralized energy supply based on private generation units, mainly Diesel and/or Photovoltaic, but it is also common to find renewable combinations of wind, solar photovoltaic and biomass in areas of difficult access, supported by a battery bank as back-up.

	Islands	**Remote villages**
Economic activities	Tourism and primary activities such as fishing, farming and agriculture	Subsistence
Demand range	-Depends on the economic activity (tourism), natural resources available, cultural habits [ranges from 111 to 754.000] MWh/year. -Higher peak demand – 24 h needs	-Depends on the geographical location and natural resources availability [ranges from 1,3t o 245,3] MWh/year. -Mostly requested only on evening hours
Possibilities for Grid connections	Very costly or impossible to become connected to mainland grid	Possibility of becoming connected to the grid, but normally the access is difficult and climate is severe.
Most common hybrid system configuration	Wind/Photovoltaic/Diesel power plant	Photovoltaic/Private diesel generator/Batteries
Common backup system	Diesel power plant (existing supplier and sub dimensioning of renewable systems) – more reliable	Batteries
Renewable penetration	Up to 80% for yearly demands lower than 20.000 MWh	Up to 100% for yearly demands lower than 2.000 kWh/household
Economic Sustainability approach	-Public/private partnership for large investment and Private investment for low demand areas. Rural electrification projects just for demonstration (do not cover all population needs) -Backup technologies are costly but necessary due to renewable intermittency. Sustainable in long term analysis.	
Social perspective	-Most successful projects of electrification involved the participation of the population in the decision process and system's operation. -Educational and Social status increases with electrification in remote villages.	

Table 2.2. Demand comparison between islands and remote villages [2.27].

2.3.2 Demand Side Management

Energy demand side management (DSM) corresponds to the term used for managing energy consumption at the consumer side. It implies taking actions to influence the time and quantity of energy used by the customers. These actions normally aim to reduce peak demand during energy supplied constraints by either, decreasing total energy use or shedding the loads to a more convenient time

The use DSM strategies in power sector have evolved significantly during the past 20 years. During the fossil-fuel shortages and energy price increment in the 70s, different governments in Europe and USA activated DSM programs for customer participation [2.52]. These programs aimed to manage peak demand in order to mitigate new generation capacity. Following to this approach, new regulatory initiatives were developed that required an Integrated Resource Planning (IRP) to provide capacity expansion and tariff approach.

Electrical generation at Isolated Areas are based on natural resources, which are non-continuous and difficult to predict, thus it is required the use of back-up systems to increase reliability of the global system, such as battery banks or diesel generator systems; however, these systems carry other environmental problems, such as the disposal after use, in the case of the batteries, or the use of a contaminant fuel as diesel. DSM strategies can significantly benefit the global HRES by alleviating daily peaks and filling load curve valleys to obtain a better fit between generation and demand curves [2.53].

Main objective of demand-side management in isolated areas is to relieve daily peaks and valleys in electric demand to maximize the efficient use of energy resources and to defer the need of installing additional power capacity. This may entail shifting energy use to off-peak hours, reducing overall energy requirements, or even increasing demand for energy during off-peak hours.

There are four basic DSM strategies as describes below [2.54]:

Peak Clipping. The peak clipping strategy seeks to reduce energy consumption at the time of the daily demand peak (about 7 p.m.). DSM programs which reduce peak load are generally performed by the utility or customer controls on appliances such as air conditioning or water heating. Timers for water heaters are a good example of this.

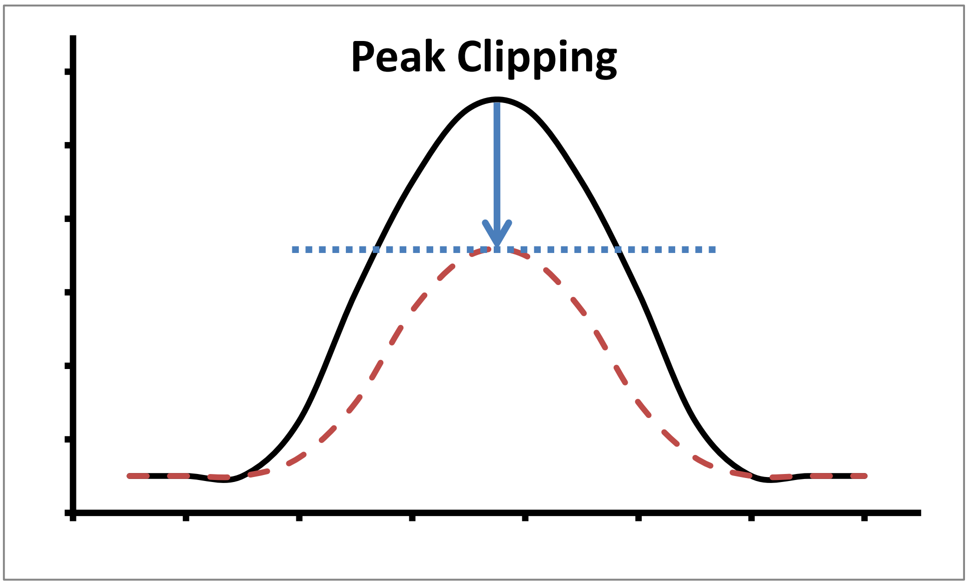

Figure 2.1. Peak clipping strategy

Valley Filling. The goal of valley filling is to build up off-peak loads in order to smooth out the load and improve the economic efficiency of the utility. An example of valley filling is charging electric vehicles at night when the utility is not required to generate as much power as during the day.

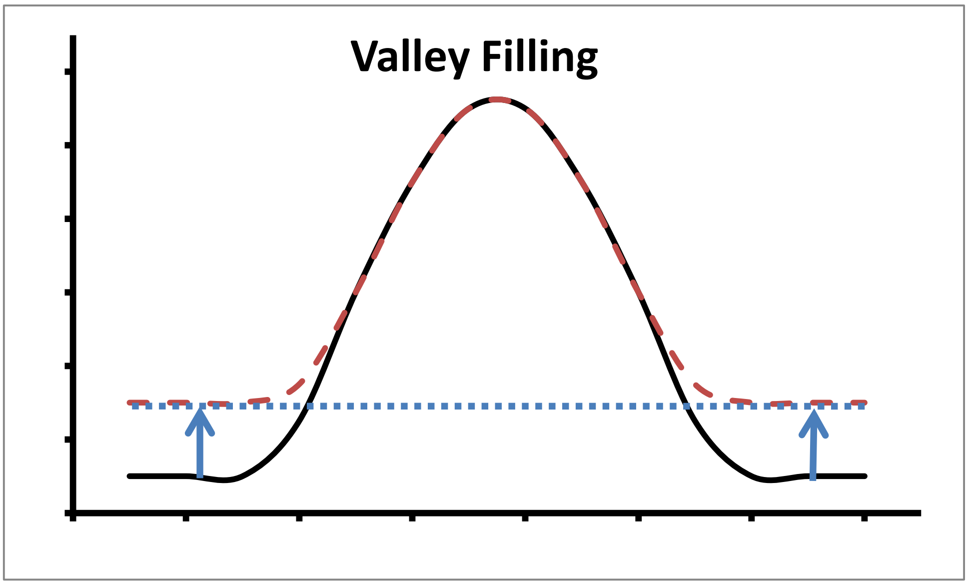

Figure 2.2. Valley filling strategy

Load Shifting. The shift in the time a load is connected is a strategy which could be accomplished through measures such as thermal storage. Thermal energy storage enables a customer to use electricity to make ice or chilled water late at night when overall electricity consumption is low. The ice or chilled water is then used to cool the building by day when overall electricity consumption is high.

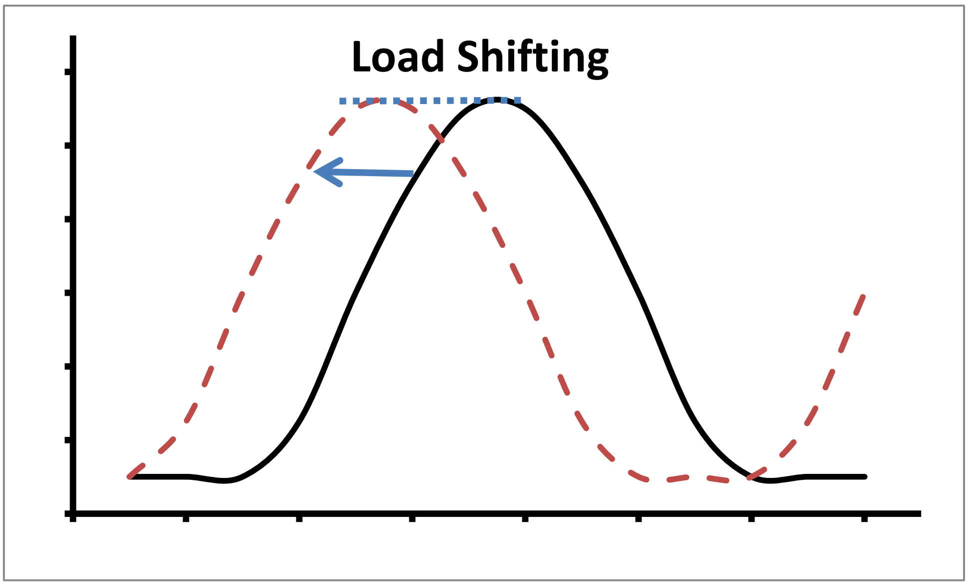

Figure 2.3. Load shifting strategy

Conservation. Conservation is the best known strategy, it involves reducing the entire energy load.

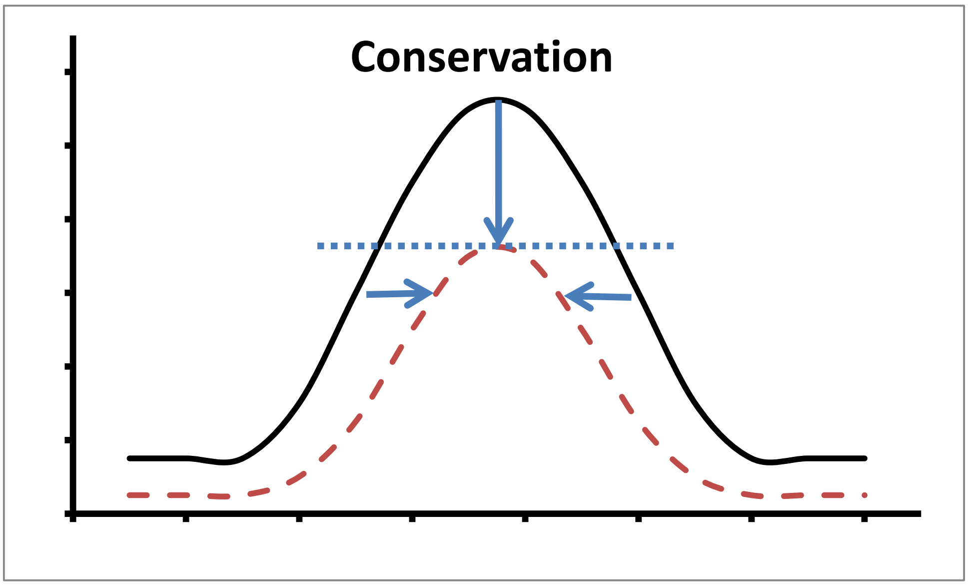

Figure 2.4. Conservation strategy

There are many DSM technologies and measures which are used by utilities to implement these four strategies. These include energy efficient appliances, time of-use rates, interruptible rates, and many other measures which are currently under study by many DSM research institutes. Demand-side-management is a concept widely used in literature; however, it has not been applied in detail to reinforce rural electrification in remote areas. Understanding the potential of demand flexibility in isolated regions may play a key role in the reduction of unpredicted electricity shortage or renewable generation uncertainty. In 2013, Kazemi et al [2.55] proposed a decentralized energy planning where, for the first time, supply-side and demand-side options were treated equally. Main conclusion of the paper is that it is worth pointing out that DSM alternatives have almost the same importance than the energy supply technologies for the system planning.

2.4 Multi-criteria Decision Methods

Multi-criteria analysis is used to select the ‘‘best fitted’’ solution from multi-attribute distinct options in a multi-dimensional space of different indicators and objectives. The use of multi-criteria decision analysis techniques provides a reliable methodology to rank alternative energy solutions for rural communities, considering renewable energy resources, technologies, demand and environmental impact.

Multi-criteria decision models (MCDM) [2.56] is a branch of operation research models in the field of decision-making. These methods tackle both quantitative as well as qualitative criteria and analyse conflict in criteria and decision making [2.57]. Several classification and categorization exist but in general these methods can be divided into two main categories [2.58]: multi-objective decision-making (MODM) and multi-attribute decision-making (MADM). In MODM, the decision problem is characterized by the existence of multiple and competitive objectives that should be optimized against a set of feasible and available constraints [2.59]. MADM is one of the most popular MCDM methods to be adopted to solve problems with different perspectives [2.60]. They contain several different methods, but the most important are:

Analytic hierarchy process (AHP), Preference Ranking Organization METHod for Enrichment Evaluations (PROMETHEE), ELimination Et Choix Traduisant la REalité (ELimination and Choice Expressing REality or more commonly—ELECTRE), and Multi-attribute utility theory (MAUT) [2.61].

The comparison of MCDM methods related to renewable energy planning is widely discussed in the literature. Pohekar´s analysis [2.57][2.62] showed that multi-attribute utility theory (MAUT) was the most common MCDM method used in energy planning bibliography, including WSM, WPM, AHP, PROMETHEE, ELECTRE, MAUT, fuzzy methods and decision support systems (DSS). The main objective of MADM is to select the alternative that has the highest score according to the set of evaluation criteria.

A descriptive summary of the most commonly used multi-criteria decision-making methods is presented below:

- **Weighted sum method (WSM)** [2.63]: is the most commonly used approach, especially in single dimensional problems If there are m alternatives and n criteria, then the best alternative is the one that satisfies the following mathematical expression:

$$A^{*}{}_{WSM} = Max \sum_{i}^{j} a_{ij} w_j \;\; for\; i = 1,2,3, \dots M \qquad \textbf{\textit{(2.1)}}$$

Where: $A^{*}{}_{\mathrm{WSM}}$ is the WSM score of the best alternative, M is the number of decision criteria, a_{ij} is the actual value of the i^{th} alternative in terms of the j^{th} criterion, and w_j is the weight of importance of the j^{th} criterion. The total value of each alternative is equal to the sum of products. Difficulty with this method emerges when it is applied to multi-dimensional decision-making problems. Combining different dimensions, and consequently different units, the addition assumption is violated [2.64].

- **The Weighted Product (WPM)**: is similar to WSM. The main difference is that instead of addition in the model there is multiplication. Each alternative is compared with the others by multiplying a number of ratios, one for each criterion. Each ratio is raised to the power equivalent to the relative weight of the corresponding criterion. In general, in order to compare the alternatives A_K and A_L the following product is obtained:

$$R\left({}^{A_K}\!/_{A_L}\right) = \sum_{j=1}^{N}\left({}^{a_{kj}}\!/_{a_{Lj}}\right)^{w_j} \tag{2.2}$$

  Where $N$is the number of criteria, a_{ij} is the actual value of the i^{th} alternative in terms of the j^{th} criterion, and w_j is the weight of importance of the j^{th} criterion. If $R\ (A_K/A_L)$ is greater than one, then alternative A_K is more desirable than alternative A_L (in the maximization case). The best alternative is the one that is better than or at least equal to the rest of alternatives[2.65].

- **Analytic Hierarchy Process (AHP)**: A MADM method was first introduced by Saaty [2.66]. In AHP, the problem is constructed as a hierarchy breaking down the decision top to bottom. The goal is at the top level, criteria and sub-criteria are in middle levels, and the alternatives are at the bottom layer of the hierarchy. Input of experts and decision makers is considered as pair-wise comparison, while output responds to a ranking with the alternatives.

- **Analytic Network Process (ANP)**: The ANP methodology is a general form of the AHP, both introduced by Saaty[2.67]. Although AHP is easy to use and apply, it cannot handle the complexity of more than one process. ANP, however, deals with the problem as a network of complex relationships between alternatives and criteria where all the elements can be connected.

- **Preference ranking organization method for enrichment evaluation (PROMETHEE)**: This method ranks the alternatives and performs a pair-wise comparison of alternatives in order to classify them with respect to a number of criteria. Up to now, the family of PROMETHEE have included PROMETHEE I & II [2.68].

- The **elimination and choice translating reality** (**ELECTRE**): This method handles discrete criteria of quantitative and qualitative constraints, providing a classification of the alternatives. The analysis is focused on the dominance relations between alternatives. It is based on the outranking relations hips and exploitation notions of concordance. The outranking method uses pair-wise comparison between alternatives [2.69]. The family of ELECTRE includes ELECTRE I, II, III, IV.

- The **technique for order preference by similarity to ideal solutions** (**TOPSIS**): The basic concept of this method is that the selected alternative is the one that has the best value for all criteria, i.e. has the shortest distance from the negative ideal solution [2.70].

- **Multi-attribute utility theory (MAUT)**: This is one of the most popular MSDM methods. The theory takes into consideration the decision maker's preferences by defining a set of attributes, where the utility of each attribute or criterion does not have to be linear [2.71].

In general, MCDM methods have four basic steps that support making the most efficient, rational decisions:

- Structure the decision process, alternative selection and criteria formulation.
- Display trade-off among criteria and determine criteria weights.
- Apply value judgment concerning acceptable trade-offs and evaluation.
- Calculate final aggregation and make decision.

2.5 Conclusions

State of the art review of research studies in decentralized planning, electrification of isolated areas and multi-criteria analysis, together with the exploration of projects for electrifying remote communities with renewable energies, reveals a significant effort carried out by the scientific community in the last years. It also denotes the noteworthy interest in the different aspects associated to remote electrification of communities: software development for decentralized planning, including HRES; strategies for HRES control to maximize demand coverage; integration of demand side management, optimization of design system's operation to respond different demand profiles; multi-criteria approaches. However, all these scientific and technical works deal with specific issues of the challenge, but it has not been identified in the literature a global methodology for HRES optimization considering decentralized planning and multi-criteria assessment of quantitative and qualitative aspects of the project, which are key in the success of real implementation projects.

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CHAPTER 3. METHODOLOGY

Renewable Hybrid Systems are one of the most promising approaches for non-connected areas with significant difficulties to be connected to the electrical distribution network. In addition to this, distributed generation resources also enhances the properly integration of different energy resources in order to maximize the coverage of the demand energy needs and facilitate the operation of such mini grids with specific problematic.

Nowadays, it exists many different software that tackle this issue, such as the popular HOMER or HYBRID2, however, none of them take into consideration the demand flexibility in the system nor a multi-criteria approach, taking into consideration qualitative assessments (social and political), and therefore the benefits associated to these aspects have not been properly analysed nor assessed.

In order to tackle this issue, research objectives should include:

1) Energy Planning
2) Identification of best techno-economic HRES configurations
3) Multi-Criteria Analysis
4) Ranking of Best HRES solutions

Figure 3.1 summarises the Integral Methodology for Isolated Electrification developed in this study in order to fulfil the abovementioned research objectives.

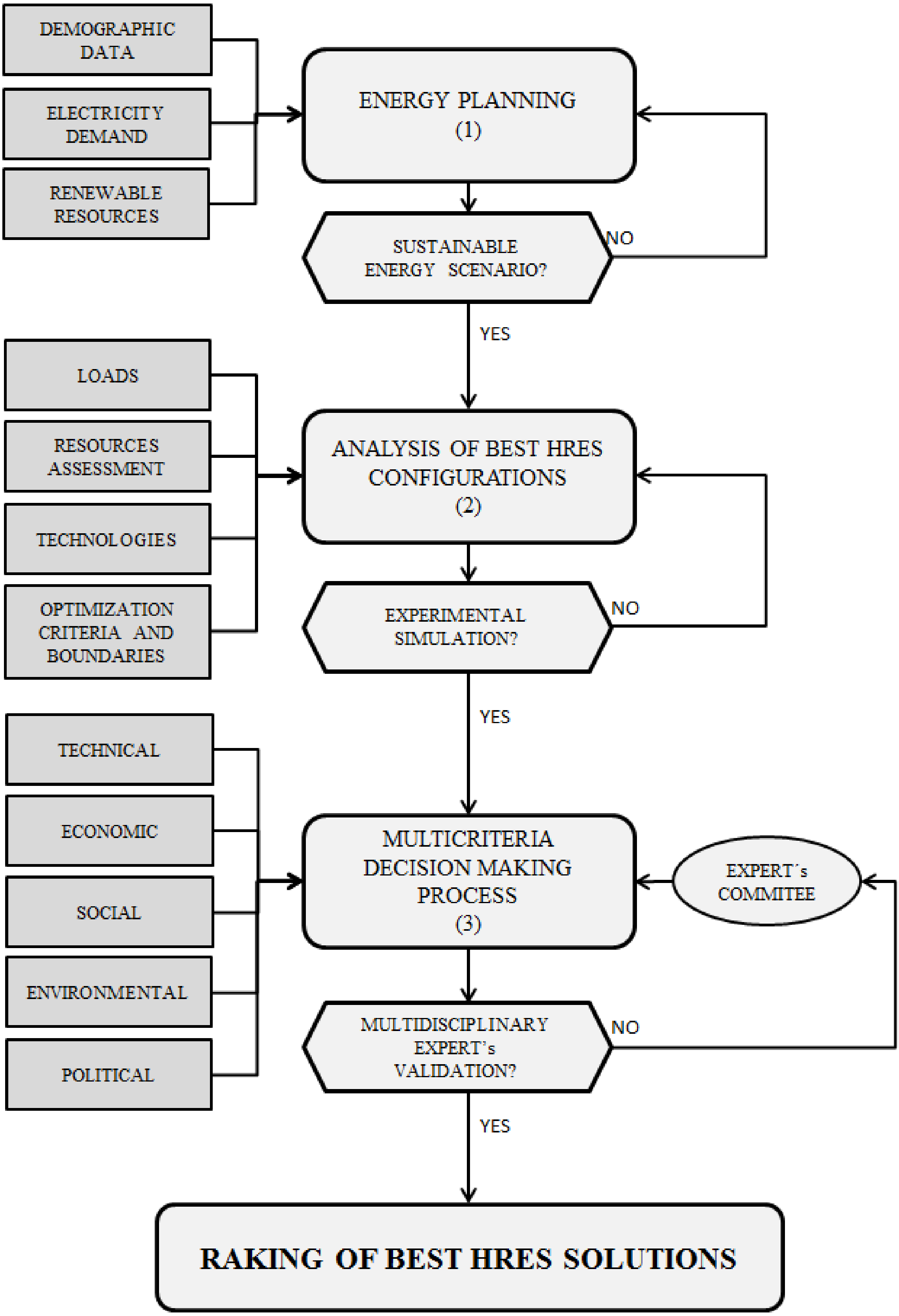


Figure 3.1. Integral Methodology for Isolated Electrification

3.1 ***Energy Planning***

A simulation tool for the simulation of energy scenarios is presented in this chapter. This tool has been specifically developed for the verification of the hybrid renewable systems potential to cover in a sustainable way the energy demand of a particular area.

Existing tools, already mentioned in the previous chapter devoted to a review of the state of the art of the different topics addressed in this study, are not specifically oriented to that task. They could be used to estimate the behaviour of a particular renewable energy system, but without the possibility to determine in a direct way the optimal HRES configuration to be installed. As established in that review, the two most remarkable software programs, EnergyPLAN and LEAP have an application range reduced to national or regional levels; in the case of EnergyPLAN is more oriented to the system operation instead of the design or economic investment optimization, while LEAP does not currently support optimization modelling and it is oriented to support a number of different modelling methodologies: on the demand-side these range from bottom-up, end-use accounting techniques to top-down macroeconomic modelling. On the supply side, it provides a range of accounting and simulation methodologies for modelling electricity generation and capacity expansion planning.

The code that has been developed in this work, SIMESEN, allows for the determination of the evolution in the short, medium and long term of a particular energy scenario using as starting point the energy demand and the primary energy availability and deducing the role that renewable energies should play to enable a sustainable scenario within the predetermined timeframe. Once this participation is determined, the possible configurations of HRES that comply with this scenario should be determined and, depending on the remaining elements to be considered: required technologies, environmental impact, costs and demand participation, obtain through a criterion of multi-criteria optimization, the most appropriate HRES to the needs of the population under study.

By applying SIMESEN at a country or region level, it will be possible to perform a benchmarking of the code comparing its output with the EnergyPLAN or LEAP results.

3.1.1 Simulation model

SIMESEN is based on a linear model that relates the demand with the possible contributions of each primary energy source and electricity, and provides for the considered scenario the evolution of each of these contributions and the emissions generated by them in order to evaluate the sustainability indicators.

The following variables are taken into consideration:

Variable	***Definition***
P (t)	Population
PIB (t)	Gross domestic product
TEP (t)	Total Primary Energy
EP (i,t)	Evolution of the primary energy demand for each source. [*i=1 (coal); i=2 (oil); i=3 (natural gas); i=4 (renewable); i=5 (nuclear); i=6 (electricity)]*
DA (i,j,t)	Evolution of the final energy demand from each sector *[j=1 (transport); j=2 (industrial); j=3 (residential); j=4 (services); j=5 (agricultural and fishing); j=6 (electricity generation)]*
TDA (j,t)	Evolution of total final energy demand from each sector
TEF (t)	Evolution of total final energy consumption
DR(i,j,t)	Evolution of the percentage of each source of energy (i) in the demand of a particular sector (j).
TEM (t)	Evolution of total CO_2 emissions
EM (i,j,t)	Evolution of the CO_2 emissions due to the use of a particular source of energy (i) in a demand sector (j).
SEM(j,t)	Evolution of the total CO_2 emissions from the sector j
CEM (i,j)	Emission coefficients due to the energy (i) use in the sector (j)
R (j,t)	Growth rate evolution for the energy demand in the sector j and for the population (j=7) and the GDP (j=8).

Table 3.1. SIMESEN variables and relationships.

The evolution of the independent variables, which are assumed to be the energy demand of each sector, can be defined by predetermined mathematical laws or, in the most usual way for this type of analysis, by annual rhythms of variation, for which we are using the vector R (j, t).

The following relationships between them are established:

$$TDA(j,t) = \sum_i DA(i,j,t) \tag{3.1}$$

$$DR(i,j,t) = \frac{DA(i,j,t)}{TDA(j,t)} \tag{3.2}$$

$$EP(i,t) = \sum_j DA(i,j,t) \tag{3.3}$$

$$TEP(t) = \sum_i EP(i,t) \tag{3.4}$$

$$TEF = \sum_{j=1}^{5} TDA(j,t) \tag{3.5}$$

$$EM(i,j,t) = DA(i,j,t) * CEM(1,j) \tag{3.6}$$

$$SEM(j,t) = \sum_i EM(i,j,t) \tag{3.7}$$

$$TEM(t) = \sum_j SEM(j,t) \tag{3.8}$$

In order to quantify the degree of compliance with the sustainability objective, and the evolution followed to achieve it, the following indicators are used:

- ✓ External dependence on the primary energy supply
- ✓ Share of renewable energies in total energy consumption
- ✓ Energy intensity, defines as the ratio energy consumption/gross domestic product, as a measure of energy saving and efficiency
- ✓ Total amount of CO_2 emitted by the energy sector

3.1.2 Code structure

SIMESEN is composed by 3 independent modules: Input data, calculation engine and results output.

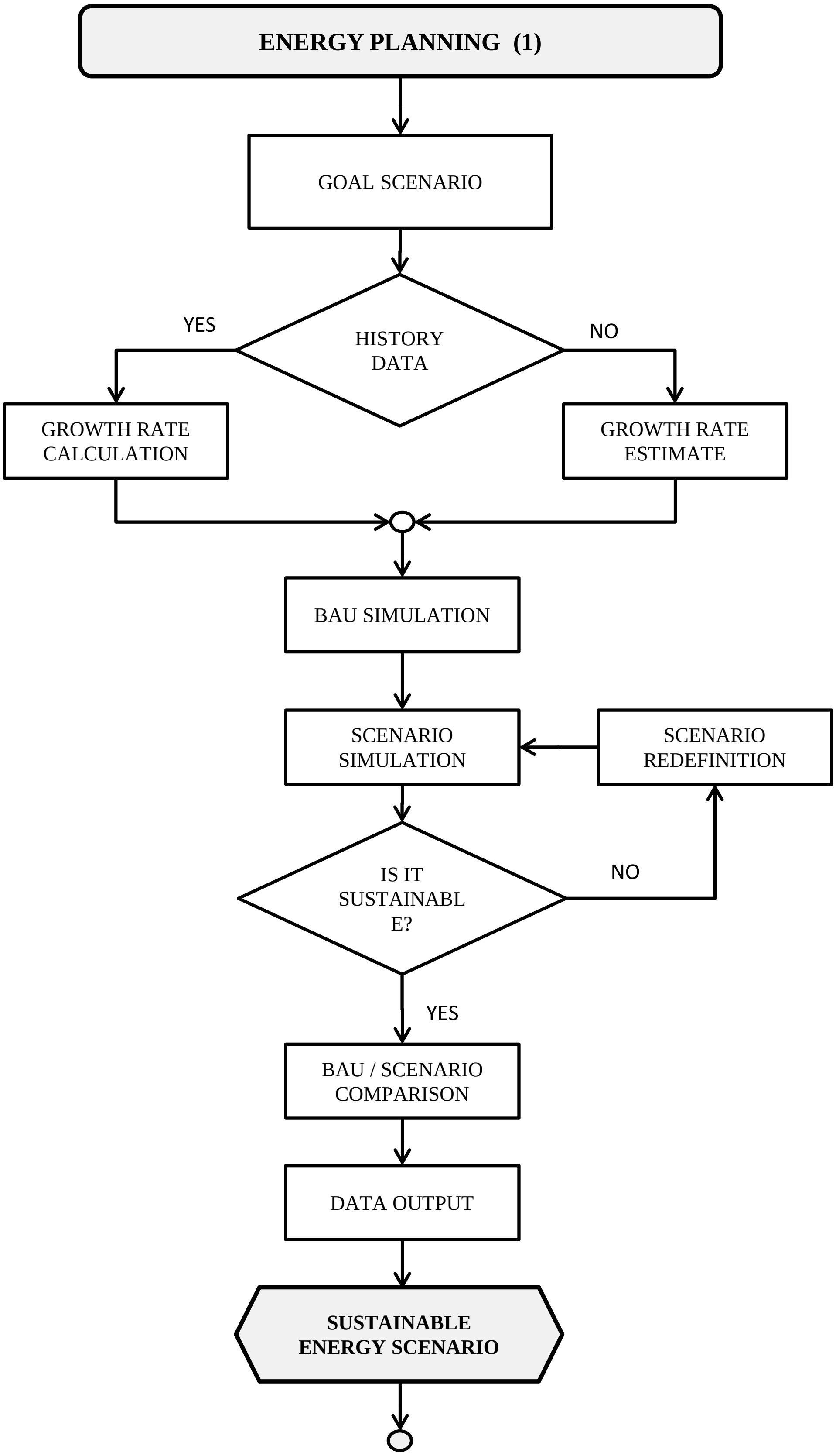
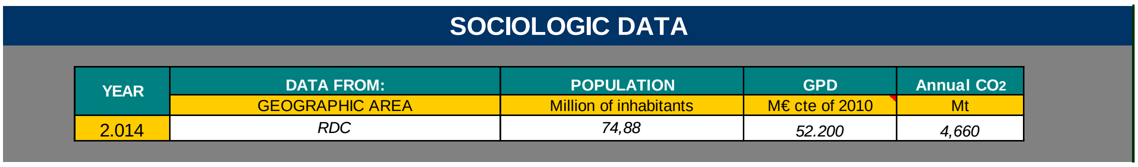


Figure 3.2. Energy Planning Model SIMESEN

Initially the code was applied to the determination of sustainable scenarios in the Valencian Community, as an example of its applicability and to do a benchmarking with other codes developed for national or regional scenarios. Subsequently, once verified its correct operation, it was applied to the study of isolated systems, as detailed in the next section of this chapter.

For this verification, the energy data of the Valencian Community compiled by the Valencian Energy Agency is used, simulating a scenario that introduces a greater penetration of the renewable energies with respect to the current values, which are maintained in the case of the scenario BAU.

The <u>first module</u> corresponds to data input, which include a first screen with the data on population, GDP energy demand, and CO_2 production rates of the analyzed community (Figure 3.3).

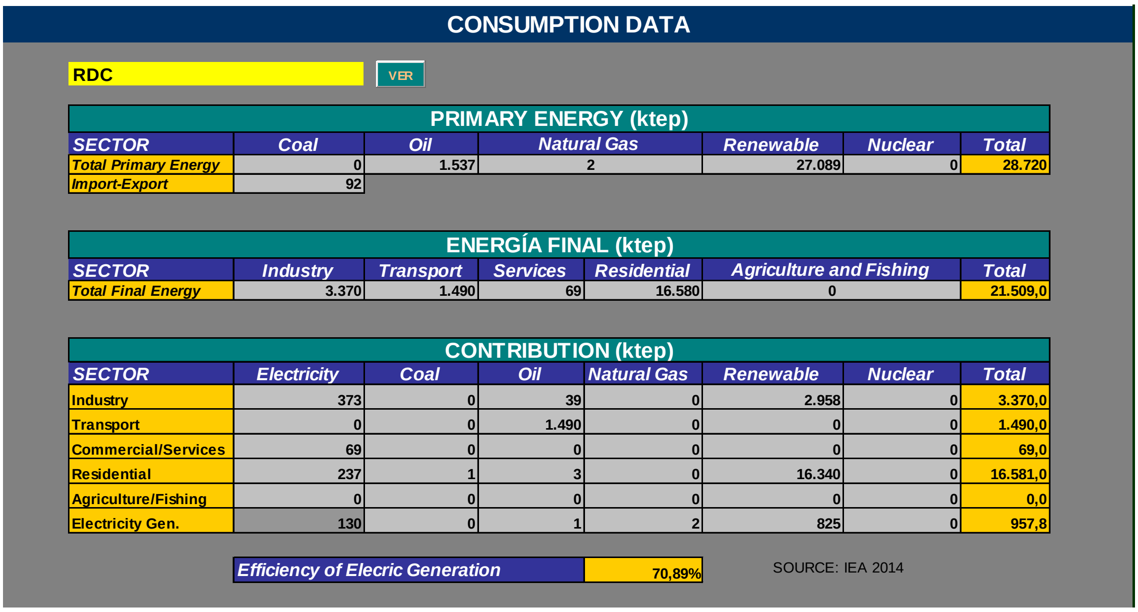


SOCIOLOGIC DATA

YEAR	DATA FROM:	POPULATION	GPD	Annual CO_2
	GEOGRAPHIC AREA	Million of inhabitants	M€ cte of 2010	Mt
2.014	*RDC*	*74,88*	*52.200*	*4,660*

Figure 3.3. SIMESEN Sociological Data

Input data for consumption includes primary and final energies required by each demand sector (Figure 3.4).



CONSUMPTION DATA

RDC

PRIMARY ENERGY (ktep)

SECTOR	Coal	Oil	Natural Gas	Renewable	Nuclear	Total
Total Primary Energy	0	1.537	2	27.089	0	28.720
Import-Export	92					

ENERGÍA FINAL (ktep)

SECTOR	Industry	Transport	Services	Residential	Agriculture and Fishing	Total
Total Final Energy	3.370	1.490	69	16.580	0	21.509,0

CONTRIBUTION (ktep)

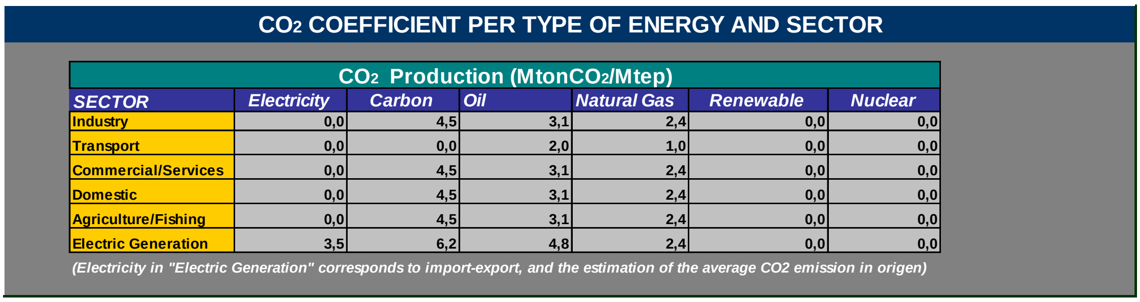
SECTOR	Electricity	Coal	Oil	Natural Gas	Renewable	Nuclear	Total
Industry	373	0	39	0	2.958	0	3.370,0
Transport	0	0	1.490	0	0	0	1.490,0
Commercial/Services	69	0	0	0	0	0	69,0
Residential	237	1	3	0	16.340	0	16.581,0
Agriculture/Fishing	0	0	0	0	0	0	0,0
Electricity Gen.	130	0	1	2	825	0	957,8

Efficiency of Elecric Generation	70,89%

SOURCE: IEA 2014

Figure 3.4. SIMESEN Consumption Data

Finally, data on the CO_2 emissions from the use of each type of energy in every demand sector, including electricity generation, are introduced in the final screen of this module (Figure 3.5).



CO_2 COEFFICIENT PER TYPE OF ENERGY AND SECTOR

CO_2 Production (MtonCO_2/Mtep)

SECTOR	Electricity	Carbon	Oil	Natural Gas	Renewable	Nuclear
Industry	0,0	4,5	3,1	2,4	0,0	0,0
Transport	0,0	0,0	2,0	1,0	0,0	0,0
Commercial/Services	0,0	4,5	3,1	2,4	0,0	0,0
Domestic	0,0	4,5	3,1	2,4	0,0	0,0
Agriculture/Fishing	0,0	4,5	3,1	2,4	0,0	0,0
Electric Generation	3,5	6,2	4,8	2,4	0,0	0,0

(Electricity in "Electric Generation" corresponds to import-export, and the estimation of the average CO2 emission in origen)

Figure 3.5. SIMESEN CO_2 Coefficients

The rates for time variation of each of the indicated variables are calculated in this module by means of a first subroutine that allows to determine for each of these parameters its evolution in the temporal range for which data are available and to extrapolate this evolution using different criteria: time series, splines, etc., to determine the expected growth rates for each of these variables, extrapolating them for the temporal range to be considered.

In addition, the scenario to be simulated is defined in this module by assigning the percentages in which each of the primary sources and electricity must contribute to cover the demand of each of the sectors.

The second module is a calculation engine that using the variables and relationships detailed in the previous section, calculates the evolution of the energy consumption and CO_2 emissions for the energy scenario defined in the input module.

As a reference element, in order to be able to determine the changes generated by the selected scenario and, thus quantify the degree of improvement that it represents, this module calculates in the first place the evolution of a scenario BAU (Business as Usual). Such BAU type scenario assumes that no qualitative changes are introduced in the evolution of the energy system, maintaining constant at the initial values defined in the input data, the percentage of contribution from each energy source to the demand from different sectors.

The evolution of the indicators of sustainability for the considered scenario is calculated in this module. Selected indicators are:

- ✓ Percentage of external dependence in primary energy supply.
- ✓ Percentage of renewable energy in overall energy consumption.
- ✓ Energy intensity, defined as the ratio between energy consumption and gross domestic product. The evolution of this parameter can be considered as an indicator of the improvement in energy saving and efficiency.
- ✓ Total amount of CO_2 emissions from the energy sector.

Finally, renewable resources required by proposed scenario are calculated in order to assess whether such a scenario is feasible with available renewable resources in the area under study. If not, code iterates until a compatible scenario with those available renewable resources is obtained.

The third module is dedicated to SIMESEN results presentation, both graphically and numerically.

The first output screen shows a diagram of consumption data in the initial year used for the calculation.

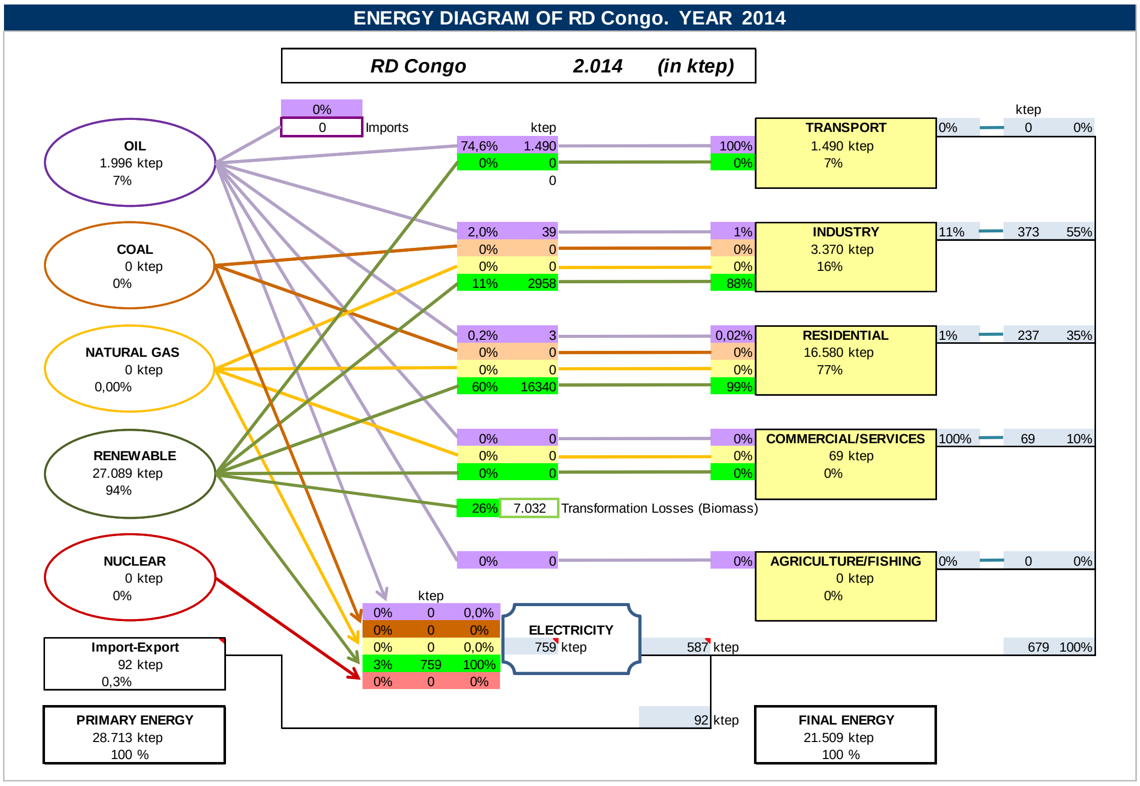


Figure 3.6. SIMESEN. Example of General Overview Output

The second output screen displays the evolution of the energy consumption, both primary and final, for the different primary energy sources and the different demand segments. Also displayed is the evolution of the CO_2 emissions. The screen compares the results for the BAU and the sustainable scenario.

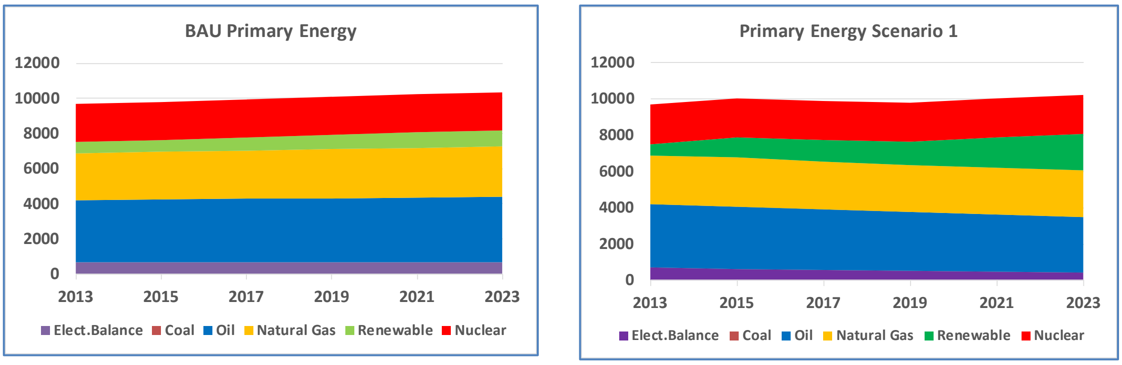


Figure 3.7. SIMESEN. Example of Primary Energy

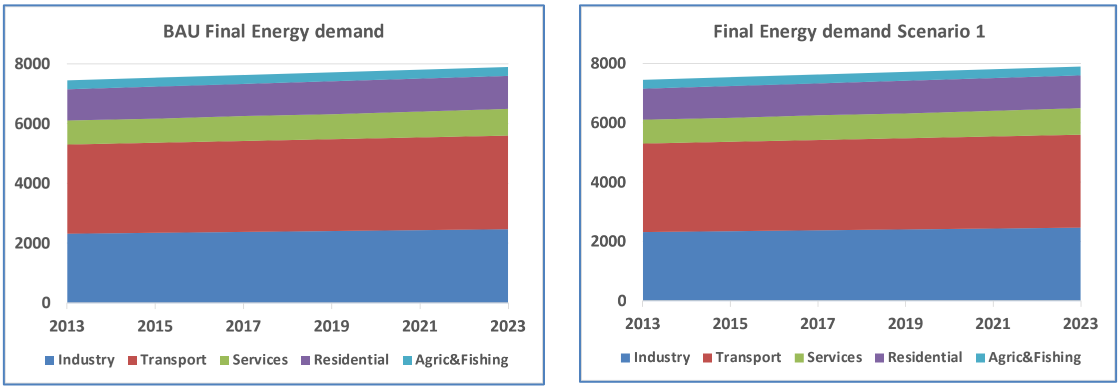


Figure 3.8. SIMESEN. Example of Final Demand

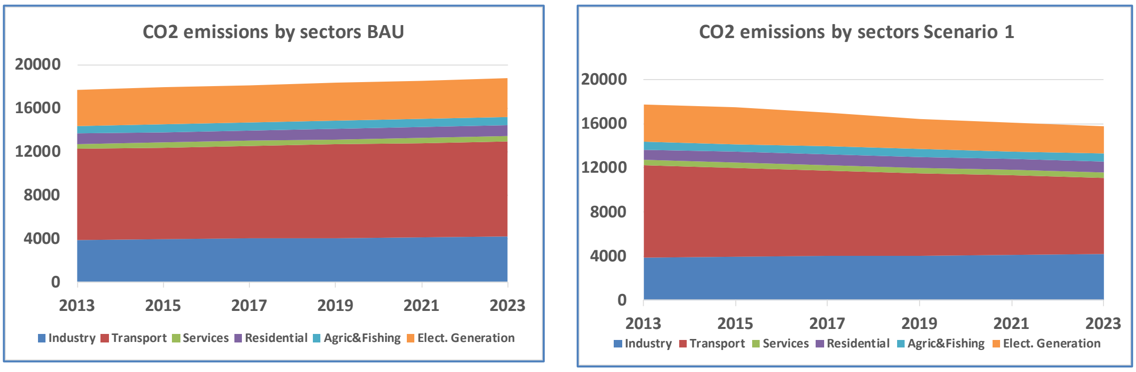


Figure 3.9. SIMESEN. Example of CO_2 Emissions

The third screen presents the comparison between the assumed scenario and the reference BAU of the sustainability indicators.

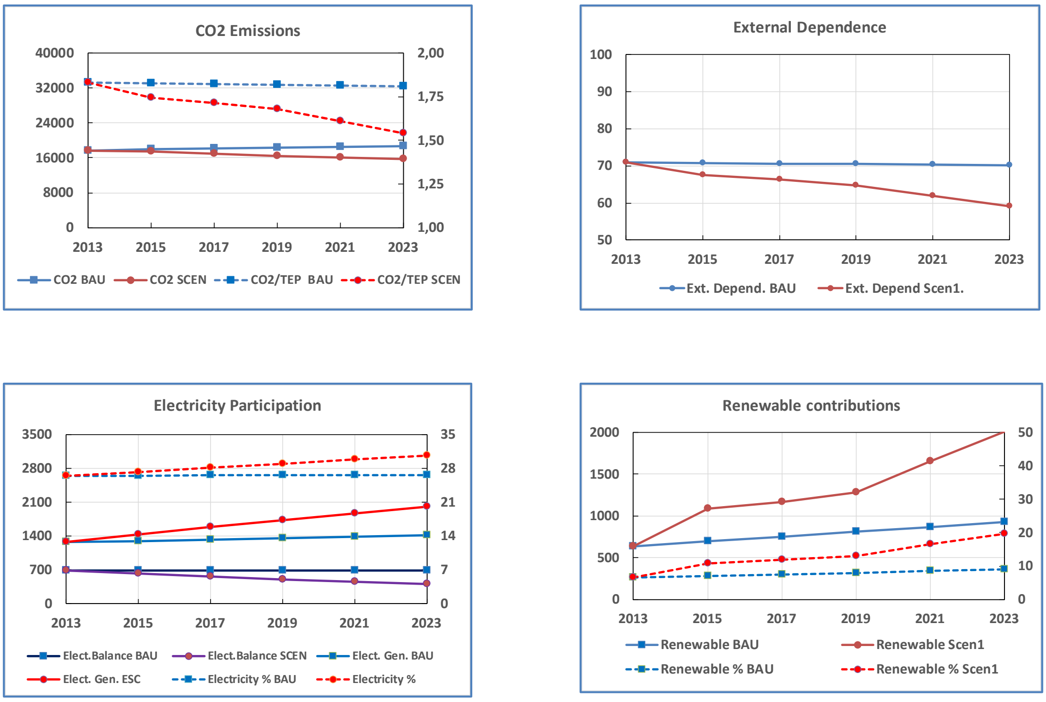


Figure 3.10. SIMESEN. Example of Indicators

The fourth, and final, screen presents diagrams of the complete energy system for the last simulated year, for the BAU scenario and for the improved scenario assumed in the simulation.

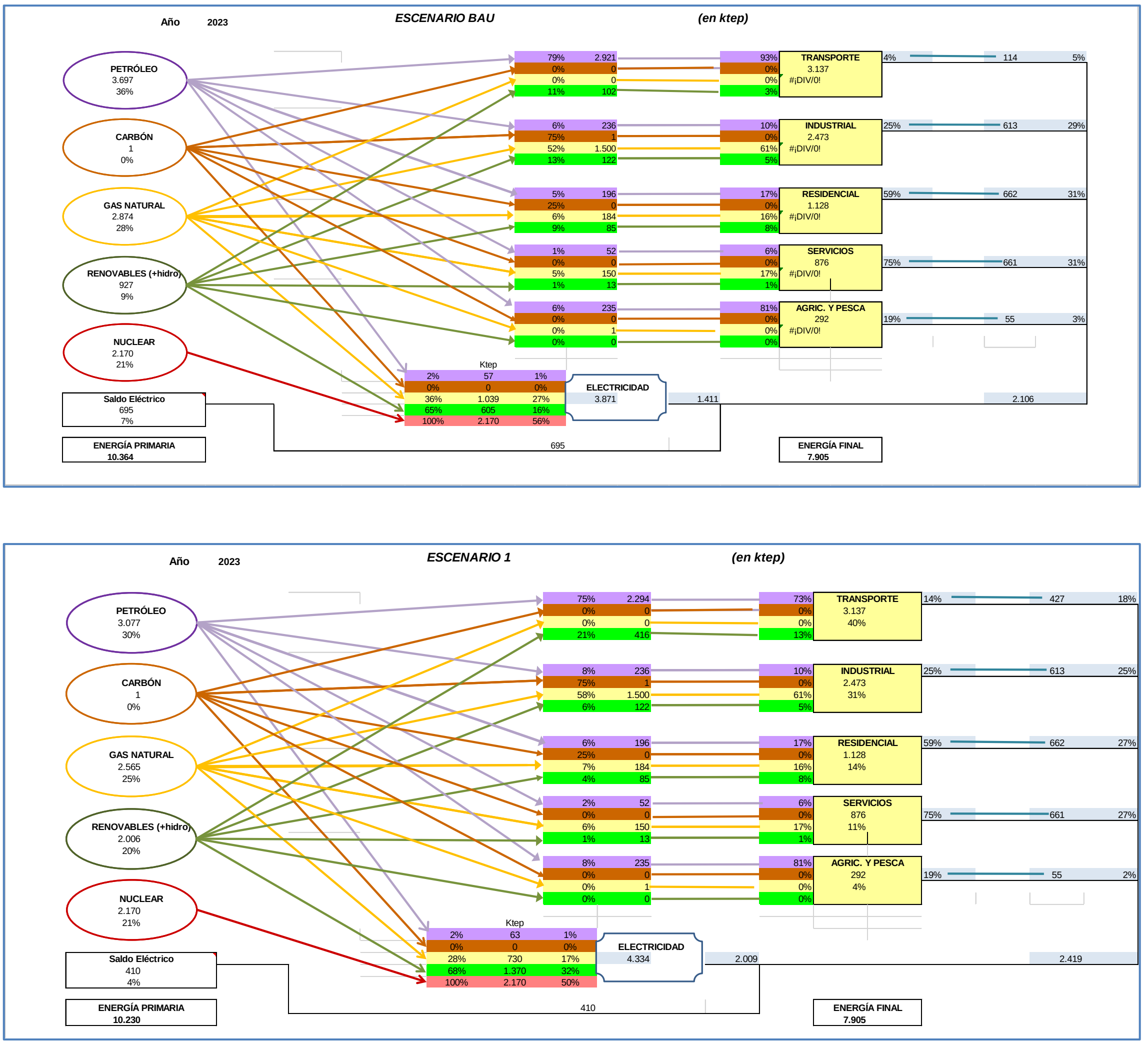


Figure 3.11. SIMESEN. Example of Energy Scenarios Comparison

The code also provides with numerical outputs with the values for the different considered parameters.

SCENARIO **BAU** **RD Congo**

Indicators	**Units**	**2014**	**2015**	**2020**	**2025**	**2030**	**2035**
Population	Million	74,9	77,2	89,9	104,6	121,8	141,8
GDPppp	M€$_{2010}$	52.200.000	52.412.599	53.488.650	54.586.794	55.707.483	56.851.180
Consumption of Electricity	TWh	7,9	8,0	8,7	9,5	10,4	11,3
CO_2 Emissions	Mt	4,53	4,85	6,82	9,64	13,68	19,45
Primary Energy (EP)	ktep	28.713	29.520	33.978	39.265	45.586	53.214
EP Generated	ktep	20.057	20.558	23.264	26.344	29.852	33.848
Import-Export	ktep	92	94	102	111	121	132
Generated Electricity	ktep	587	597	648	706	771	843
Exterior Dependency	%	30,15	30,36	31,53	32,91	34,51	36,39
GDPppp/capita	M€$_{2010}$/inhab	0,70	0,68	0,60	0,52	0,46	0,40
TEP/capita	tep/hab	0,383	0,382	0,378	0,375	0,374	0,375
TEP/GDPppp	tep/M€$_{2010}$	0,55	0,56	0,64	0,72	0,82	0,94
Electricity/capita	kWh/inhab	0,11	0,10	0,10	0,09	0,09	0,08
CO_2/TEP	t/tep	0,16	0,16	0,20	0,25	0,30	0,37
CO_2/GDPppp	t/M€$_{2010}$	0,09	0,09	0,13	0,18	0,25	0,34
CO_2/capita	t/inhab	0,060	0,063	0,076	0,092	0,112	0,137
Fraction ER in EP*	%	69,9	69,6	68,5	67,1	65,5	63,6
Fraction ER in EE*	%	86,5	86,5	86,5	86,5	86,5	86,5

Fraction ER in EP and EE*: % of renewable energies contribution to primary energy and electrical generation.

Table 3.2. SIMESEN. Example of Simulation Results.

3.2 HRES Configuration Set

Once the energy planning study is completed, the methodology will address the optimisation of the HRES configuration, following the scheme depicted at the Figure 3.12. Main components of this approach are described in the next paragraphs.

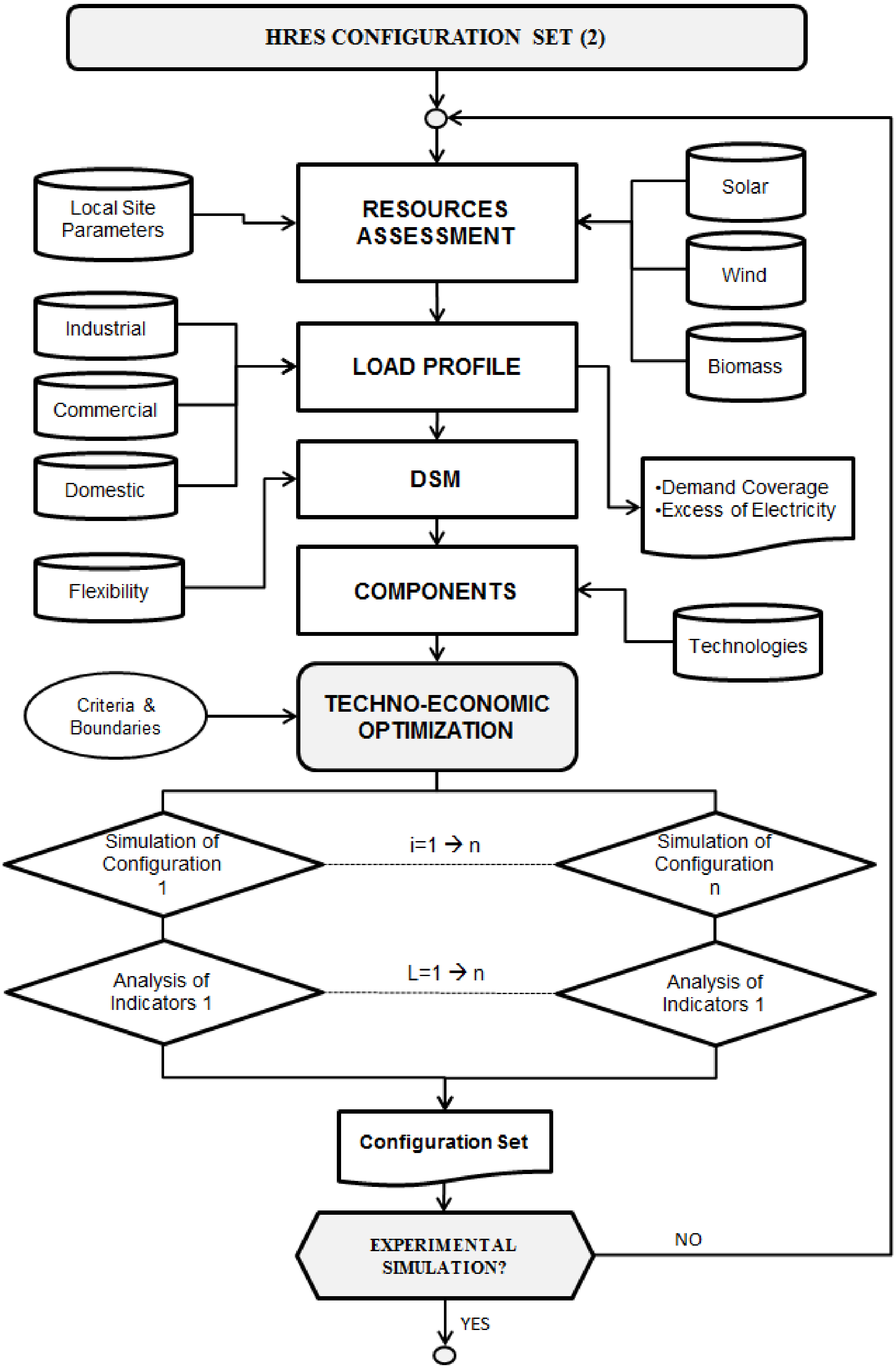


Figure 3.12. Method for identifying HRES Feasible Configurations

3.2.1 Resources Assessment

Natural resource evaluation is based on local site parameters, such as meteorological data and geographic profile of the area. Meteorological data include solar radiation, wind speed and direction, temperature, humidity, etc. This data will help determining the potential for RES power generation in an area, together with power technologies. Depending on the natural resource availability, a zone will have higher or lower potential. The majority of isolated villages are characterized by having generous solar radiation and/or wind speeds (especially in the case of mountainous regions), as well as significant biomass residues since most isolated communities have agriculture as main subsistence activity.

3.2.1.1 Solar

According to Dan Chiras [3.1], solar energy annually reaching Earth’s surface is roughly ten thousand times the total energy consumed by human being. Solar energy is one of the most common natural resources used in electrifying isolated areas, together with wind micro-turbines. Solar radiation is available everywhere and it can be forecasted, which makes this source perfectly suitable for electrical generation. Sun profile follows a well-known monthly and daily pattern.

Prior estimating solar power potential of an area, it is important to be familiar with the following concepts:

- *Irradiance:* is the incident solar density power over and area (W/m^2).
- *Irradiation:* corresponds to the solar energy during a time period (kWh/m^2).
- *Air mass (AM)*: coefficient characterizing solar spectrum once solar radiation has travelled through the atmosphere. It is commonly used to characterize the performance of solar cells under standardized conditions.
- *Solar constant*: The amount of solar radiation incident on earth’s atmosphere at a vertical angle of air mass (AM=0). Its magnitude is approximately 1,367 W/m^2.
- *Global solar radiation*: Total solar radiation, including sunbeam and diffuse radiations. In case of horizontal laid surfaces, global solar radiation is the

summation of vertical and diffuse radiation. This is part of the constant solar radiation hitting the ground.

- *Beam radiation*: Sunbeam reaching the earth directly from the sun.
- *Diffuse radiation*: Solar irradiance that reaches the ground from the sky where its direction is changed by the atmosphere. The diffuse radiation magnitude depends on solar height, and atmospheric transparency. The higher the cloud in the sky, the higher the dispersed radiation is.
- *Albedo radiation*: It is the reflected sunlight from the ground.
- *Extraterrestrial normal radiation*: Amount of solar irradiance reaching the atmosphere on a perpendicular surface.
- *Extraterrestrial horizontal radiation*: is the quantity of solar radiation reaching on a flat surface positioned on top of the atmosphere. If the entire direct solar radiation source is converted into usable form of energy in the earth, it would be more than enough to supply the energy requirement of the world.

Estimating solar radiation requires data of global solar radiation over the horizontal Earth’s surface of a location, which depends on several factors:

- atmospheric effects, such as absorptivity and reflectivity of the radiation in the surface;
- local variations in the atmosphere, such as water vapour, clouds, and pollution;
- latitude of the location,
- annual season (summer, winter, spring, fall)
- time of day (at nigh time, solar radiation is often zero and it starts increasing from sunrise until noon, when it normally reaches its highest value; then, it begins decreasing until sunset when it drops to zero again).

In order to determine global solar radiation reaching the Earth’s surface, it is necessary to calculate first global solar radiation striking the top of the atmosphere and understanding sun’s position at each season and time of the day for a specific location. For the purpose of this study, Duffie and Beckman method [3.2] is used. *Global* *horizontal radiation* represents the total amount of solar radiation reaching the horizontal surface on the earth, which varies over the year since the distance between the sun and the earth follows earth's orbit. The amount of solar radiation reaching the top of Earth's atmosphere varies over the year as Earth moves in its elliptical orbit around the sun. ***Extraterrestrial normal radiation***, solar radiation striking a surface normal (perpendicular) to the sun’s rays at the top of Earth’s atmosphere may be determined using the following expression:

$$G_{ext-perp} = G_{sc}\left(1 + 0{,}033\, cos\,\frac{360\, n}{365}\right) \qquad \textbf{\textit{(3.9)}}$$

Where:

G_{ext-n}: extraterrestrial normal radiation, radiant power density outside the Earth's atmosphere (kW/m^2)

G_{sc}: is the value of the solar constant, 1353 W/m^2

n: day of the year (a number between 1 and 365)

Next, solar radiation striking a horizontal surface at the top of the atmosphere is defined as the ***extraterrestrial horizontal radiation***.

$$G_0 = G_{ext-n} \cos\theta_Z \qquad \textbf{\textit{(3.10)}}$$

Where:

G_0: extraterrestrial horizontal radiation (kW/m^2)

θ_Z: zenith angle (°)

Zenith angle is the angle between the sun and the vertical. The zenith angle is similar to the elevation angle but it is measured from the vertical rather than from the horizontal. Zenith angle is zero when the sun is directly overhead and 90° when the sun is at the horizon. Precisely, zenith angle may be calculated by means of the next equation:

$$\cos\theta_Z = \cos\emptyset \cos\delta \cos\omega + sen\,\emptyset\, sen\,\delta \qquad \textbf{\textit{(3.11)}}$$

Where:

θ: angle of incidence (°)

$\emptyset$: latitude (°)

δ: solar declination (°)

ω: hour angle (°)

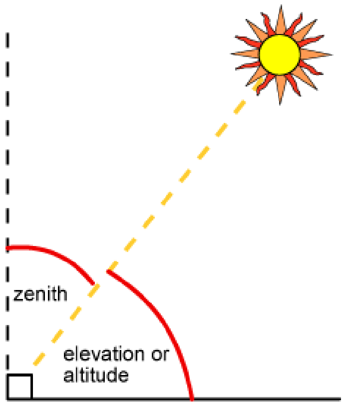


Figure 3.13. Zenith and elevation angle. Source: PV-Education

Latitude, time of the year (solar declination), and time of day (hour angle) are also relevant factors in sun position. Latitude specifies the north–south position of a specific point on Earth's surface. It is the angle which ranges from 0° at the Equator to 90° (North or South) at the poles. *Solar declination* provides the time of the year, it corresponds to the angle between the equator and a line drawn from the centre of the Earth to the centre of the sun.

$$\delta = 23{,}45° \, sen\left(360° \, cos \frac{284 + n}{365}\right) \tag{3.12}$$

Where:

n: is the day of the year (a number 1 through 365).

Hour angle determines the time of day. Per convention the hour angle is zero at solar noon (the time of day at which the sun is at its highest point in the sky), negative before solar noon and positive after solar noon.

$$\omega = (t_s - 12hr) * \frac{15°}{hr} \tag{3.13}$$

Where:

t_s: solar time (hr)

Once extraterrestrial horizontal radiation is defined, it is then estimated the *Clearness Index*, which characterizes the attenuation effect of atmosphere and clouds over global solar radiation reaching Earth's surface. It corresponds to the ratio between solar radiation at the surface of the earth to extraterrestrial radiation:

$$K_T = \frac{G_s}{G_0} \tag{3.14}$$

Where:

G_S: global horizontal radiation on earth's surface (averaged over time) (kW/m^2)

G_0: extraterrestrial horizontal radiation (averaged over time) (kW/m^2)

Regarding to solar radiation striking Earth's surface, this is characterized by two types: beam and diffuse. Beam radiation, also known direct radiation, corresponds to solar radiation travelling from the sun to the earth's surface without any scattering by the atmosphere; while diffuse refers to solar radiation reaching Earth's from all parts of the sky since its direction has been changed by the earth's atmosphere. Summation of both radiations, beam and diffuse, is the *Global Solar Radiation* at horizontal Earth's surface. The distinction between beam and diffuse radiation is important when calculating the amount of radiation incident on an inclined surface. The orientation of the surface has a stronger effect on the beam radiation, which comes from only one part of the sky, than it does on the diffuse radiation, which comes from all parts of the sky.

$$G_s = G_b * G_d \tag{3.15}$$

Where:

G_b: beam radiation (kW/m^2)

G_d: diffuse radiation (kW/m^2)

However, PV panels are generally inclined and oriented at a certain angle from the sun, so global solar radiation calculations over the arrays' surface need to be carried out at each time step (hourly) to obtain actual (real) photovoltaic output power. These calculations are carried out by means of two parameters, the slope and the azimuth. The *slope* (β) is the angle formed between the surface of the panel and the horizontal, so a slope of zero indicates a horizontal orientation, whereas a 90° slope indicates a vertical orientation. The *azimuth* is the direction towards which the surface faces with respect to the south. Per convention, zero degrees azimuth corresponds to south and positive values refer to west-facing orientations. Similarly, an azimuth of -45° corresponds to a southeast-facing orientation and an azimuth of 90° degrees corresponds to a west-facing orientation.

$$G_{PV} = G_s(\beta, azimuth) \qquad (3.16)$$

Where:

G_{PV}: solar global radiation reaching the tilted and oriented solar array (kW/m^2)

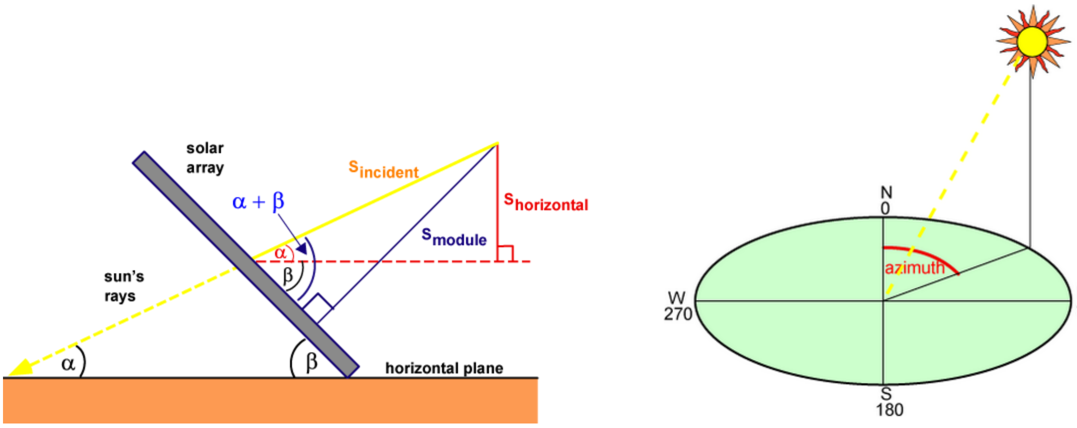


Figure 3.14. Tilting of the module and azimuth. Source: PV-Education

3.2.1.2 Wind

Wind is a form of solar energy; it is the result of pressure gradient differences in earth's atmosphere due to irregular air heating around the globe. Wind power converts wind speed and direction into energy by means of wind turbines, which get the power from the wind flow by the aerodynamic lift and drag forces. Wind turbines collect and convert the kinetic energy that wind produces into electricity. Theoretical power available in the wind depends on the wind speed, rotor swept area and air density [3.3][3.4][3.5][3.6][3.7], according to the following mathematical relation:

$$P_{Av} = \frac{1}{2} * \rho * A * v^3 \qquad (3.17)$$

Where:

P_{Av}: power available within the wind (kW)

ρ: air density (kg/m^3)

A: rotor swept area (m^2)

v: wind speed (m/s)

Air flow density refers to mass within the air. Heavier the air, more energy harnessed by the turbine. It is proportional to air pressure and inversely proportional to air temperature of the location.

$$\rho = \frac{P}{R * T} \tag{3.18}$$

Where:

P: air pressure (Pascal)

R: gas constant (287 J/kg ºK)

T: absolute air temperature (ºK)

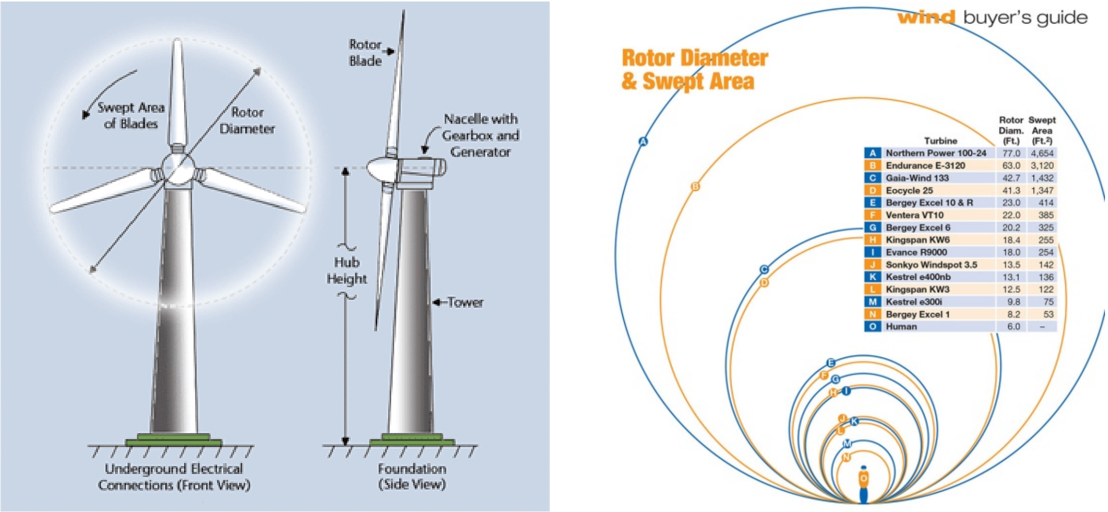
Rotor swept area is the area covered by the rotation of the turbine blades and it is determined by the turbine blade length. Area increases as the length of the blades increases. Also, power output of the turbine increases as the rotor diameter gets higher. The rotor swept area may be calculated according to the following equation:

$$A = \frac{\pi * D^2}{4} \tag{3.19}$$

where:

A: The rotor area (m^2)

D: Diameter of the rotor (m)



	Turbine	Rotor Diam. (Ft.)	Swept Area (Ft.^{2})
A	Northern Power 100-24	77.0	4,654
B	Endurance E-3120	63.0	3,120
C	Gaia-Wind 133	42.7	1,432
D	Eocycle 25	41.3	1,347
E	Bergey Excel 10 & R	23.0	414
F	Ventera VT10	22.0	385
G	Bergey Excel 6	20.2	325
H	Kingspan KW6	18.4	255
I	Evance R9000	18.0	254
J	Sonkyo Windspot 3.5	13.5	142
K	Kestrel e400nb	13.1	136
L	Kingspan KW3	12.5	122
M	Kestrel e300i	9.8	75
N	Bergey Excel 1	8.2	53
O	Human	6.0	–

Figure 3.15. Swept area of blades of a wind turbine. Source: ESN & Wind Buyer's guide

Moreover, rotor swept area in wind turbines with vertical axis can be estimated by the following mathematical expression: [3.8].

$$A = \frac{2 * w_r * h_r}{3} \qquad \textbf{\textit{(3.20)}}$$

where:

w_r: rotor width (m)

h_r: rotor height (m)

Wind speed is a key parameter in power production. Wind flow varies across the turbine rotor according to Figure 3.16. Wind speed drops as it reaches the turbine, whereas the wind pressure increases in the upstream of the turbine decreases below atmospheric pressure after the turbine. The increase in pressure at the rotor surface is due to the part of kinetic energy of the wind is changed into potential energy [3.3][3.4][3.5][3.6][3.7][3.8][3.9].

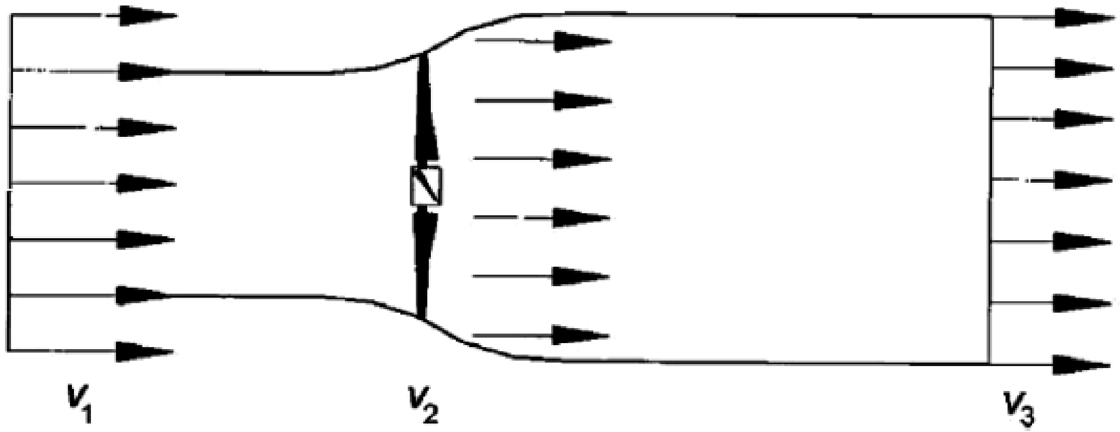


Figure 3.16. Wind flow across the rotor. Source: [3.9]

However, wind power obtained from the rotor blade is limited by Betz limit, which states that wind turbine rotor cannot extract all the available power, the performance coefficient (C_p) of the rotor efficiency has a theoretical maximum value of 0,593. In real cases, this coefficient is between 0,4 and 0,5 for two blade rotor, and between 0,2 and 0,4 for more than 2 blades as well as low speed turbines [3.10].

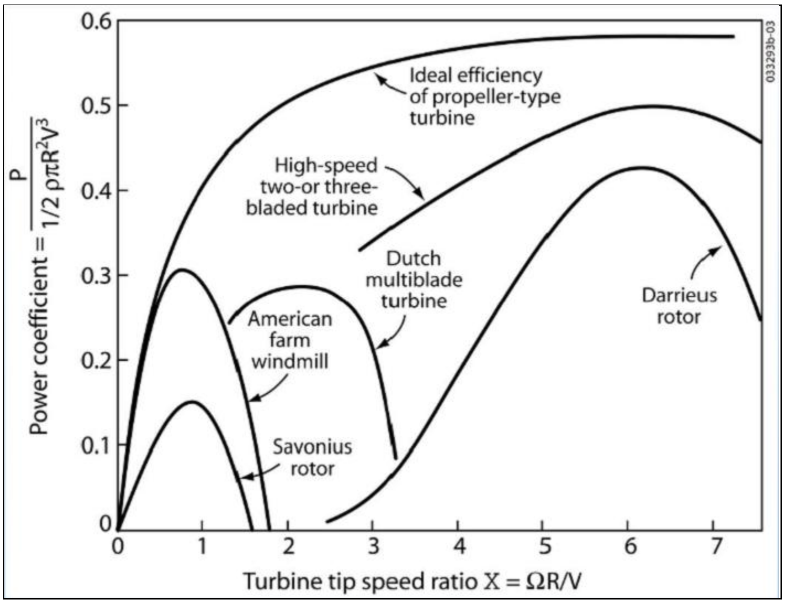


Figure 3.17. Betz limit. Source: [3.6]

$$P_{w-max} = \frac{1}{2} * C_p * \rho * A * v^3 \qquad \textbf{\textit{(3.21)}}$$

Where

P_{w-max}: theoretical maximum wind power output (W)

This maximum theoretical power does not consider mechanical nor electrical efficiencies of the generation system.

Weibull Distribution

In addition to the wind speed and direction, it is important to evaluate the wind speed distribution within a time period (normally a year) to determine wind power potential of a specific area. Wind is an intermittent resource, so it is necessary to use the probability density distribution of wind speeds in the area in order to evaluate the average power output of a wind turbine according to its power curve. Weibull is a probabilistic function used to measure annual distribution of wind speeds. It shows the proportion of time spent by the wind within narrow bands of wind speed [3.3][3.6][3.11][3.12] and may be characterised based on the following expression:

$$h(v) = \left(\frac{k}{c}\right) * \left(\frac{v}{c}\right)^{k-1} * e^{\left[-\left(\frac{v}{c}\right)^{k}\right]} \qquad \text{For} \quad 0 < v < \infty \qquad \textit{(3.22)}$$

where:

$h(v)$: probability distribution function.

k: shape factor, describing the dispersion of the wind speed.

c: scale parameter in (m/s)

v: wind speed in (m/s)

Most wind sites have values of shape factor k varying from 1,5 to 3 and the scale parameter c from 5 to 10 m/s [3.3][3.11].

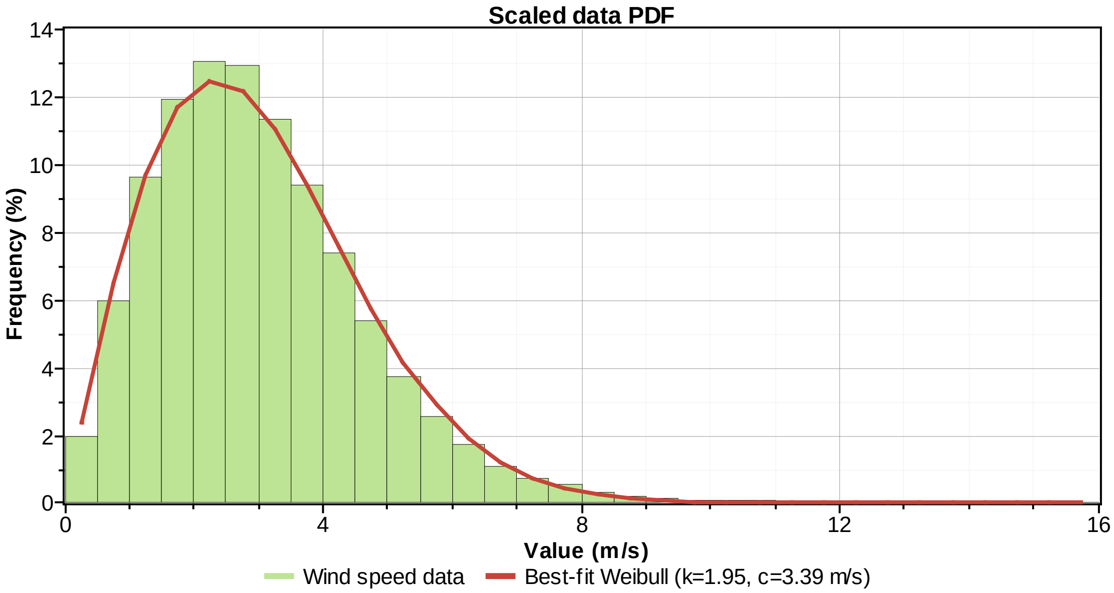


Figure 3.18. Wind Speed Probability Distribution. Source:[3.11]

Wind Shear: Furthermore, it is important to estimate wind speed at a certain height of the wind turbine. Wind shear is the wind profile, the variation of wind speed with above ground height. As wind turbine height rises, wind speed and wind power output also increases. This effect may be characterised by two methods, the exponential and the logarithmic functions [3.13][3.14]. First method uses the **power law profile**, given by the following mathematical expression:

$$\frac{v_2}{v_1} = \left(\frac{h_2}{h_1}\right)^{\alpha} \tag{3.23}$$

where:

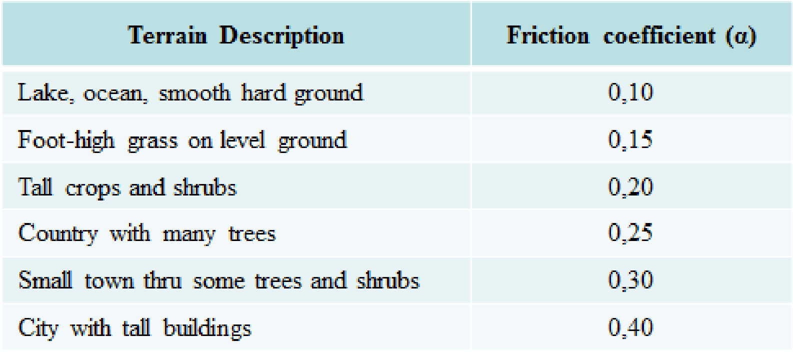
v_2: wind speed estimated at hub height h_2 (m/s)

v_1: wind speed at reference height h_1 (m/s)

h_2: hub height (m)

h_1: reference height above ground level (m)

α: power law exponent. It depends on the elevation, time of the day, season, terrain, wind speed and the temperature of the site.



Terrain Description	Friction coefficient (α)
Lake, ocean, smooth hard ground	0,10
Foot-high grass on level ground	0,15
Tall crops and shrubs	0,20
Country with many trees	0,25
Small town thru some trees and shrubs	0,30
City with tall buildings	0,40

Table 3.3. Power Law Exponent (α). Source: [3.3]

Second method corresponds to the **logarithmic function**, which characterises wind speed above ground level using the logarithmic heights (reference and hub) and the surface roughness length of the terrain and its surroundings (z_0).

$$\frac{v_2}{v_1} = \frac{ln\left(\frac{h_2}{z_0}\right)}{ln\left(\frac{h_1}{z_0}\right)} \tag{3.24}$$

where:

v_2: wind speed estimated at hub height h_2 (m/s)

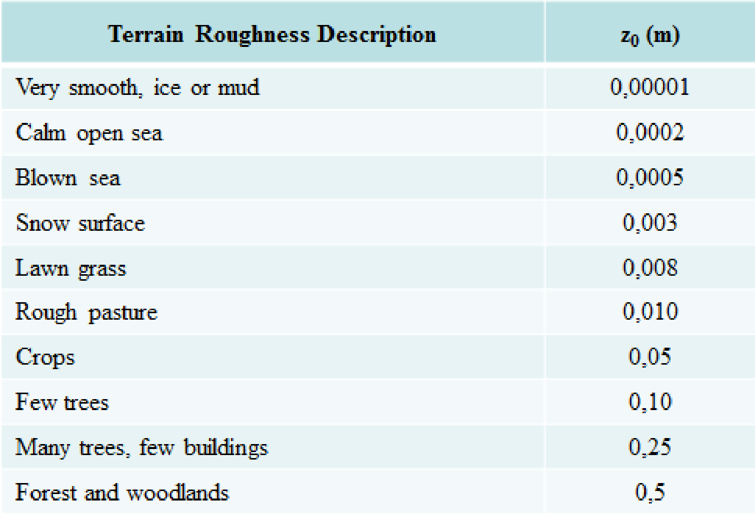
v_1: wind speed at reference height h_1 (m/s)

h_2: hub height (m)

h_1: reference height above ground level (m)

z_0: surface roughness length coeffcient (m);

Surface roughness coefficient is typified according to the following table:



Terrain Roughness Description	z_0 (m)
Very smooth, ice or mud	0,00001
Calm open sea	0,0002
Blown sea	0,0005
Snow surface	0,003
Lawn grass	0,008
Rough pasture	0,010
Crops	0,05
Few trees	0,10
Many trees, few buildings	0,25
Forest and woodlands	0,5

Table 3.4. Surface Roughness Lengths. Source: [3.11]

As an example, Figure 3.19 represents wind speed profile with a surface roughness coefficient of 0,01 (area of rough pasture). Wind speed increases as wind hub is risen, following a logarithmic function.

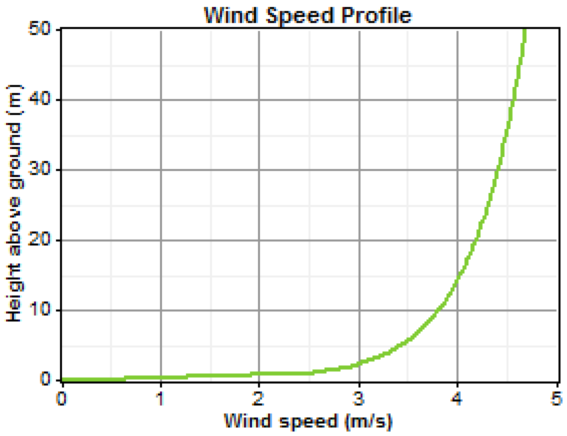


Figure 3.19. Wind speed profile with height. Source: [3.11]

3.2.1.3 <u>Biomass</u>

Biomass sources are very heterogeneous and autochthone, so their energy valorisation is carried out locally. An assessment of biomass use as fuel requires a study of the different types of biomass residues, including an analysis of their basic properties, characteristics and performance. Main biomass residues used for electricity production include biomass residues derived from forestry, agricultural crops and/or agro-industries.

Forestry and landscape conservation activities may generate biomass that can be valorised energetically, solving the environmental problem of how to manage them. However, the potential of using these residues as energy source may create a profitable market leading to deforestation, so energy valorisation of forest biomass needs to be clearly articulated as a conservation task. Moreover, many agricultural residues may also be used as fuels, such as woody like fruit trees and herbaceous crops such as cereal straw. In addition, cultivation of biomass crops for direct use as fuel is another option for fuel production. However, in these cases biomass production should be coordinated with the food requirements of the area, so biomass crops don't substitute traditional food farming. Agroindustry biomass refers to industry residues that may transform in fuel, such as dry fruits peeling plants, rice mills, etc.

For the purpose of this study, evaluation of biomass potential of an isolated area is approached using the methodology developed by the Institute of Energy Engineering at the *Universitat Politècnica de València*, which considers five main steps to evaluate biomass power potential of a region [3.15][3.16].

1. Characterization of biomass residues.
2. Quantification.
3. Seasonality (annual).
4. Dispersion.
5. Accessibility.

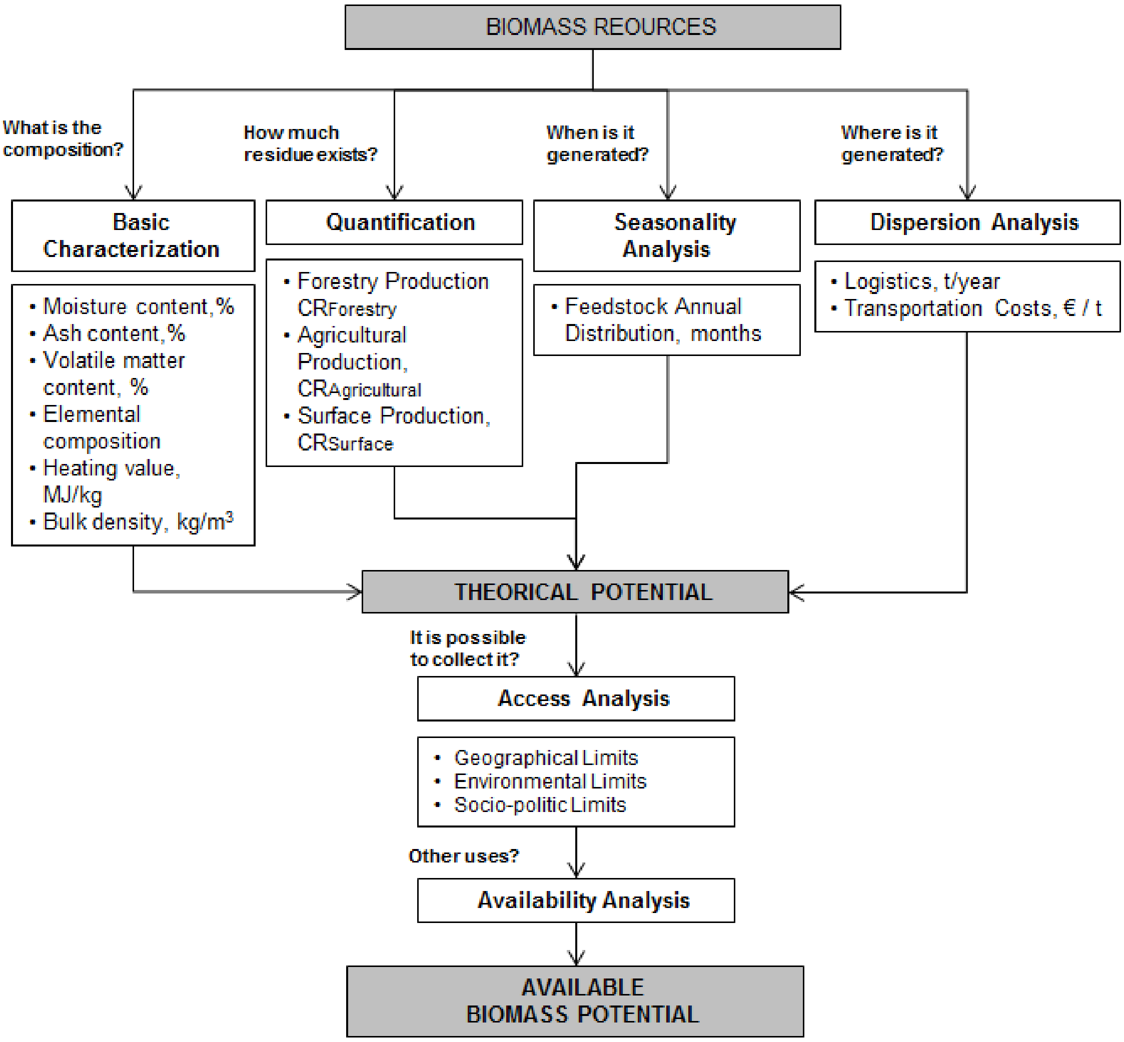
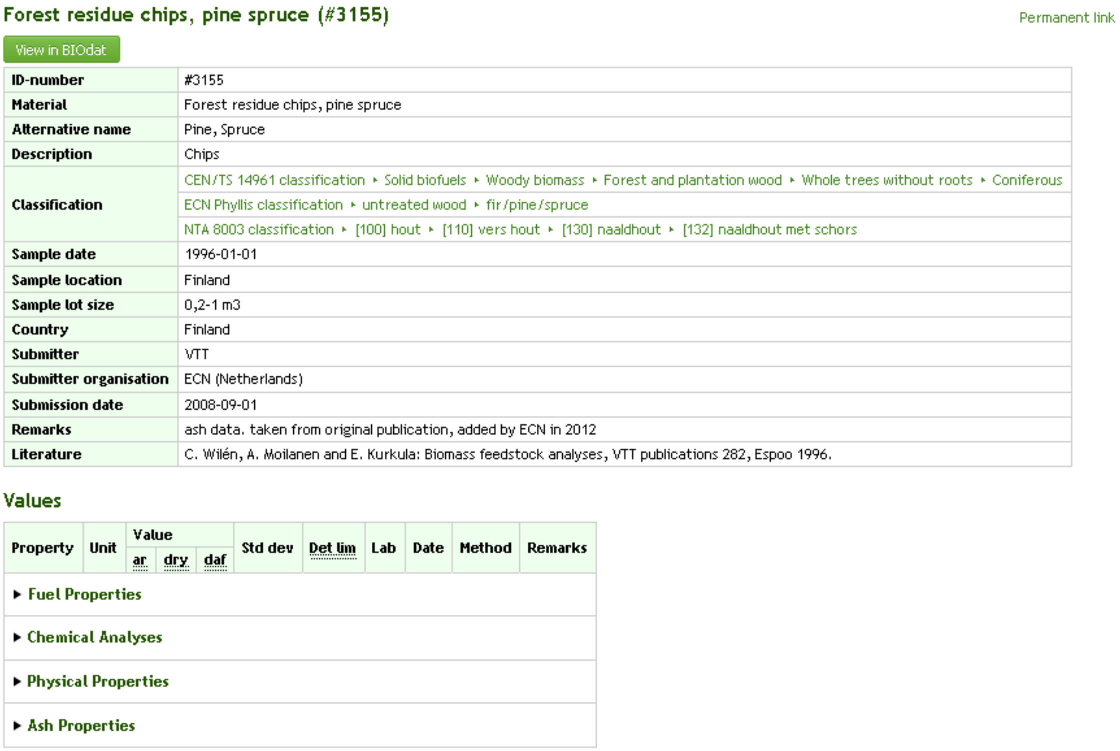


Figure 3.20. Methodology for evaluating biomass resources. Source: [3.15][3.16]

Basic Characterisation: Each type of biomass has specific physical and chemical properties that determine its performance as energy source. Main parameters to be taken into consideration include: water content, volatiles, hydrogen and carbon content, heating value, ash content and bulk density.



Forest residue chips, pine spruce (#3155)

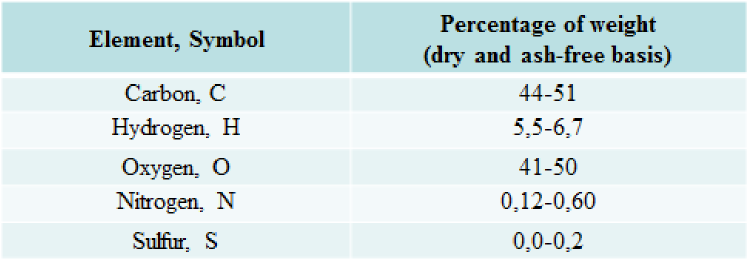
ID-number	#3155
Material	Forest residue chips, pine spruce
Alternative name	Pine, Spruce
Description	Chips
Classification	CEN/TS 14961 classification ▸ Solid biofuels ▸ Woody biomass ▸ Forest and plantation wood ▸ Whole trees without roots ▸ Coniferous ECN Phyllis classification ▸ untreated wood ▸ fir/pine/spruce NTA 8003 classification ▸ [100] hout ▸ [110] vers hout ▸ [130] naaldhout ▸ [132] naaldhout met schors
Sample date	1996-01-01
Sample location	Finland
Sample lot size	0,2-1 m3
Country	Finland
Submitter	VTT
Submitter organisation	ECN (Netherlands)
Submission date	2008-09-01
Remarks	ash data. taken from original publication, added by ECN in 2012
Literature	C. Wilén, A. Moilanen and E. Kurkula: Biomass feedstock analyses, VTT publications 282, Espoo 1996.

Values

Property	Unit	Value			Std dev	Det lim	Lab	Date	Method	Remarks
		ar	dry	daf						
▸ Fuel Properties										
▸ Chemical Analyses										
▸ Physical Properties										
▸ Ash Properties										

Figure 3.21. General Information of Pine spruce chips. Source: [3.22]

- *Moisture content* (%) is the quantity of water in the biomass residue expressed as percentage of the material's weight, which may be provided as wet, dry or dry-and-ash-free basis. This is particularly important parameter since biomass moisture can range from 10-70% on a wet basis, so it should always be mentioned.
- *Volatile matter content* (%) refers to the part of the biomass that is released when biomass residues are heated between 400° and 500°C. In this process biomass is separated into volatile gases and solid char, reaching a high volatile matter content of 80%, approximately.
- *Elemental composition*. Organic components of biomass are generally uniform. Major elements are carbon, oxygen, and hydrogen, together with small proportions of nitrogen.

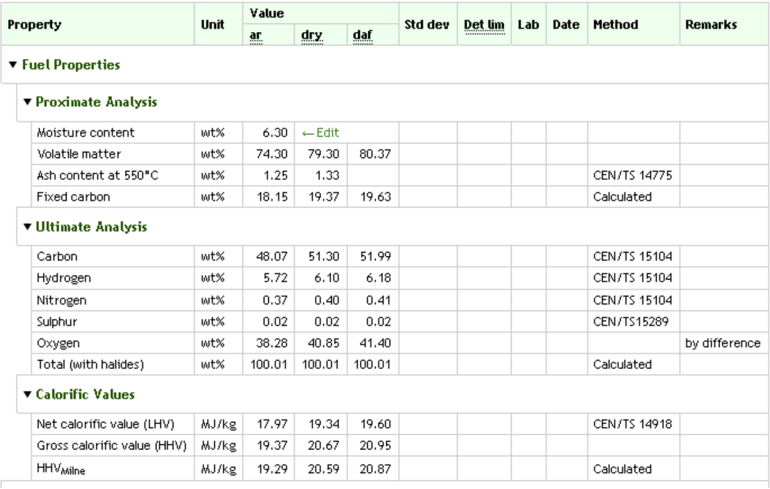


Element, Symbol	Percentage of weight (dry and ash-free basis)
Carbon, C	44-51
Hydrogen, H	5,5-6,7
Oxygen, O	41-50
Nitrogen, N	0,12-0,60
Sulfur, S	0,0-0,2

Table 3.5. Elemental composition of biomass. Source: [3.24]

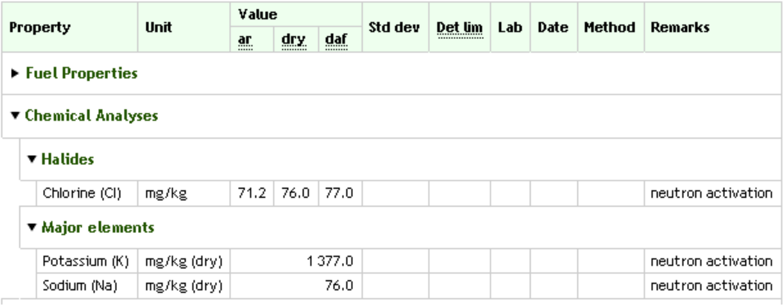
- *Heating value (MJ/kg)* specifies the chemical energy bound in the fuel in a standardized environment, expressed in Joule (J) per amount of matter (kg). It should be distinguished between lower heating value (LHV) and higher heating value (HHV). LHV refers when water is in a gaseous state while HHV, water is in liquid state. Heating value depends on the moisture of the material. Higher heating values as obtained as moisture content of biomass is reduced.
- *Ash content (%)* corresponds to the fraction of inorganic matter within biomass.
- *Bulk density (kg/m^3)* relates biomass weight with volume. It is commonly expressed as oven-dry-weight basis (moisture equal to cero) or as-is basis together with an indication of the moisture content. Similarly to the moisture, the range is very wide, from 150-200 kg/m^3 (cereal grain straws) to 600-900 kg/m^3 (solid wood). Together with heating value, bulk density represents the energy density, the potential energy per unit of biomass volume.

Information related to biomass elemental characterization is carried out using Phyllis database [3.22], actual measured data and scientific literature. Next it is provided an example of the information provided by Phyllis database: elemental biomass characterisation, chemical and physical properties of pine spruce chips.



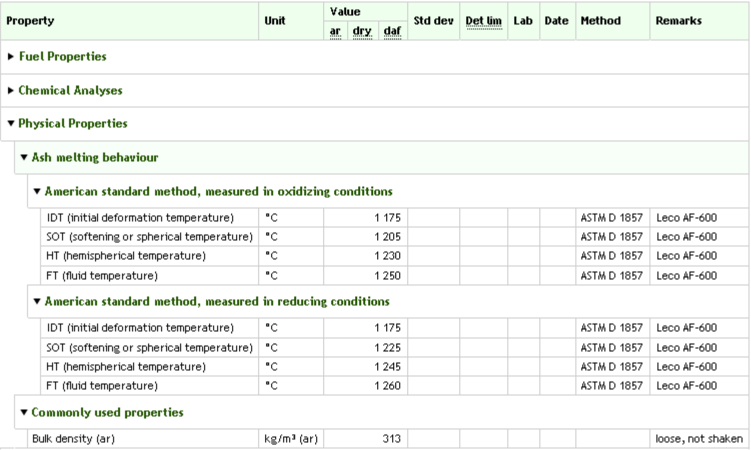
Property	Unit	Value			Std dev	Det lim	Lab	Date	Method	Remarks
		ar	dry	daf						
▼ Fuel Properties										
▼ Proximate Analysis										
Moisture content	wt%	6.30	← Edit							
Volatile matter	wt%	74.30	79.30	80.37						
Ash content at 550°C	wt%	1.25	1.33						CEN/TS 14775	
Fixed carbon	wt%	18.15	19.37	19.63					Calculated	
▼ Ultimate Analysis										
Carbon	wt%	48.07	51.30	51.99					CEN/TS 15104	
Hydrogen	wt%	5.72	6.10	6.18					CEN/TS 15104	
Nitrogen	wt%	0.37	0.40	0.41					CEN/TS 15104	
Sulphur	wt%	0.02	0.02	0.02					CEN/TS15289	
Oxygen	wt%	38.28	40.85	41.40						by difference
Total (with halides)	wt%	100.01	100.01	100.01					Calculated	
▼ Calorific Values										
Net calorific value (LHV)	MJ/kg	17.97	19.34	19.60					CEN/TS 14918	
Gross calorific value (HHV)	MJ/kg	19.37	20.67	20.95						
HHV$_{\text{Milne}}$	MJ/kg	19.29	20.59	20.87					Calculated	

Figure 3.22. Fuel Properties of Pine spruce chips. Source: [3.22]



Property	Unit	Value			Std dev	Det lim	Lab	Date	Method	Remarks
		ar	dry	daf						
▶ Fuel Properties										
▼ Chemical Analyses										
▼ Halides										
Chlorine (Cl)	mg/kg	71.2	76.0	77.0						neutron activation
▼ Major elements										
Potassium (K)	mg/kg (dry)	1 377.0								neutron activation
Sodium (Na)	mg/kg (dry)	76.0								neutron activation

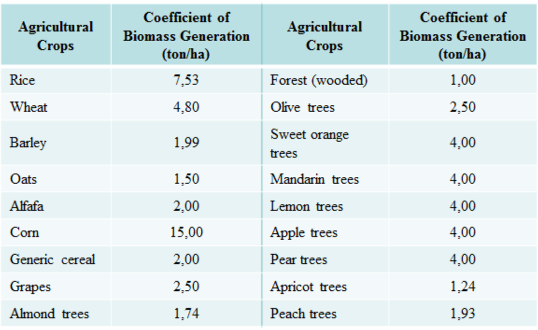
Figure 3.23. Chemical analysis of Pine spruce chips. Source: [3.22]



Property	Unit	Value			Std dev	Det lim	Lab	Date	Method	Remarks
		ar	dry	daf						
▶ Fuel Properties										
▶ Chemical Analyses										
▼ Physical Properties										
▼ Ash melting behaviour										
▼ American standard method, measured in oxidizing conditions										
IDT (initial deformation temperature)	°C	1 175							ASTM D 1857	Leco AF-600
SOT (softening or spherical temperature)	°C	1 205							ASTM D 1857	Leco AF-600
HT (hemispherical temperature)	°C	1 230							ASTM D 1857	Leco AF-600
FT (fluid temperature)	°C	1 250							ASTM D 1857	Leco AF-600
▼ American standard method, measured in reducing conditions										
IDT (initial deformation temperature)	°C	1 175							ASTM D 1857	Leco AF-600
SOT (softening or spherical temperature)	°C	1 225							ASTM D 1857	Leco AF-600
HT (hemispherical temperature)	°C	1 245							ASTM D 1857	Leco AF-600
FT (fluid temperature)	°C	1 260							ASTM D 1857	Leco AF-600
▼ Commonly used properties										
Bulk density (ar)	kg/m³ (ar)	313								loose, not shaken

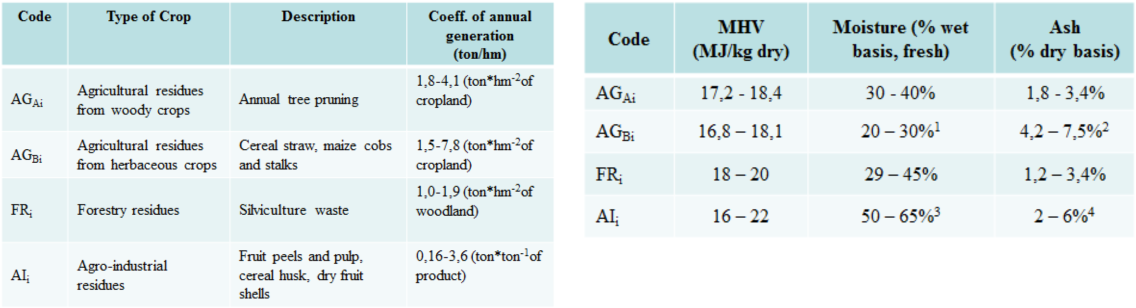
Figure 3.24. Physical properties of Pine spruce chips. Source: [3.22]

Quantification: provides the amount of biomass residues in a delimited area. It is expressed using coefficients of generation type of biomass, relating generated biomass residues per area (cultivated or forest). These coefficients are based on superficial generation coefficients, agricultural production versus generated residue, and industrial/agricultural activity in the area. They are defined for each agriculture type and forest zones by assigning a value for each residue production per cultivated hectare. Coefficients of generation of waste biomass are obtained from specialized literature [3.17][3.18][3.19][3.20][3.21] [3.22] and the experimental studies within the framework of BIOVAL[1] and PROBIOGAS projects.



Agricultural Crops	Coefficient of Biomass Generation (ton/ha)	Agricultural Crops	Coefficient of Biomass Generation (ton/ha)
Rice	7,53	Forest (wooded)	1,00
Wheat	4,80	Olive trees	2,50
Barley	1,99	Sweet orange trees	4,00
Oats	1,50	Mandarin trees	4,00
Alfafa	2,00	Lemon trees	4,00
Corn	15,00	Apple trees	4,00
Generic cereal	2,00	Pear trees	4,00
Grapes	2,50	Apricot trees	1,24
Almond trees	1,74	Peach trees	1,93

Table 3.6. Coefficients of biomass generation. Source: [3.16]



Code	Type of Crop	Description	Coeff. of annual generation (ton/hm)
AG$_{Ai}$	Agricultural residues from woody crops	Annual tree pruning	1,8-4,1 (ton*hm^{-2}of cropland)
AG$_{Bi}$	Agricultural residues from herbaceous crops	Cereal straw, maize cobs and stalks	1,5-7,8 (ton*hm^{-2}of cropland)
FR$_{i}$	Forestry residues	Silviculture waste	1,0-1,9 (ton*hm^{-2}of woodland)
AI$_{i}$	Agro-industrial residues	Fruit peels and pulp, cereal husk, dry fruit shells	0,16-3,6 (ton*ton^{-1}of product)

Code	MHV (MJ/kg dry)	Moisture (% wet basis, fresh)	Ash (% dry basis)
AG$_{Ai}$	17,2 - 18,4	30 - 40%	1,8 - 3,4%
AG$_{Bi}$	16,8 – 18,1	20 – 30%^{1}	4,2 – 7,5%^{2}
FR$_{i}$	18 – 20	29 – 45%	1,2 – 3,4%
AI$_{i}$	16 – 22	50 – 65%^{3}	2 – 6%^{4}

1 Fresh Maize cobs and stalks have a moisture content of 55-65%
2 Rice straw has ash content (in % dry basis) of around 18%
3 Dry fruits' shells and rice husk have low moisture content in the range 8-12% (in % wet basis)
4 Rice husk has an ash content (in % dry basis) of around 17%

Table 3.7. Quantification of Biomass resource. Source: [3.15]

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[1] BIOVAL is a project titled ''Optimization of the Energy Use of Biomass Resources in the Valencia Region'', funded by Valencian regional government and the European Fund of Regional Development; and PROBIOGAS corresponds to "Development of sustainable systems for biogas generation and use of agro-industrial residues in Spain", funded by the National government.

Biomass quantification is then estimated according to the following mathematical expression:

$$BQ_i = CA_i * CG_i \qquad \textbf{\textit{(3.25)}}$$

Where,

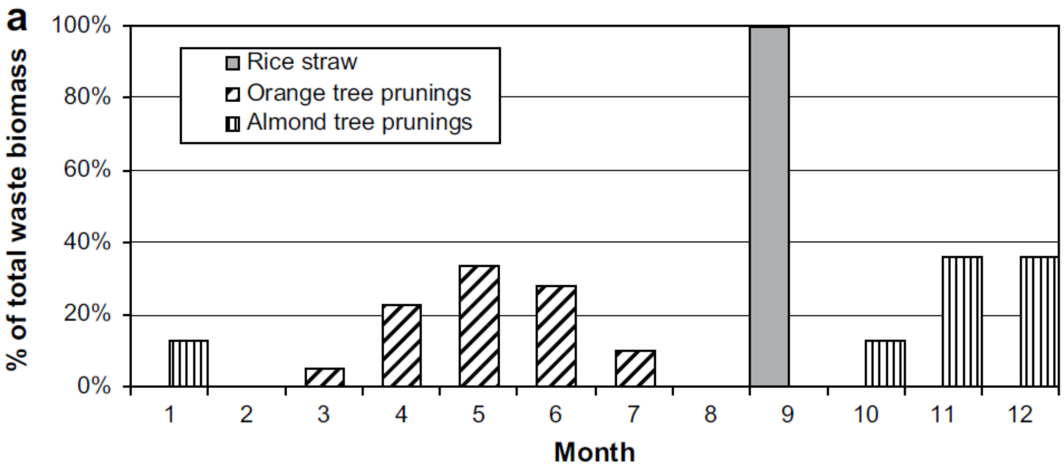
BQ_i: Quantification of biomass type *i* (ton/year).

CA_i: Cultivated area of biomass type *i* (ton/year).

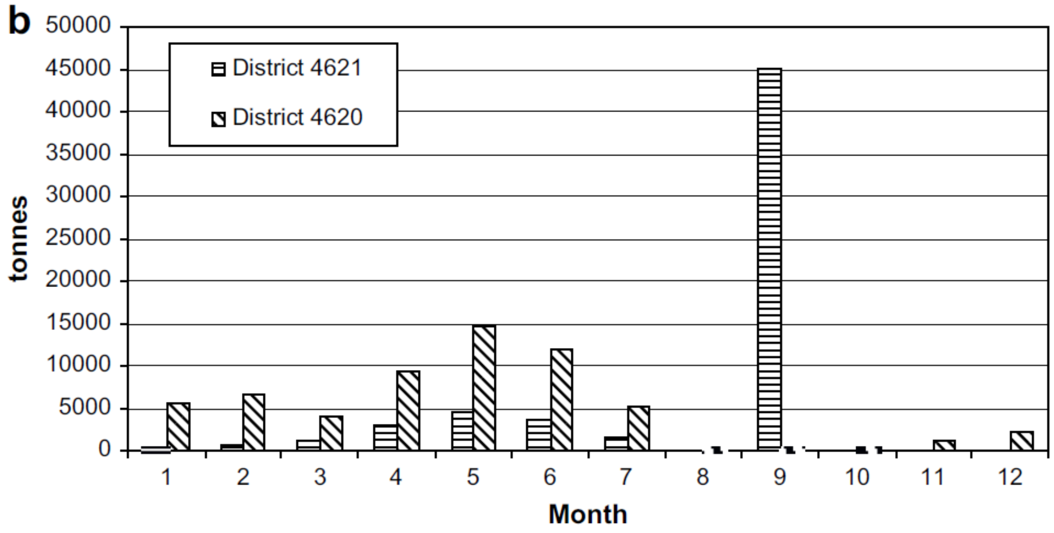
CG_i: Coefficient of generation for biomass type *i* (ton/year).

Seasonality indicates when biomass residues are produced and collected. It can be evaluated in a monthly basis according to typical labour operations during the year for each crop (for agricultural wastes) and typical production cycles for industries. Figure 3.25 provides an example of a typical seasonality analysis for several agricultural crops (tree pruning and cereal straw). Besides, it shows the aggregated seasonality analysis of an area or district, estimated as the addition of all biomass mass per month.

Dispersion refers to the transport time and distances between biomass recollection points (x_i) and their destination (y_j). Computing transport time and distances between two generic points x (origin) and y (destination) are based on road network characteristics and accessibility of the biomass in the area under study. Sources or origins of biomass are known and destination can be either fixed by the restrictions of the considered scenario (i.e. presence of small power plants, clinics, industrial customer, etc.) or by applying an algorithm of transport costs minimization (according to transport time or distance), which is the most usual approach to define optimum location of the biomass plant for a considered area.



(a) Single crops



(b) Aggregated seasonality for areas.

Figure 3.25. Seasonality of agricultural waste biomass

In addition, dispersion analysis deals with logistic structure and cost of biomass transportation (maximum weight of transport unit and previous densifications in bales, if any). Biomass transport cost function is composed by fixed costs and distance dependent costs.

$$BTC\ (x,y) = \frac{FC + DC * Dist\ (x_i, y_j)}{TUC * NR} \qquad \textbf{\textit{(3.26)}}$$

Where,

$BTC\ (x,y)$: cost of a single run transporting biomass from point x to point y (€/ton).

FC: fixed cost due to loading/unloading (FC_f) and compaction (FC_v) operations (k€/unit).

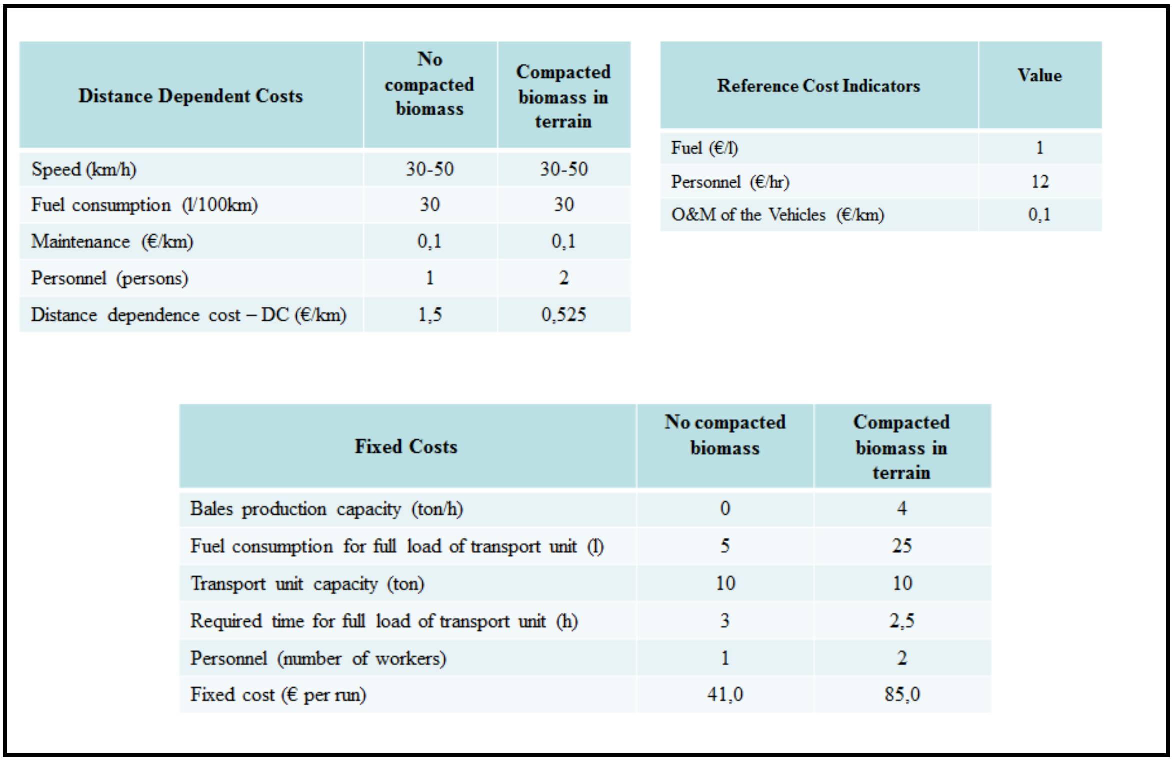
DC: distance dependent costs (fuel consumption, operation and maintenance of a transport unit), (k€/km).

$Dist\ (x_i, y_j)$: one-way distance between point x and point y (km).

TUC: transport unit or truck capacity (ton).

NR: number of runs.

These considerations are based on real experience of enterprises dealing with biomass collecting and transport in Spain, and machinery specifications from manufacturers.

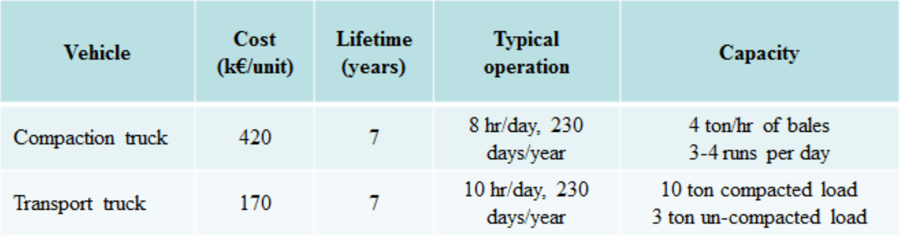


Distance Dependent Costs	No compacted biomass	Compacted biomass in terrain
Speed (km/h)	30-50	30-50
Fuel consumption (l/100km)	30	30
Maintenance (€/km)	0,1	0,1
Personnel (persons)	1	2
Distance dependence cost – DC (€/km)	1,5	0,525

Reference Cost Indicators	Value
Fuel (€/l)	1
Personnel (€/hr)	12
O&M of the Vehicles (€/km)	0,1

Fixed Costs	No compacted biomass	Compacted biomass in terrain
Bales production capacity (ton/h)	0	4
Fuel consumption for full load of transport unit (l)	5	25
Transport unit capacity (ton)	10	10
Required time for full load of transport unit (h)	3	2,5
Personnel (number of workers)	1	2
Fixed cost (€ per run)	41,0	85,0

Table 3.8. Parameters costs for Biomass transportation. Source: [3.15]



Vehicle	Cost (k€/unit)	Lifetime (years)	Typical operation	Capacity
Compaction truck	420	7	8 hr/day, 230 days/year	4 ton/hr of bales 3-4 runs per day
Transport truck	170	7	10 hr/day, 230 days/year	10 ton compacted load 3 ton un-compacted load

Table 3.9. Vehicles for biomass compacting and transportation. Source: [3.15]

At this point, it is possible to have a first estimation of the theoretical potential of biomass in the area, since it has been studied the biomass residues properties and had been quantified by means of analysing their physical and chemical properties, quantification coefficients, seasonality and dispersion. However, not all theoretical biomass identified in the area can be used for energy generation. In many cases, biomass is not available because the trucks don't have accessibility to the terrain, because environmental or governmental constraints, or just because biomass residues are employed for other uses, besides energy production.

Accessibility: refers to the areas where biomass cannot be collected, due to social, political or environmental limitation, or just because the transportation vehicles don't have accessibility to the farm. Some of these restricted areas include environmental protected areas, wetlands and lakes, electric lines, etc., or for the case of agricultural waste biomass, global accessibility is estimated between 20–40% [3.18] and [3.19].

Availability represents the part of the theoretical biomass that has other uses besides energy production. Some of these are domestic fuel for heating and cooking, animal feeding, or furniture use.

Finally, total available biomass for energy valorisation is then estimated according to the following mathematical expression:

$$TAB = BP * C_{ac} * C_{av} \qquad \textbf{\textit{(3.27)}}$$

Where,

BP: Theoretical biomass potential (ton/year).

C_{ac}: Accessibility coefficient

C_{av}: Availability coefficient.

3.2.2 Load Profiles

A detailed study of the different load profiles of a village (residential, commercial and industrial) is important for determining the electrical needs of the community. Using this profile, it could be possible to identify renewable hybrid configurations to supply energy to it. Initial step is the identification of the main consumption in residential (households), commercial (health clinic, school, etc.) and industry (bakery, small business, etc.).

Most typical load curve for rural villages is normally composed by 3 main components: a base load, a morning/middle peak and an evening peak (see Figure 3.26). First one is the base load, which generally represents night and early morning hours with limited or non-existent load during nocturne hours in the case of small communities. This load level is generally low compared with the morning-middle and evening peaks. Second one is the morning-middle peak, which builds from base load and refers to the activities from breakfast to lunch. Last one corresponds to evening activities, which is the highest peak and refers to lighting and entertaining activities, such as TV watching. In many cases this peak load is two to five times higher than the highest power level of the base load. As it may be deduced, this day profile is very similar to the one in residential sector (households). In this context, power generation systems are generally based on renewable technologies such as PV, wind, hydro or biomass, together with a storage system (battery bank) and a back-up generation system like a diesel generator.

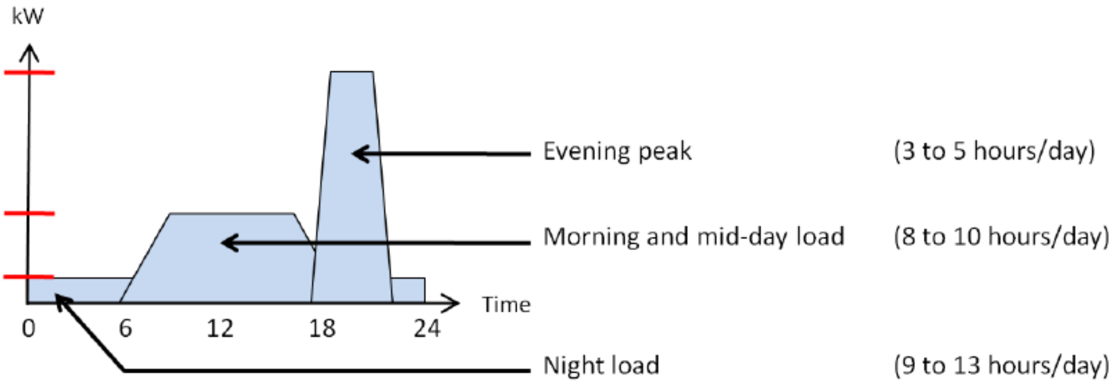


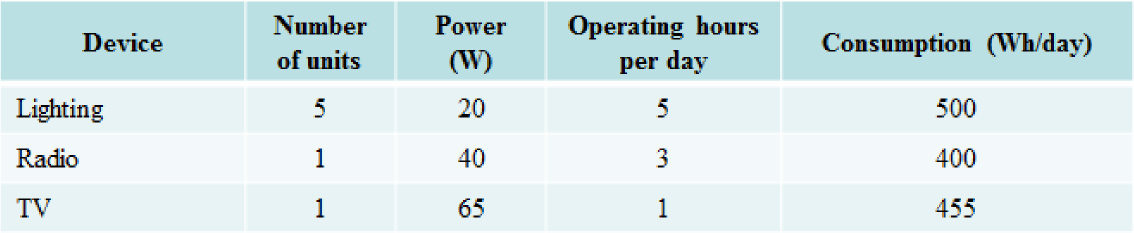
Figure 3.26. Typical load of a village. Source: [3.25]

Electric demand of the community is estimated by the load demanded by each appliance or device during time period. In order to design and dimension an appropriate HRES system to supply electric demand to a village, it is necessary to assess its electrical needs, either estimating user's behaviour or carrying out a measuring campaign. Next sections describe most common loads within each sector (residential, commercial and industrial).

3.2.2.1 Residential

Residential demand generally depends on economic status of the family and power supply availability. **Households** profile usually shows that electricity is used during two or three periods during the day, as mentioned in the previous section. Morning and evening peaks are most common, although a middle peak is observed in prosperous homes. In general base load is cero, although in some cases a minimum demand was observed as a result of the radio, TV or lights operating 24 hours per day, especially in the family that could afford it [3.26].

Main consumptions include lighting and entertainment devices, such as radio, tape recorder and TV devices. No fridge is identified due to the natural conservation of the food that is a habit in rural villages. A typical daily load profile of a single home with four family members normally includes 5 hours of lighting (5 lamps of 20W), 10 hours with the radio on, especially in the morning and mid-day, and 7 hours of TV watching, mainly during mid-day and evenings.



Device	Number of units	Power (W)	Operating hours per day	Consumption (Wh/day)
Lighting	5	20	5	500
Radio	1	40	3	400
TV	1	65	1	455

Table 3.10. Typical household loads.

Daily energy demand of a household may range from 160 to 2750 Wh/day depending on the economic status of the family. Thus, total residential demand of a village is estimated according to the number of households in the community.

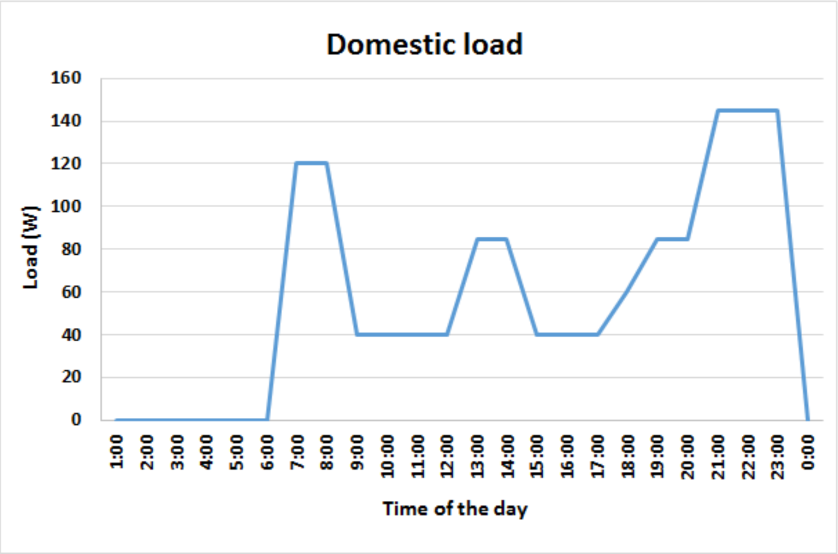
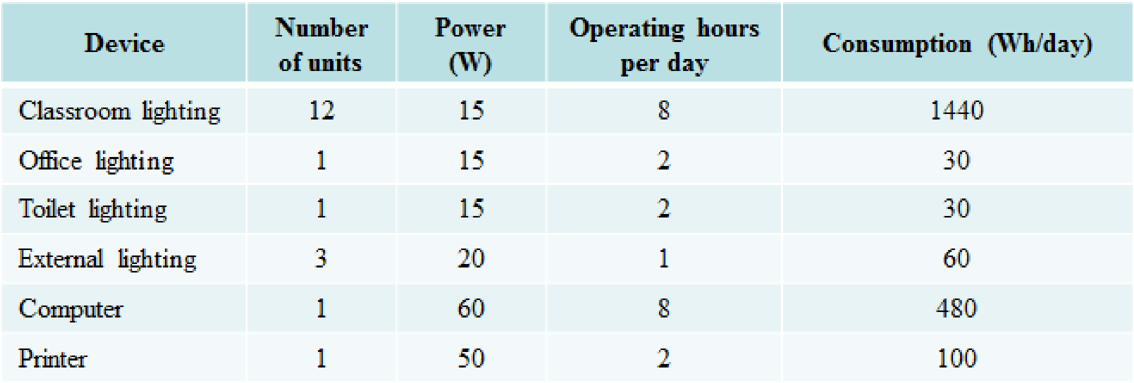


Figure 3.27. Typical load profile of a household.

3.2.2.2 Commercial

Commercial load normally refers to community services, which generally include schools and health centres, two essential services for the socio-economic development of a community.

Schools load profile shows primarily lighting demand in classrooms, offices and external areas, computer and printer usage, and, occasionally, radio or TV utilisation for lesson topics. If the school includes an evening programme for adult education or a distant learning programme, energy consumption associated to these activities should also be considered. Load profile in schools differs within seasons (winter and summertime) and type of day (workday or weekend). Next it is provided a typical load that may be found in a school during workdays in a school period.



Device	Number of units	Power (W)	Operating hours per day	Consumption (Wh/day)
Classroom lighting	12	15	8	1440
Office lighting	1	15	2	30
Toilet lighting	1	15	2	30
External lighting	3	20	1	60
Computer	1	60	8	480
Printer	1	50	2	100

Table 3.11. Typical school loads.

Main energy demand occurs occur from 9:00 – 12:00 hr and 14:00-18:00 hr due to classrooms teaching. The computer is being used in the time intervals 9:00 – 12:00 hr and 14:00-18:00 hr while printer is only on from 15:00 to 17:00 hr. External lighting is operating between 18:00 and 19:00 hr once natural light is not available and students are exiting school to go home.

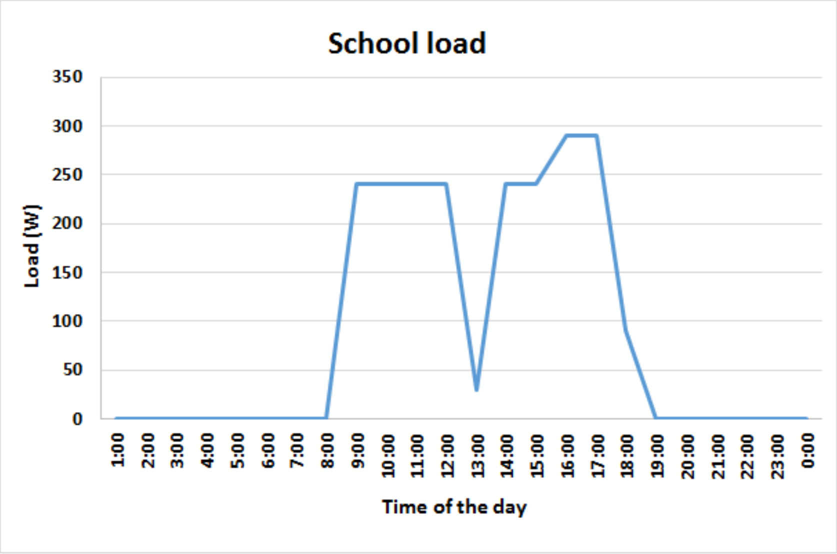


Figure 3.28. Typical load profile of a school

Main loads in a **health centre** are external and indoor lighting, a vaccine freezer, a communication system, a microscope, a printer, a computer and a TV. Based on the fact that is a health clinic attending medical urgencies, external lighting is operating all night between 21:00 and 9:00 hr, while rooms lighting is on from 11:00 to 15:00 hr and from 16:00 to 20:00 hr. The vaccine freezer is working 24 hr per day to preserve the medical supply. Communication devices are in operation from 11:00 to 15:00 hr and from 16:00 to 20:00 hr, together with the computer. Printer only work from 14:00 – 16:00 hr. The microscope is in operation from 8:00 to 12:00 hr. Finally, the TV is considered to be turned on between 8:00 and 20:00 hr.

Device	Number of units	Power (W)	Operating hours per day	Consumption (Wh/day)
Room lighting	8	15	8	960
External lighting	2	20	12	480
Communication radio	1	5	8	40
TV	1	65	12	780
Computer	1	60	8	480
Printer	1	50	2	100
Microscope	1	20	5	100
Vaccine Freezer	1	60	24	1440

Table 3.12. Typical health centre loads.

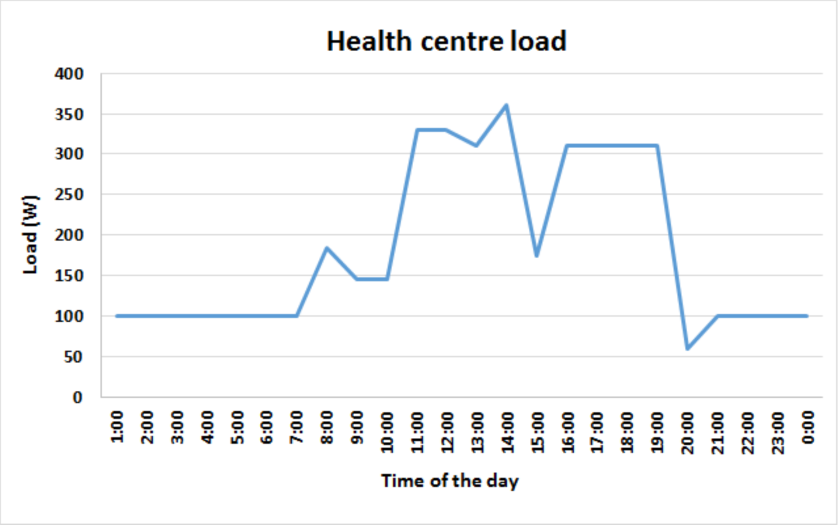


Figure 3.29. Typical load profile of a health centre

3.2.2.3 <u>Industrial</u>

Basic local industry generally involves a bakery and a milling process to grinder the cereal or the flour capable to serve nearby communities. **Milling machine** has a power capacity of 12,5 kW and it normally operates on a daily basis from 9:00 to 12:00 hr and from14:00 to 16:00 hr, which requires a power supply of approximately 62,5 kWh per day.

The **baking** machine has a power rating of 2,5 kW and its operation takes place in two work shifts. The first one is in the morning between 7:00 and 9:00 and the other between 16:00 and 18:00 hr.

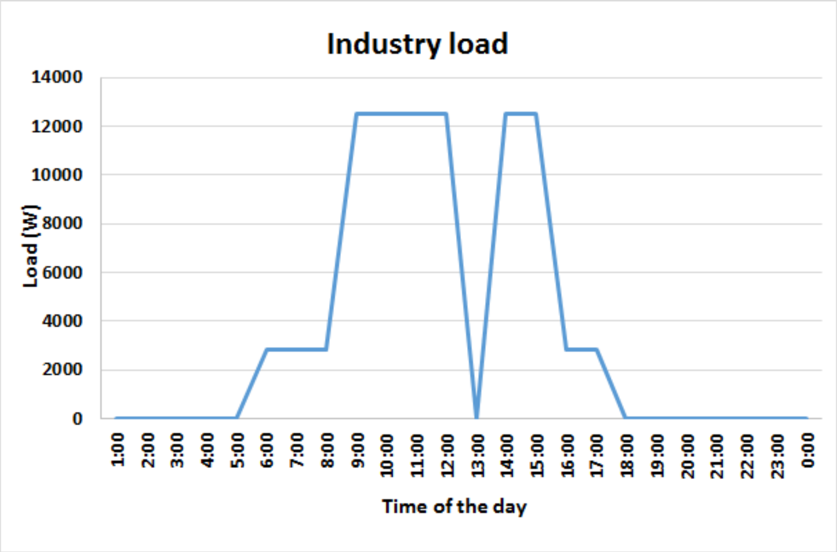


Figure 3.30. Typical load profile of a bakery and milling process

3.2.2.1 <u>Agricultural</u>

Main load in agriculture is irrigation, which refers to the water needed for sustainable faming of crops. Water demand for this purpose is provided throughout electrical water pumping from water reservoirs and storm water deposits to the farms using pump units of approximately 500-600W, each delivering approximately 20-25 m^3

per day. This pump operates 8 hours with an estimated electric consumption of 4-5 kWh per day except during rainy seasons, where irrigation is not necessary and the pumps are inoperative. This type of demand can be fulfilled at any time during the day, since pumped water can be storage in deposits nearby the farms. Therefore, this demand has a high level of flexibility.

3.2.3 Demand Side Management

Demand side management (DSM) are activities designed to influence how customers use electricity to produce changes in the load shape, such as the time pattern or the magnitude of the load. DSM generally encourages customer's participation through economically incentivizing modification in energy usage patterns, changes in energy consumption timing or the amount of energy demanded. Benefits from these actions derive in energy savings, power shedding reduction, reliability improvement of the micro-grid and mitigation of the harness produced by renewable energies fluctuation.

DSM strategies are performed by customers but carried out automatically by utilities using communication and embedded system technologies which are usually cheaper than a new power plant or a storage system. Different types of Demand Response (DR) strategies guide customer participation to achieve a more reliable grid through responsible consumer's behaviour by means of energy conservation, energy efficiency, load curtailment and fuel substitution programs. Advanced metering infrastructure (AMI) with intelligent switching devices allows easy access to real time data, facilitating DSM actions; however it requires investment on infrastructure. It also needs to be highlighted that key aspects in DSM implementation are social acceptance and consumer awareness in order to be successful [3.27][3.28].

Main types of demand response mechanisms are tariff pricing and economic incentives for customers.

Price-based [3.29]. In this instrument, customers decide when to consume. There are different electricity prices depending on the time of the day. This instrument encourages consumers to have specific usage patterns, consuming energy during periods with lower tariffs in order to reduce their electrical bills [3.30].

- *Time of use (TOU):* Tariffs are designed based on the time electricity is used, leading to changes in consumption patterns. These rates may be different for weekdays/weekends and/or season time (summer and winter), since usage patterns are also variable.
- *Time of day (TOD)*: Similar to TUD, tariffs are defined based on daily time slots generally organised in *on-peak*, *off-peak* and *shoulder peak*. Electricity rates vary depending on the time slot, allowing consumers to shift their activities to off peak and mid peak periods, thereby achieving financial savings.
- *Real Time Pricing*: In this mechanism, the price of electricity varies on an hourly basis according to the electricity price in the wholesale energy exchange market. Customers are usually priced-updated on a daily or hourly ahead basis.
- *Critical Peak Pricing* (CPP): This mechanism introduces high prices in specific time periods to dissuade customers from energy consumption in case of critical events, such as power system emergencies or high electricity prices in wholesale.

Incentive-based [3.30]. In this different approach, programs are implemented by the energy utilities, while customers are incentivized for allowing them to reduce their load. Most common instruments are:

- *Direct Load control:* Customers willingly enrol in this program allowing utilities to control their loads in previously agreed situations (thermostat, water heat, etc.). Energy companies install electrical control devices in the customer side to remotely control their energy consumption while customers are incentivized.

- *Interruptible Load:* This instrument involves a contract between the customer and the energy utility, wherein the customer agrees to be electrically interrupted when there is a peak in power demand and/or energy generation is limited. In compensation, the customer receives discount rates in their bills or other concessions from the energy company. Once the customer gets a notice from the system operator, electrical supply is suspended. In these cases, the customer is noticed with enough time to shift the loads to other time period, or redirect their loads to other local generators or storage system.
- *Emergency Program:* This instrument is used by utilities when an emergency event occurs, such as limited renewable generation or reserve shortfall. Customers are incentivized for curtailing loads.

3.2.4 Technologies

Renewable hybrid systems (HRES) are a combination of several renewable power systems supported by a storage system. By combining different technologies, individual weaknesses of the systems may be overcome achieving a more reliable alternative. HRES power systems in rural environments are widely used for off-grid electrification, providing energy access to millions of customers, especially in developing countries. Within this context, HRES power systems are normally installed using three main configurations, from simplest to more complex.

- Renewable stand-alone power systems (with or without storage).
- HRES with batteries or other storage systems.
- Micro-grid systems.

Throughout this section, technical and economical characterization of single technologies is provided in order to understand the limitations, but also strong aspects, of each component. Studying each of the three main renewable technologies will allow identifying their synergies for electrifying isolated villages.

3.2.4.1 *Solar Photovoltaic System*

The need for low cost but reliable energy in isolated areas is the main driver for photovoltaic system implementation in these areas. Many of the applications in remote communities are powered by photovoltaic systems due to its reduced cost compared with the rest of alternatives. PV technology converts solar energy into electricity using semiconductor cells made of crystalline silicon, transforming approximately 15-20% of solar radiation into electricity; although there is a continuous research development in this area (see Figure 3.31).

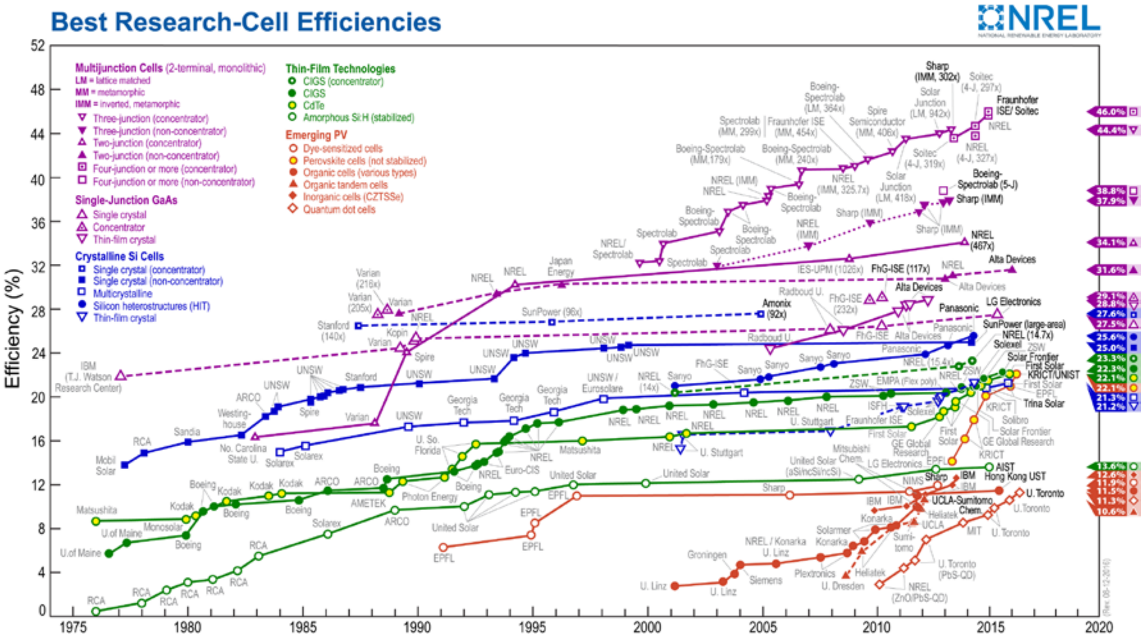


Figure 3.31. PV cells efficiencies (National Renewable Energy Laboratory, 2016)

Mainly, it can be distinguished three categories, depending on the material used: monocrystalline, polycrystalline and thin film [3.31].

- *Mono-crystalline PV Cells*: this type of cell has a high efficiency in terms of power output and panel capacity, but the cost is also high. This technology has the ability to convert 1000 W/m^2 of solar radiation to around 140W of electricity per m^2 of panel surface [3.31]. Most manufacturers of this type of cells offer a 25-year warranty on their solar panels.

- *Polycrystalline PV Cells:* it is the most used type of cell nowadays since it is less expensive than monocrystalline and offer efficiency ratios close to monocrystalline panels. It is capable to convert an incident solar radiation of 1000 W/m^2 into approximately 130W per m^2 of surface area, but perform better than the mono-crystalline in slightly shaded conditions [3.31]. Lifetime of these types of cells is between 20-25 years.
- *Thin Film PV Cells:* These types of cells are less expensive than the other two mentioned, but are also less efficient, showing efficiencies ranging from 5% to 13% with a lifespan of approximately 15-20 years.

In addition, solar energy exploitation depends on the tracking system mounting the PV panel, which is basically used to position the PV panel towards the sun. This allows harvesting additional solar radiation striking the PV array. Solar tracking systems are organized according the number and position of the tracking axes:

- *No tracking*: It is the simplest and cheapest method, since no tracking is used. Photovoltaic panels are mounted at a fixed slope and azimuth, preferably toward equator (south in the northern hemisphere) and the tilt angle is based on the latitude.
- *Horizontal axis:* This type of tracking system rotates horizontally from east to west direction adjusting the angle of the PV inclination to the sun. Static adjustment is carried out on a time basis, such as daily, weekly or monthly basis. Moreover, in the continuous adjustment, the slope is automatically adjusted in order to maximize incident solar radiation.
- *Vertical axis*: axis of rotation is vertical with respect to the ground surface. The slope is fixed, but the azimuth is continually adjusted to minimize the angle of incidence.
- *Two axes*: Solar panels are rotated in both axes, from east to west and from north to south. However, this is the most expensive method.

PV technology is the most competitive solution for areas with no access to the electric grid and small power requirements (around10 kW_p or less). In these cases, PV generation is used in load-following mode and then, by charging the batteries with the excess of energy produced by the PV array when load demand is less than the production, thus allowing extending electric power during night hours. Another option would be to design the PV and storage system to respond to a battery bank charging cycle, thus guaranteeing electrical supply despite solar radiation is not available.

Moreover, main applications in off-grid set ups are:

- Stand-alone PV systems with or without a battery bank.
- PV array with a storage system and a genset as back-up unit.
- Single PV systems specifically for water pumping.

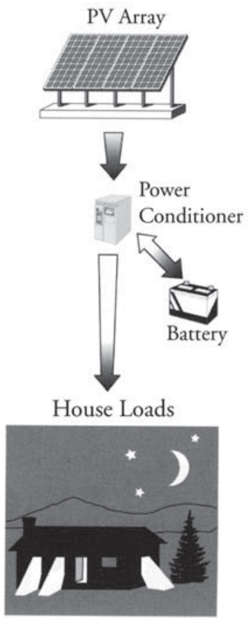


Figure 3.32. Stand-alone Off-grid PV system. Source: [3.32]

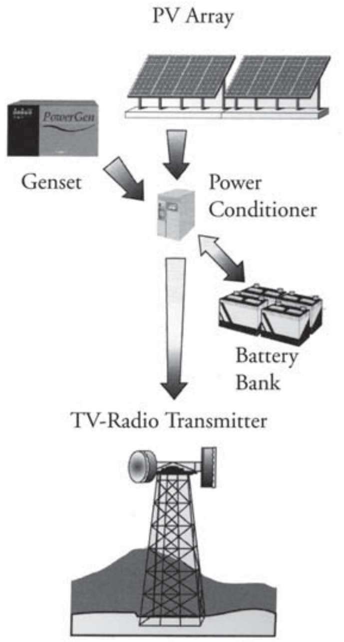


Figure 3.33. Hybrid off-grid PV system. Source: [3.32]

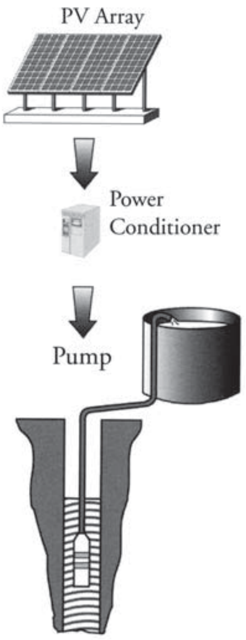


Figure 3.34. Water pumping PV system. Source: [3.32]

Calculation of PV power output is carried out considering: incident solar radiation, PV power capacity under standard conditions (incident solar radiation of 1 kW/m2, cell temperature equal to 25°C, and no wind), a PV derating factor to consider real conditions (factors as panels soiling, wiring losses, shading, etc.) and temperature.

$$P_{PV} = P_{PV,STC} * f_{PV} * \left(\frac{G_{PV}}{G_{PV,STC}}\right) * \left[1 + \alpha_{PV}\left(T_c - T_{c,STC}\right)\right] \qquad \textbf{\textit{(3.28)}}$$

Where,

P_{PV}: Actual PV power output (kW).

$P_{PV,STC}$: PV power output under standard conditions (kW).

f_{PV}: PV derating factor (%).

G_{PV}: solar radiation reaching the PV array at each time period (kW/m^2).

$G_{PV,STC}$: incident solar radiation at standard conditions (kW/m^2).

α_{PV}: temperature coefficient of power (%/ºC).

T_c: PV cell temperature at each time period (ºC).

$T_{c,STC}$: PV cell temperature at standard conditions (25ºC).

3.2.4.2 Wind Turbines

During many years, windmills have been used to harvest energy from the wind using wind turbines. Similarly to photovoltaics systems, they may work as stand-alone systems, integrated in a HRES system or within a micro-grid approach. In the case of stand-alone wind systems, these are mainly used when solar radiation is not available, since its high variability and intermittence makes difficult to predict the generation and to follow the load. Wind power systems are mainly used together with a battery bank in order to storage the energy when it is produced and use it when it is needed. Furthermore, small wind power machines may be integrated in a micro-grid, generating energy when wind is available and using the micro-grid as a global approach to manage generation, supply and demand.

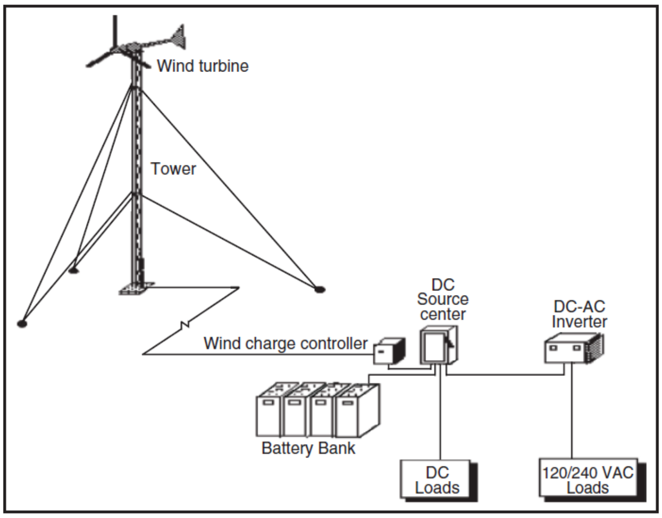


Figure 3.35. Wind power with storage system. Source: [3.33]

Power output from wind turbines mainly depends on the wind speed, but there are also other parameters that should be considered, as it was showed in previous sections. Rotor area, rotor efficiency and wind flow, together with electrical and mechanical losses will determine the final electrical output, which will be less than the power obtained from the turbine blades. At this stage, mechanical and electrical efficiencies of the generation system are considered to obtain final power output [3.34]. Thus, additional efficiencies to characterise these processes are applied to the theoretical maximum wind power output (W).

$$P_w = \frac{1}{2} * C_p * \rho * A * v^3 * \eta_m * \eta_e \qquad \textit{(3.29)}$$

Where

P_w: is the wind power output (kW)

C_p: is the coefficient of performance (%)

ρ: air density (kg/m^3)

A: rotor swept area (m^2)

v: wind speed (m/s)

In addition to this, final electrical output depends on the working curve of the wind turbine. This is specific from each wind machine and it is characterised and provided by the manufacturer. In general terms, this working curve may be divided in three main areas: Cut-in wind speed, nominal wind speed and cut-out wind speed. Figure 3.36 illustrates the power curve of a wind turbine, which shows power output variation with respect to the wind speed variation.

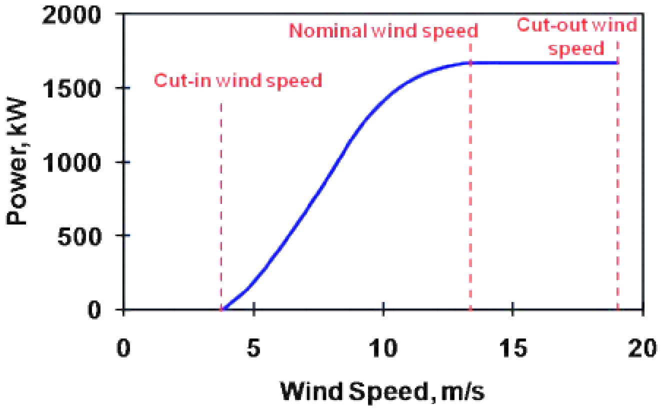


Figure 3.36. Characteristic power curve of wind turbine. Source: [3.35]

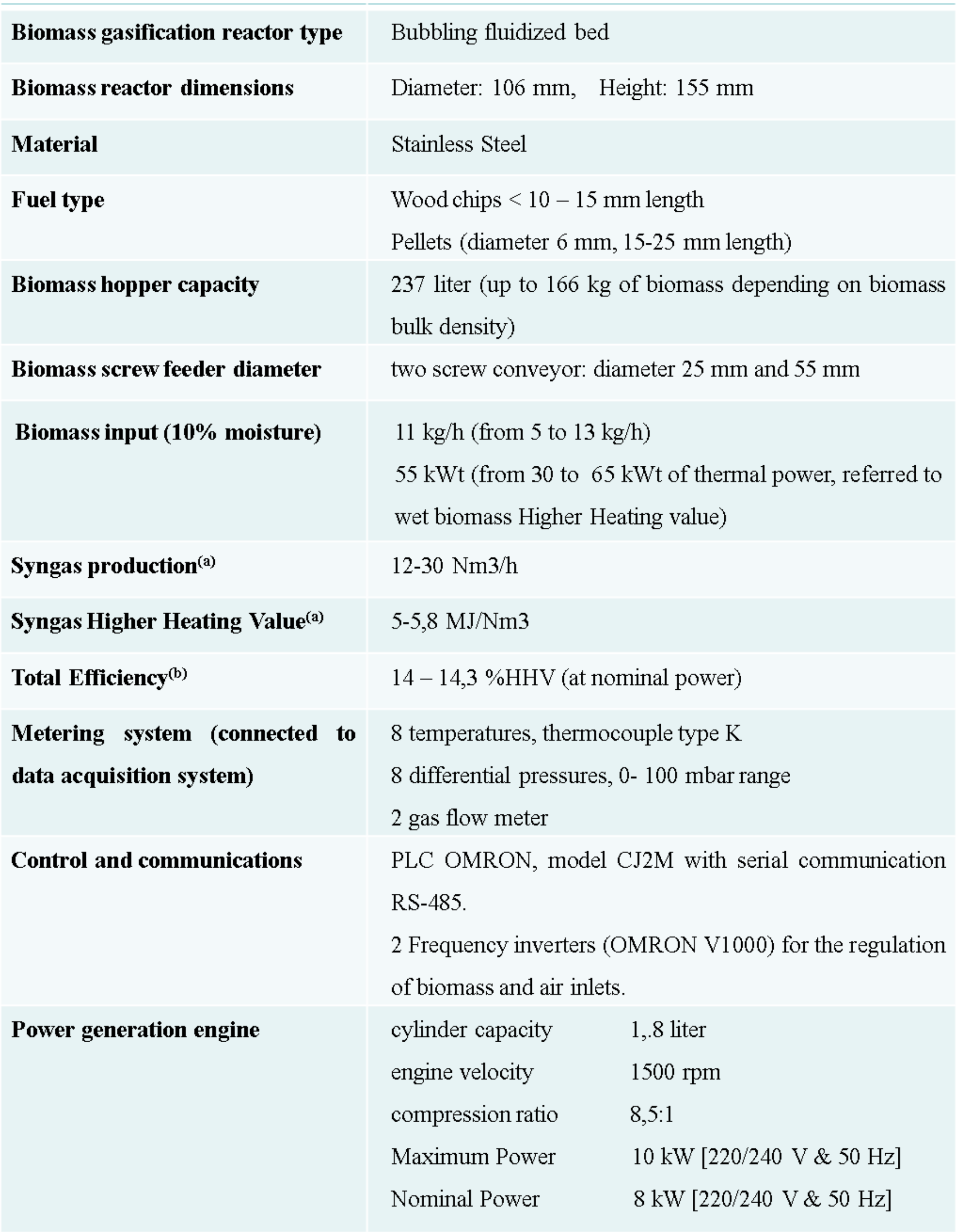
- *Cut-in Wind Speed:* Corresponds to the wind speed at which the wind turbine starts generating power. Below this wind speed limit, the wind machine will not operate and therefore, will no generate any power output. Small power capacity windmills have normally a cut-in around 2-4 m/s.
- *Cut-off Wind Speed*: refers to the high limit wind speed at which the wind turbine operates. Above this limit, the turbine stops in order to avoid damage and does not generate any more power. For most turbines the cut off speed is 25 m/s [3.36].

- *Nominal or Rated Wind Speed*: denotes the wind speed at which maximum power output is delivered by the wind turbine. For most turbines the rated wind speed is between 11,5 to 15 m/s [3.36].
- *Survival Speed*: represents the wind speed beyond the cut out wind speed that the wind turbine machine cannot withstand. The range of survival speed is usually between 50 to 60 m/s [3.36].

3.2.4.3 Biomass gasification

Biomass gasification power system (BGPS) is composed by a biomass feeding system, a bubbling fluid bed reactor, a gas cleaning & cooling system (including cyclone, heat exchanger and multi-stage filter) and a gas internal combustion engine for power generation, together with the control and monitoring system. BGPS is based on an experimental system developed and tested at the Institute for Energy Engineering. The gasification power system has a capacity output of 10 kW and requires a biomass input of 11-13 kg/h (10% of moisture), producing around 27-33 Nm^3/h of syngas that is burnt in an internal combustion engine that moves an electricity generator.

Next, Table 3.12 includes main features of the experimental BGPS. For the feasibility analysis, BGPS in the range of 0 – 100 kW have been considered. Nominal electric efficiency and partial load efficiency of these plants have been considered as the tested experimental BGPS, minimum partial load has been considered as 50% [3.37][3.38].



Biomass gasification reactor type	Bubbling fluidized bed
Biomass reactor dimensions	Diameter: 106 mm, Height: 155 mm
Material	Stainless Steel
Fuel type	Wood chips < 10 – 15 mm length Pellets (diameter 6 mm, 15-25 mm length)
Biomass hopper capacity	237 liter (up to 166 kg of biomass depending on biomass bulk density)
Biomass screw feeder diameter	two screw conveyor: diameter 25 mm and 55 mm
Biomass input (10% moisture)	11 kg/h (from 5 to 13 kg/h) 55 kWt (from 30 to 65 kWt of thermal power, referred to wet biomass Higher Heating value)
Syngas production(a)	12-30 Nm3/h
Syngas Higher Heating Value(a)	5-5,8 MJ/Nm3
Total Efficiency(b)	14 – 14,3 %HHV (at nominal power)
Metering system (connected to data acquisition system)	8 temperatures, thermocouple type K 8 differential pressures, 0- 100 mbar range 2 gas flow meter
Control and communications	PLC OMRON, model CJ2M with serial communication RS-485. 2 Frequency inverters (OMRON V1000) for the regulation of biomass and air inlets.
Power generation engine	cylinder capacity 1,.8 liter engine velocity 1500 rpm compression ratio 8,5:1 Maximum Power 10 kW [220/240 V & 50 Hz] Nominal Power 8 kW [220/240 V & 50 Hz]

a Syngas production and higher heating value referred to normal cubic meter, Nm3, so volume at temperature of 0 ºC and absolute pressure of 1 atmosphere (101325 Pa).

[b] Total efficiency computed as the ratio generated electricity to wet biomass input.

Table 3.13. Main features of experimental biomass gasification power plant. Source: [3.37].

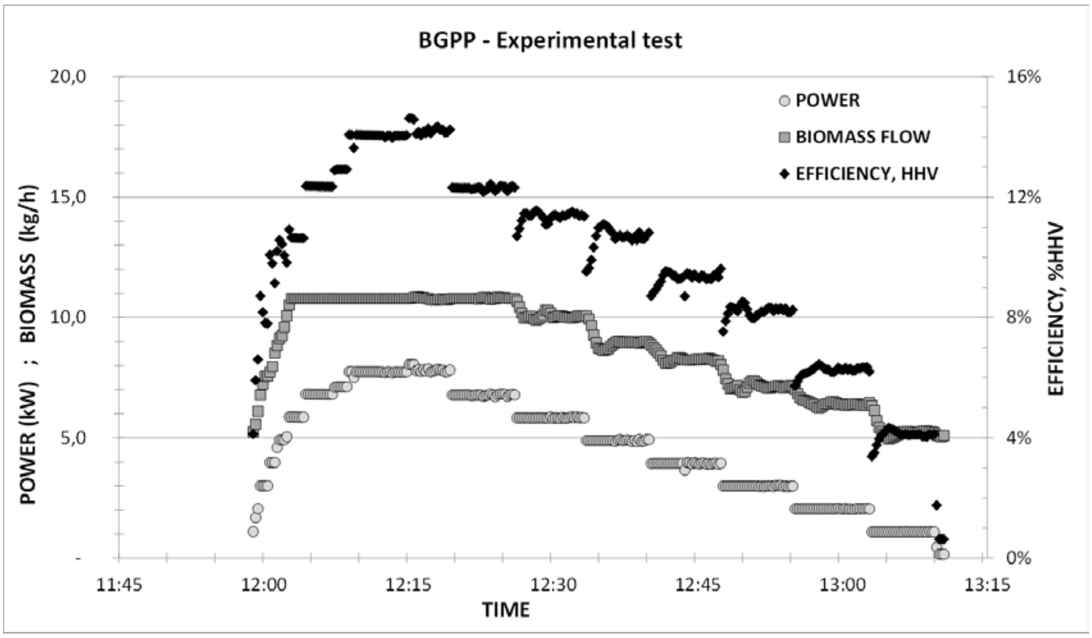


Figure 3.37. Biomass gasification power plant efficiency with pellets. Source: [3.37].

3.2.4.1 Diesel genset

Combustion engines are the simplest and most common non-renewable solution to generate electricity in remote areas due to its low initial investment. Fuel engines are generally used as back-up generators to optimize renewable hybrid power output, mitigating the effects of renewable intermittencies and minimising battery degradation due to overcharging or undercharging. Diesel generators allow reducing capacity storage which is more expensive. Diesel genset have higher efficiency at full load operation, therefore it is normally use it at full capacity mode to charge the battery bank once it reaches its lower depth of discharge level.

There are two basic types of generators, DC and AC. Most used AC machines in off-grid applications are synchronous generators.

- *Synchronous generators:* machines that convert mechanical power into AC electricity, providing accurate control of frequency and voltage. It can be used for both grid and off-grid power systems [3.8].

- *Fuel curve:* represents the amount of fuel consumed by the generator to generate electricity, in units per hour. [3.11].

$$F = F_0 * Y_{gen} + F_1 * P_{gen} \tag{3.30}$$

Where

F: is the fuel consumption of the generator (unit/hr)

F_0: is the coefficient of fuel curve interception (unit/hr/kW)

Y_{gen}: is the slope of the fuel curve (unit/hr/kW)

F_1: is the rated capacity (kW)

P_{gen}: is the generated electric output (kW)

- *Efficiency curve:* corresponds to the ration between the generated electrical energy and the chemical energy of the fuel consumed by the generator. [3.11].

$$\eta_{gen} = \frac{3{,}6 * \ P_{gen}}{\dot{m}_{fuel} * LHV_{fuel}} \tag{3.31}$$

Where

η_{gen}: is the efficiency of the generator (%)

P_{gen}: is the generated electric output (kW)

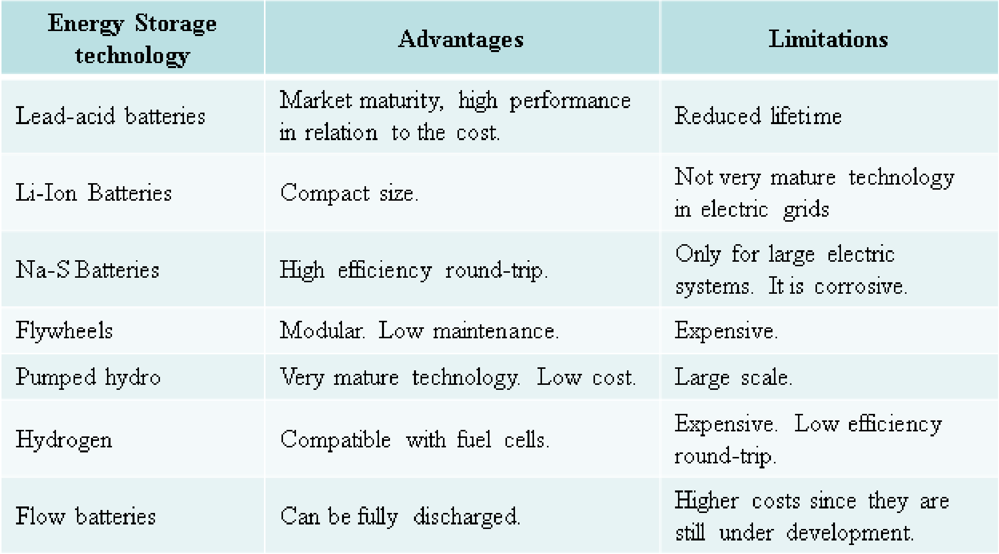
$\dot{m}_{fuel}$: is the mass flow rate of the fuel (kg/hr)

LHV_{fuel}: is the lower heating value of the fuel (MJ/kg)

3.2.4.2 Batteries

Energy storage in remote areas, which mainly depend on local and renewable sources, is essential to respond to the continuous energy needs of their inhabitants and to the economic development of the community. During the day time, solar radiation and wind speed may provide amounts of energy higher than the required by the load; however, during night hours, cloudy skies and/or reduced wind flow, energy demand could exceed generation, leading to a deficit of supply. In order to balance supply and demand, technologies for storage support hybrid systems, enabling to storage the excess of energy generated by renewable sources for later use, should be considered.

Several technologies can be used for energy storage. Most common one is lead-acid battery which is generally used in renewable stand-alone systems due to its high performance-cost ratio and maturity.



Energy Storage technology	Advantages	Limitations
Lead-acid batteries	Market maturity, high performance in relation to the cost.	Reduced lifetime
Li-Ion Batteries	Compact size.	Not very mature technology in electric grids
Na-S Batteries	High efficiency round-trip.	Only for large electric systems. It is corrosive.
Flywheels	Modular. Low maintenance.	Expensive.
Pumped hydro	Very mature technology. Low cost.	Large scale.
Hydrogen	Compatible with fuel cells.	Expensive. Low efficiency round-trip.
Flow batteries	Can be fully discharged.	Higher costs since they are still under development.

Table 3.14. Energy storage technologies. Source:[3.39].

In remote areas with low energy needs, the most common storage systems are batteries, which are mainly characterized by the following parameters:

- *Energy storage capacity (kWh)*: refers to the energy that can be stored in the battery bank according to its capacity. However, the capacity for useful storage also depends on the charging/discharging rates. Retrieving power quickly will reduce its capacity.
- *Charge and discharge rates (kW)*: measures how quickly energy power is removed and added from the battery. It is affected by the level of energy stored and the deepness of charging and discharging cycles (DOD).

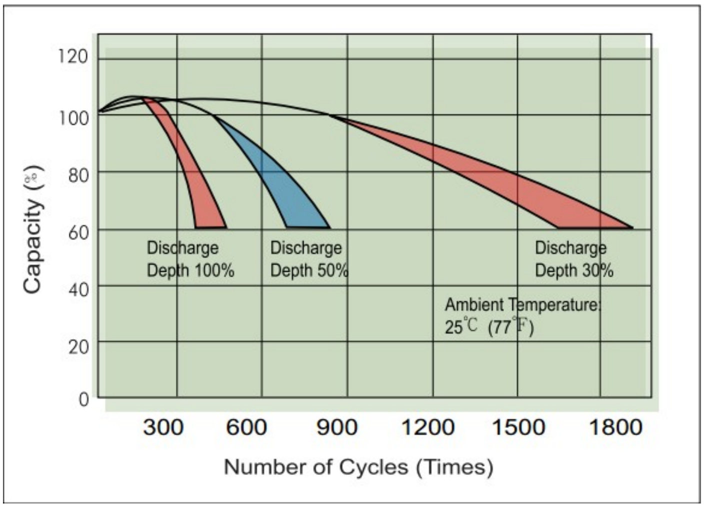


Figure 3.38. Capacity-Cycles Relationship for a lead-acid battery.

- *Lifetime*: life-use of batteries is measured by the numbers of charging and discharging cycles.
- *Round-trip efficiency*: corresponds to the loss of energy derived from a complete charging-discharging cycle. It is represented by the ratio of discharged and charge energy storage. A less efficient storage system requires more electricity to store the same amount of electricity supplied than a more efficient storage system. It largely affects the cost of storage.
- *Energy and power density (Wh/kg or Wh/m^3; W/kg or W/m^3)*: Energy density indicates how much energy per unit weight or volume can be stored; whereas power density is the amount of power available from the storage system per unit of kg.

Furthermore, sizing the battery bank is mainly determined by analyzing the electrical load demand, the days of autonomy required and the maximum depth of discharge of the battery. Concretely, total capacity of the batteries is calculated using the following mathematical expression:

$$C_B = \frac{E_L * S_D}{V_B * DOD_{max} * T_{cf} * \eta_B} \qquad \textbf{\textit{(3.32)}}$$

Where

C_B: is the capacity of the battery (Ah)

E_L: is the electrical load (Wh)

S_D: is the autonomy (days)

V_B: is the storage battery voltage (V)

DOD_{max}: is the maximum depth of discharge for the battery (%)

T_{cf}: is the correction factor based on the temperature

η_B: is the round trip efficiency of the battery (%)

During charging and discharging processes, the state of the battery depends on the generation sources (PV, wind and biomass power, and diesel genset) and load requirements:

- *Battery charging state:* state at which battery is in a charging mode. It occurs when generation is larger than demand and therefore, a process of energy charging is initiated.

$$SOC(t) = SOC(t-1) * (1-\sigma) + \left[E_{gen}(t) - \frac{E_{L(t)}}{\eta_{inv}}\right] * \eta_B \qquad \textbf{\textit{(3.33)}}$$

Where

$SOC(t)$: is the state of the battery capacity at time t (Wh)

$SOC(t-1)$: is the state of the battery capacity at time t-1 (Wh)

σ: is the battery hourly self-discharging rate provided by the manufacturer

$E_{gen}(t)$: is the generated energy (Wh)

$E_{L(t)}$: is the load requirement at time t (Wh)

η_{inv}: is the inverter efficiency (%)

η_B: is the battery charging efficiency (%)

- *Battery discharging state*: when power generated is less than demand needs, battery is used to respond to the load, and therefore enters in the discharging process.

$$SOC(t) = SOC(t-1) * (1-\sigma) + \left[\frac{E_{L(t)}}{\eta_{inv}} - E_{gen}(t)\right] \qquad \textbf{\textit{(3.34)}}$$

3.2.4.3 Converter

Converters are electronic devices used to transform DC voltage or current into AC, and vice versa. A converter is required for hybrid configurations in which DC components are serving AC loads. A converter can be an inverter (DC-AC), a rectifier (AC-DC) or both. Direct current (DC) electricity generated by PV is converted using an inverter, in order to supply AC loads, such as household's appliances.

The inverter mathematical model for renewable hybrid systems is defined as:

$$E_{INV} = E_{DC} * \eta_{inv} \tag{3.35}$$

$$E_{BAT-In} = \frac{E_{BAT} * E_{Load}}{\eta_{inv} * \eta_{DOD}} \tag{3.36}$$

Where

E_{INV}: is the energy output from the inverter (kWh)

E_{DC}: is the energy output from the DC energy generator such as PV (kWh)

η_{inv}: is the inverter efficiency (%)

E_{BAT-In}: is the energy output from the battery (kWh)

E_{BAT}: is the energy stored in the battery at t-1 (kWh)

E_{Load}: is the energy demanded by the load (kWh)

η_{DOD}: is the discharging efficiency of the battery (%)

Rectifier is used to convert the excess of power generated from AC sources such as wind or diesel to DC for battery charging. Energy surplus is calculated as:

$$E_{RECT} = E_{AC} * \eta_{rect} \tag{3.37}$$

Where

E_{RECT}: is the energy output from the rectifier (kWh)

E_{AC}: is the energy input to the rectifier from AC sources (kWh)

η_{rect}: is the energy demanded by the load (kWh)

3.2.5 Techno-economic Optimization

Once resource assessment, load requirements and available technologies have been analysed, it is necessary to define the boundary and criteria for the techno-economic optimisation. Throughout this section, the boundary and criteria are defined in order to obtain a set of possible HRES configurations that satisfy all constrains, ranked from cheaper to more expensive systems.

One of the most powerful tools for HRES configurations and sizing is Hybrid Optimization Model for Electric Renewables (HOMER) software [3.11], developed by National Renewable Energy Laboratory (NREL). HOMER software is one of the most used tools in energy studies for remote areas without grid access. This software compares the energy generated by each HRES alternative with load needs at each hour for a complete year (8760 hrs). It simulates each possible HRES configurations, calculating the Net Present Cost (NPC) of each system.

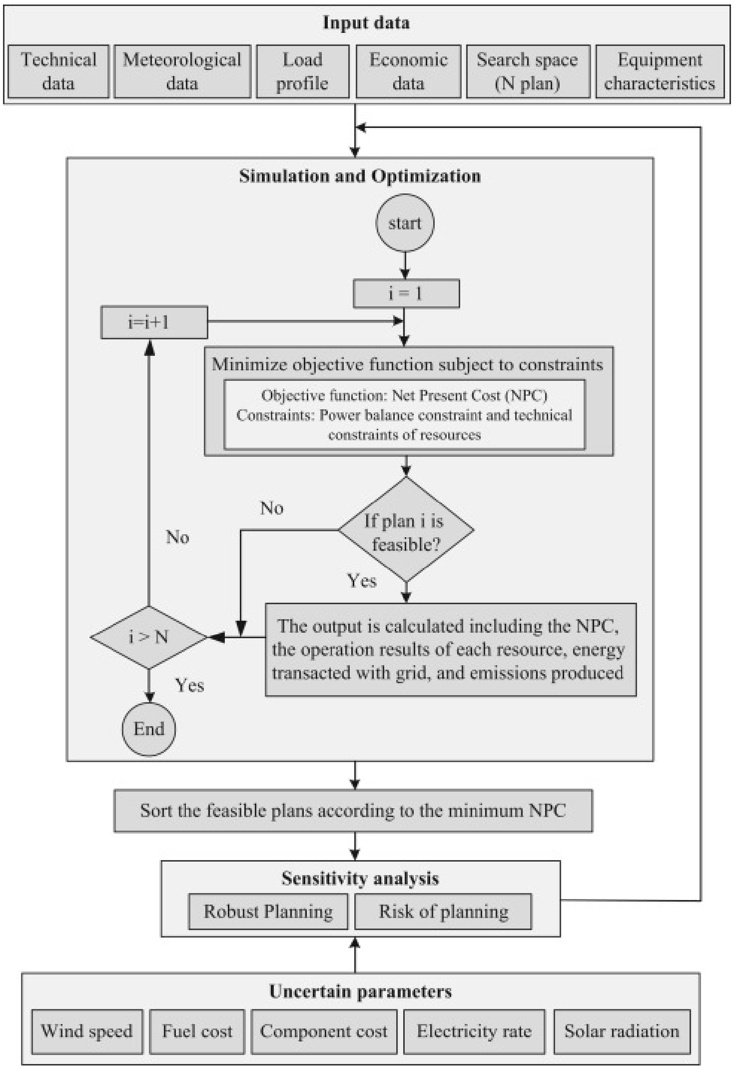


Figure 3.39. HOMER's techno-economic optimization process. Source:[3.40]

3.2.5.1 Criteria

The optimization criterion is to minimize the net present cost (NPC) of power systems in order to supply electricity to an isolated village. NPC output includes the costs of the initial investment in construction, the replacement of component within the project lifetime, its maintenance and fuel expenses. Another important economic parameter is the levelized cost of energy (COE) as the average cost per kWh of useful electrical energy produced by the system. COE takes into account the annualized capital (initial) cost, annualized replacement cost, annual O&M cost and annual fuel cost.

The concept of annualized cost (C_{ACAP}), especially for initial investment, is mathematically expressed as:

$$C_{ACAP} = C_{CAP} * CRF\left(i, R_{Proj}\right) \tag{3.38}$$

Where

C_{CAP}: is the initial capital cost of the component (Eur).

$CRF\left(i, R_{Proj}\right)$: is the capital recovery factor.

i: is the real interest rate

R_{Proj}: is the project lifetime

Capital recovery factor (CRF) is a ratio used to calculate the present value of an annuity (a series of equal annual cash flows), using the following equation:

$$CRF\left(i, N_{Proj}\right) = \frac{i * \ (1+i)^{N}}{i * \ (1+i)^{N} - 1} \tag{3.39}$$

Where

i: is the real interest rate

N: is the number of years

3.2.5.2 Constraints

Constraints are conditions set by the power system designer that need to be satisfied by power systems in order to be feasible. Throughout the evaluation of all possible combinations of renewable hybrid systems and sizes, the optimization process will discard any solution that does not comply with these restrictions. Considered aspects are:

- *Maximum annual capacity shortage (MACS)*: The maximum allowable value of the capacity shortage fraction, which is the total capacity shortage divided by the total annual electric load. If no shortage is considered, parameter is set to 0%.
- *Minimum renewable fraction (MRF)*: The renewable fraction is the portion of the system's total energy production generated from renewable power sources. It refers to the minimum allowable value of the annual renewable fraction regarding total energy consumption.
- *Load following strategy*: it is a dispatch strategy based on the fact that whenever a generator is needed, it only produces enough power to meet the demand. Load following tends to be optimal in systems with a lot of renewable power, when the renewable power output sometimes exceeds the load.
- *Cycle charging strategy*: is a dispatch strategy whereby whenever a generator needs to operate to serve the load, it operates at full output power. Surplus electrical production goes toward charging the battery bank or serving flexible loads (such as pumping).

3.3 Multi-criteria Assessment

Decision making is a process for analysing a series of alternatives in order to select the best solutions for the specifics of the case, which is often extremely complex due to the presence of competing and conflicting objectives among the available criteria or alternatives. Multi-criteria decision process is a decision making method which consists on defining criteria and attributes to adequately select the most suitable solution for achieving the objective. Each attribute should provide a means for objectively assessing each criterion.

In this study, multi-criteria assessment is applied to analyse and evaluate feasible HRES solutions from a wider approach. It considers not just the technical or economics parameters of the implementation of HRES in isolated communities, but also the environmental, social and political variables taking part on the final decision. Multi-criteria approach allows integrates in the evaluation process quantitative and qualitative aspects of the solution.

3.3.1 Analytic Hierarchy Process (AHP)

Last step in the Integral Methodology presented in this study is the multi-criteria assessment of HRES feasible solutions, which is approached using the Analytic Hierarchy Process (AHP), a well-known method proposed by Thomas Saaty [3.41][3.42][3.43]. Analytical Hierarchy Process (AHP) is one of the most commonly used methods of multi-criteria analysis, which considers hierarchical process with multiple levels. At the top level of the hierarchy is the **goal**, next level includes selected **criteria**, and the lowest level consists of the possible **alternatives**. In each hierarchical level paired comparisons are made with judgments using numerical values taken from the AHP absolute fundamental scale of 1 to 9 (see Figure 3.41). These comparisons are used to set matrices in which eigenvectors are defined from ratio scales. AHP combines multidimensional scales of measurement into a single one-dimensional scale of priorities. The method also calculates a consistency ratio (CR) to verify the coherence of the judgments, which must be around 0,10, or less, to be acceptable.

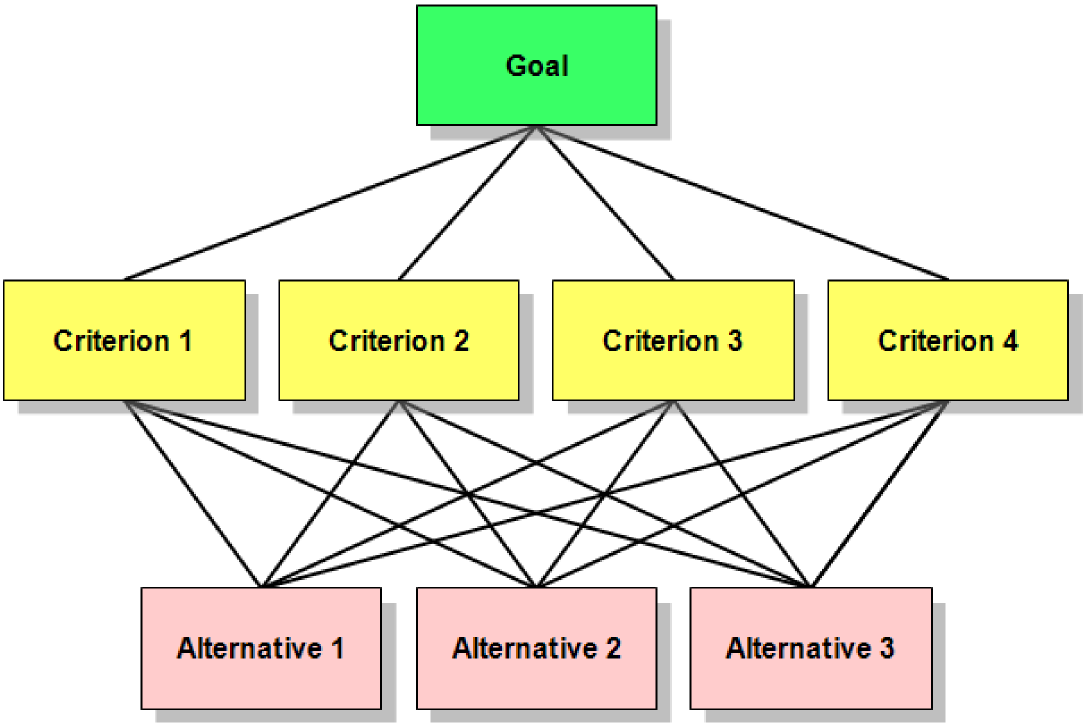
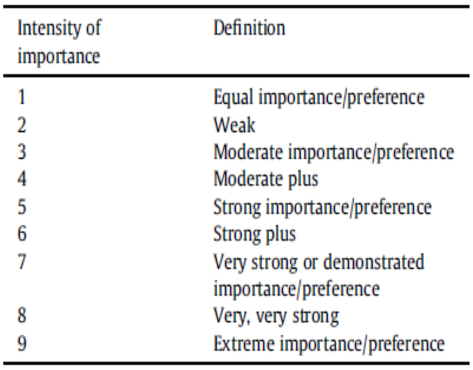


Figure 3.40. AHP Hierarchical model

AHP process is implemented in four stages:

1. *Structuring the problem*. Define the problem in hierarchical levels represented by attributes. AHP carries out mutual comparison of elements in one hierarchical level with the elements at a higher level. The general AHP case includes three levels (goal-criteria-alternatives), thus criteria are compared in relation to the goal, in order to determine their mutual importance, and alternatives to each of the criteria set.

2. *Data Collection*. Second phase of the AHP method is data collection, which involves data and information gathering. These include:
    - Data collection and/or measurement;
    - Define importance assessments by pairs with attributes of one hierarchical level in relation to the higher level. Assign a related importance value using Saaty's scale as shown in Table 3.14.
    - Repeat the process for all levels of the hierarchy.



Intensity of importance	Definition
1	Equal importance/preference
2	Weak
3	Moderate importance/preference
4	Moderate plus
5	Strong importance/preference
6	Strong plus
7	Very strong or demonstrated importance/preference
8	Very, very strong
9	Extreme importance/preference

Table 3.15. Saaty's importance scale. Source:[3.41]

Following this method of ranking, the experts will assign a weight for each pair separately, as a measure of how important is one attribute from another. Upon completion of this process will result in the appropriate matrix of pairwise comparisons corresponding to each level of the hierarchy:

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \qquad \textit{(3.40)}$$

The matrix A will be characterised by:

$$a_{ii} = 1$$

$$a_{ji} = {}^{1}/_{a_{ij}} \quad \text{for } i,j = 1,\ldots,n$$

$$detA \neq 0$$

3. *Evaluation of the relative weight.* Third step of the AHP method is to estimate the relative weight. Based on matrix A with elements a_{ij} the priorities of criteria, sub-criteria and alternatives are determined using a method for:
    - Arithmetic mean,
    - Geometric mean, and

- The method of difference.

Furthermore, it needs to be validated the **consistency of the assessments** in order to guarantee they are coherent with each other. Thus, once the weights are determined based on the experts' evaluations, the credibility of the outcomes needs to be checked. This is carried out by determining the consistency of matrix A. If the evaluation is consistent and consequent for which $a_{ij} = a_{ik} * a_{kj}$, satisfies the following mathematical expression:

$$Aw = nw, \text{ or}$$

$$A = \begin{bmatrix} \frac{w_1}{w_1} & \frac{w_1}{w_2} & \cdots & \frac{w_1}{w_n} \\ \frac{w_2}{w_1} & \frac{w_2}{w_2} & \cdots & \frac{w_2}{w_n} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{w_n}{w_1} & \frac{w_n}{w_2} & \cdots & \frac{w_n}{w_n} \end{bmatrix} * \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} = n * \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} \qquad \textbf{\textit{(3.41)}}$$

Determining the weights is calculated solving a matrix equation with matrix columns *w* solution for eigenvalues λ different from 0, as

$$Aw = \lambda w, \text{ or}$$

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} * \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} = n * \begin{bmatrix} \lambda_1 w_1 \\ \lambda_2 w_2 \\ \vdots \\ \lambda_n w_n \end{bmatrix} \qquad \textbf{\textit{(3.42)}}$$

If the matrix A contains inconsistent assessments, the weight vector *w* can be obtained by solving the following equation:

$$(A - \lambda_{max1})w = 0 \;\; if \; \sum w_i = 1 \qquad \textbf{\textit{(3.43)}}$$

Where

λ_{max}: is the largest eigenvalue of the matrix A

or by:

$$\lambda_{max} = \frac{1}{n}\sum_{i=1}^{n}\frac{(Aw)_i}{w_i} \qquad \textbf{\textit{(3.44)}}$$

Considering the properties of matrix A, $\lambda_{\max} \geq n$ is valid and $\lambda_{\max} - n$ may be used to measure the consistency of assessment, or to calculate the index of consistency:

$$CI = \frac{\lambda_{max} - n}{n - 1} \qquad \textbf{\textit{(3.45)}}$$

Based on this index, it is determined the index of inconsistency according to:

$$CR = \frac{CI}{RI} \qquad \textbf{\textit{(3.46)}}$$

Where:

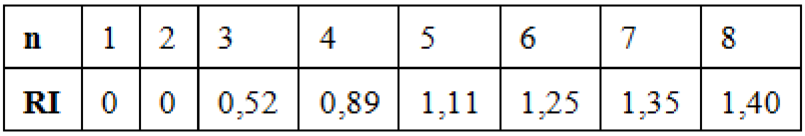
RI: is the parameter representing the Random Index (RI)

The RI (Random Index) is an experimental value which depends on n. Table 3.16 from Ref. [3.42] shows RI values. Whether CR is less than a threshold value, then the matrix is considered as having an acceptable consistency, and the derived priorities from the comparison matrix are meaningful.

Matrix size (n)	Consistency ratio
3	5%
4	9%
5 or more	10%

Table 3.16. Consistency limits. Source:[3.41]

If CR exceeds the threshold value, then the judgments in matrix A should be reviewed.



n	1	2	3	4	5	6	7	8
RI	0	0	0,52	0,89	1,11	1,25	1,35	1,40

Table 3.17. Random index value. Source: [3.42]

If CR ≤ 0,10 estimates for *a* and *j* are consistent. Otherwise, the evaluation should be repeated.

4. *Determination of the problem solutions:* Last stage in implementing AHP method is determining the composite normalized vector. Since hierarchy levels are interconnected, single composite vector of unique normalized weight vectors for the entire hierarchy is determined by multiplying the weight vectors of all successive levels. Composite vector is used to determine the relative priority of the entities at the lowest (hierarchical) level, which allows the achievement of the set goals of the overall problem.

3.3.2 AHP applied to HRES

3.3.2.1 Goal

Selecting the best HRES solution for supplying electric power to a specific community in a remote area without access to the electrical grid.

3.3.2.2 Criteria

The criteria identified for this study allows a holistic evaluation of particular HRES configurations in order to identify which one responds better to the needs and exigencies of the community or area. The four criteria identified are technical, economic, environmental, social and political, with several sub-criteria each.

C1. Technical Criteria.

C1.1. Maturity: A mature technology is a technology that has been in use for long enough that most of its initial faults and inherent problems have been removed or reduced by further development.

C1.2. Demand coverage: percentage of total demand covered by HRES configuration.

C1.3. Excess of electricity: surplus electrical energy that must be discarded because it cannot be used to serve a load or charge the batteries.

C1.4. Autonomy: battery bank autonomy, as the ratio of the battery bank size to the electric load.

C2. Economic Criteria.

C2.1. Initial investment: is the total installed cost of the power HRES system at the beginning of the project, including all components.

C2.2. O&M: cost associated with operating and maintaining HRES system. The total O&M cost of the system is the sum of the O&M costs of each system component.

C2.3. Cost of Electricity (COE): average cost per kWh of useful electrical energy produced by the system.

C2.4. Net Present Cost: is the present value of the HRES system, including all the costs of installing and operating the system over its lifetime. It is the same as the lifecycle cost.

C3. Social Criteria

C3.1. Public acceptance: Public mind-set towards the different HRES architectures. Mainly based on the type of technology used.

C3.2. Job creation: Potential of employment opportunities to be created by constructing and operating the energy power system.

C4. Environmental Criteria

C4.1. CO_2 emission: Capability of HRES architectures to alleviate CO_2 emissions.

C4.2. Renewable fraction: percentage of HRES´s total energy production generated from renewable power sources.

C4.3. Impact on environment: Effect of HRES power plant installation in the surroundings, visual and biodiversity.

C4.3. Land requirements: Land requirement for physical installation of a HRES power plant and its fuel supply.

C5. Political Criteria

C5.1. Political acceptance: political priorities in terms of energy and the promotion of renewable power supply.

C5.2. Alignment with national/regional energy policies: degree of relation with the actual national and regional policies in energy, mainly in energy accessibility and promotion of renewable energies.

3.3.2.3 Alternatives

Alternatives correspond to the HRES feasible solutions identified in previous section, where different system architectures are suitable for fulfilling technically the load needs of the remote community.

Next it is provided the hierarchical scheme of AHP implementation to HRES selection, used in this work.

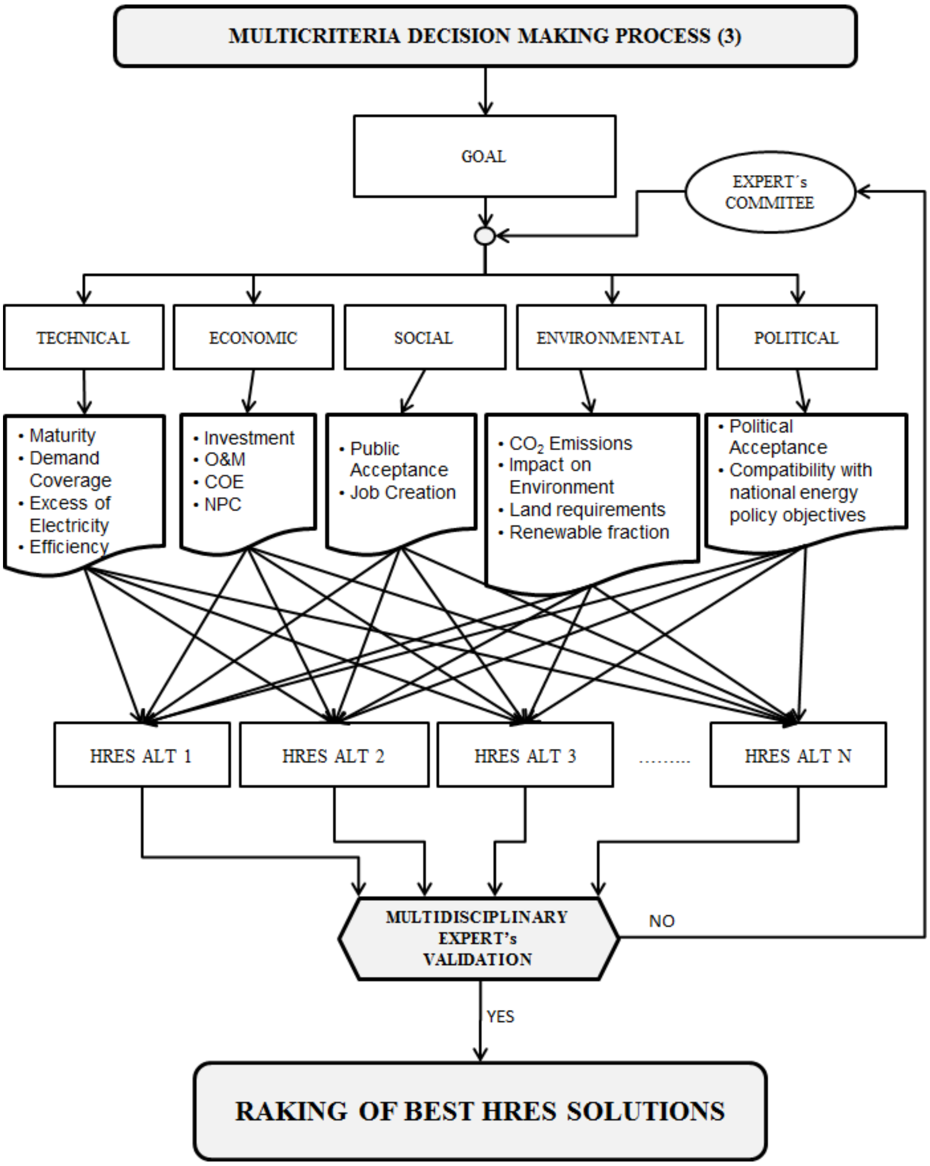


Figure 3.41. Multi-criteria Decision Making Process

3.4 Conclusions

In this chapter, it has been presented the integral methodology for supplying electricity to remote areas with no access to the grid using Hybrid Renewable Energy Systems (HRES). The methodology follows a top-down approach and it is based on three main pillars: energy planning, feasibility of HRES solutions and multi-criteria assessment. Firstly, it is studied the energy situation of the country and how it will evolve with a "*Business As Usual*" scenario. Then, it is analysed the transformation towards a more sustainable scenario using HRES, its requirements and limitations. Understanding the overall energy goal of the country toward sustainability, secondly, a series of different HRES configurations are studied for providing energy access to small and isolated communities, while complying with national sustainable energy guidelines. Finally, a decision making process is integrated in the methodology using AHP, which will guarantee the implementation of the best power HRES configuration in the area.

The methodology presented in this work shows how to evolve towards a more sustainable energy scenario without penalising the economic and energy development of small communities. It aligns the national energy directives for sustainability with providing energy access to isolated areas, promoting the economic development of these communities without increasing CO_2 emissions to the atmosphere. Furthermore, it includes a decision making process based on a multi-criteria approach where qualitative and quantitative aspects of the different energy solutions are considered.

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CHAPTER 4. APPLICATION TO A STUDY CASE

In this chapter it is presented a case study implementing the integrated methodology presented in previous unit. The methodology has been applied to an isolated village situated in Central Africa in Republic Democratic of Congo. The village is a rural community mainly dedicated to agriculture for subsistence.

Figure 4.1. Case Study Area (RDC)

4.1 <u>*Energy Planning*</u>

Electricity is necessary for the development of any community. However, electricity supply becomes a challenge for remote and isolated communities. Renewable hybrid energy systems may safely generate electricity for minimum demand requirements without implementing large facilities or networks. Throughout this section it is studied the integration of HRES in the national energy context as a strategy for isolated areas electrification.

In this section, an energy scenario based on the implementation of HRES is explored as a means for providing energy access to a higher percentage of the population and economic development to the country. Then, it is compared with scenario BAU (Business As Usual), representing a continuous tendency of the actual context.

4.1.1 Energy Context of RDC

Republic Democratic of Congo (RDC) is located in the centre of Africa, near the equator. It is the second largest country in Africa in terms of area (2,345,441 km²) with an estimated population of 74,88 million of inhabitants, having a growth rate of 3,1% from 1990 to 2014. Approximately, 75% of the total population lives in rural areas and it is dependent on agriculture, being land cultivation and forestry their major economic activities. RDC owns approximately 52% of total freshwater reserves in Africa and land characterized by dense tropical rainforest in the basin and central west, dry forests and savannahs in the southern part and mountain ecosystems along the eastern border.

RDC is also characterized by its immense natural forest reserves (about 155 million ha) together with a natural rainforest which represents 60% of the forests in Congo Basin and an important carbon storage area. In terms of energy, RDC has a great potential with abundant and varied energy resources: biomass, solar, wind, hydraulic energy, hydrocarbons, including methane gas from Lake Kivu, mineral coal, oil shale, etc. The sustainable development of these energy resources for contributing to economic and social development of the country will certainly be the main agenda of the national and regional Governments.

RDC's energy sector is currently centralised and characterised by a state monopoly. However, it has a high energy potential for distributed energy supply over the country's territory which is almost unexploited. Estimations of RDC's energy potential are around 100 GW of exploitable capacity, of which almost half (44 GW) is concentrated at the Inga site. Despite this extraordinary energy potential, especially for renewable energy generation (mainly hydro based), RDC’s national electrification rate is 9% with strong disparities between urban and rural areas (Kinshasa is 44%, while Bandundu is 0,6%)[4.1]. Moreover, transport and distribution electricity network is out of date and unable to support actual current consumption, which results in constant power outages. In the places where electricity is essential, such as hospitals, hotels, public buildings, etc., the problem is circumvented by using fossil fuel generators to get some security in electricity supply. However, it exits many remote areas where grid extension is costly and simply do not have access to electricity [4.1], [4.2]. In these cases, renewable hybrid systems may be the best alternative to provide energy access and economic development to the societies, without large initial investment in network extension.

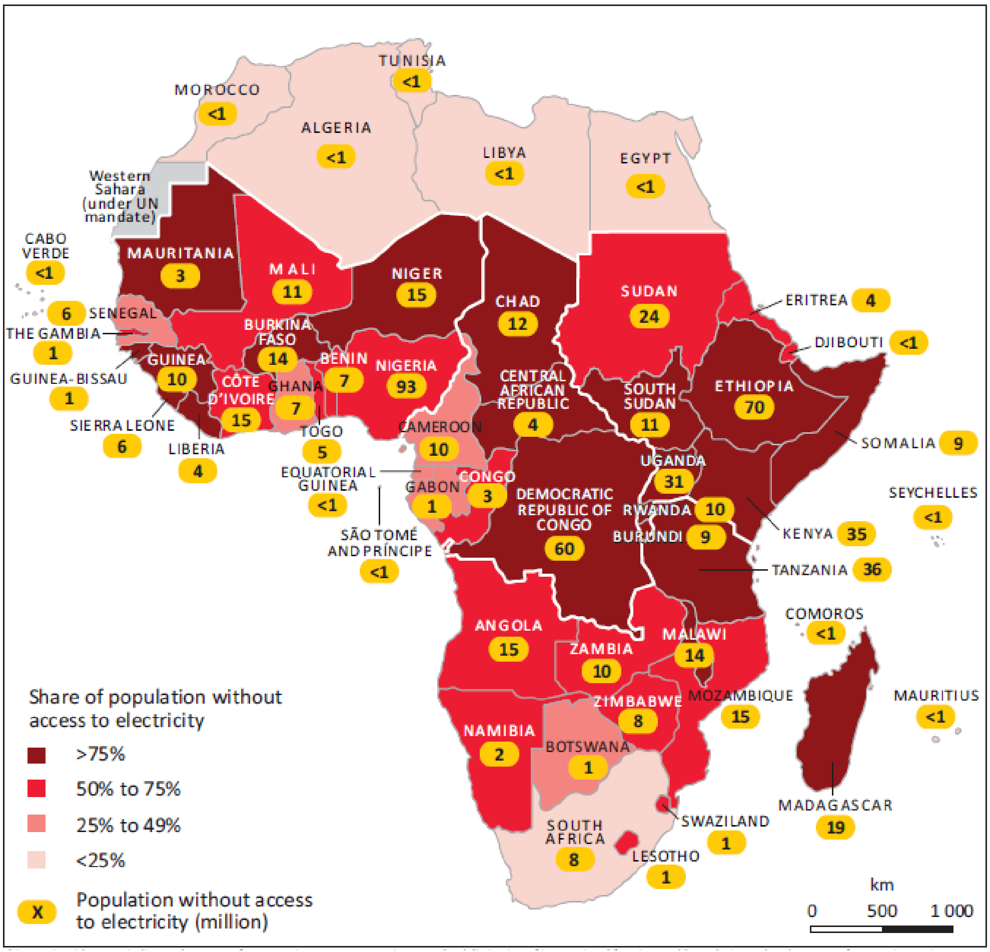


Figure 4.2. Population without access to electricity. Source: [4.3]

Data from 2014, provided by International Energy Agency (IEA) [4.3][4.4], represented in a Sankey's Energy diagram for RDC shows a national energy supply of 30,04 Mtep in contrast to 28,79 Mtep in 2013, mainly based in three energy sources: oil, biomass and hydro. Produced oil is exported to other countries (1,07 Mtep) while oil products such as gasoline and diesel are imported in large quantities (1,78 Mtep), so RDC presents an oil product dependency from the exterior, mainly in transport (1094 ktep). Biomass is the highest energy supply in the country, and it is based on traditional fuels such as firewood, charcoal and waste, which denotes the low level of electrification in the country. Hydro is the only source for electricity generation, together with minor contributions from coal and natural gas in the country.

Total final energy consumption reached 21,51 Mtep, an increment of 12,5% from previous year (19,11 Mtep in 2013). Main consuming sector is the residential (74%), followed by industry (15%) and transport (7%), while other forms of energy such as electricity contributes with only 4.1%.

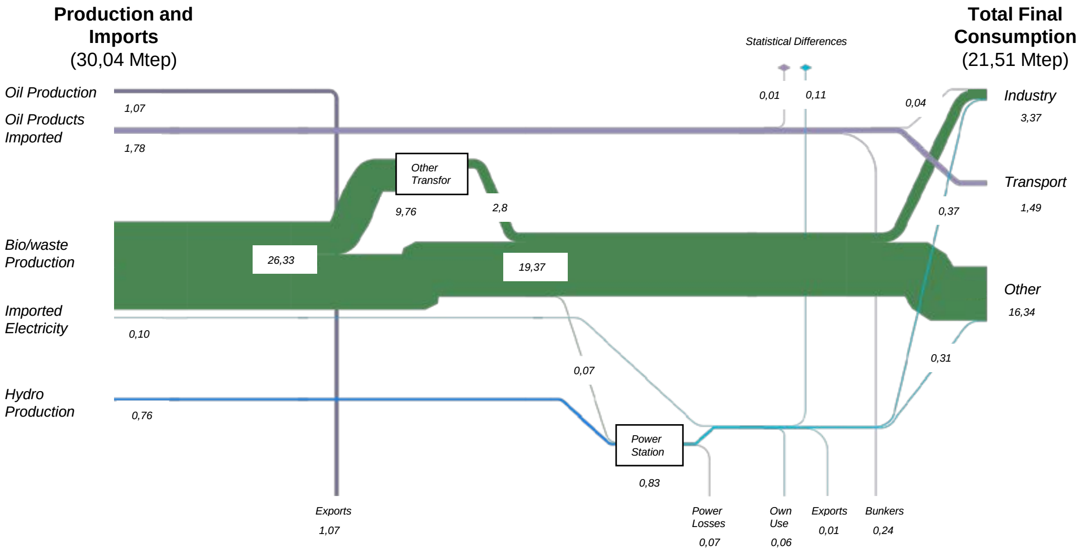
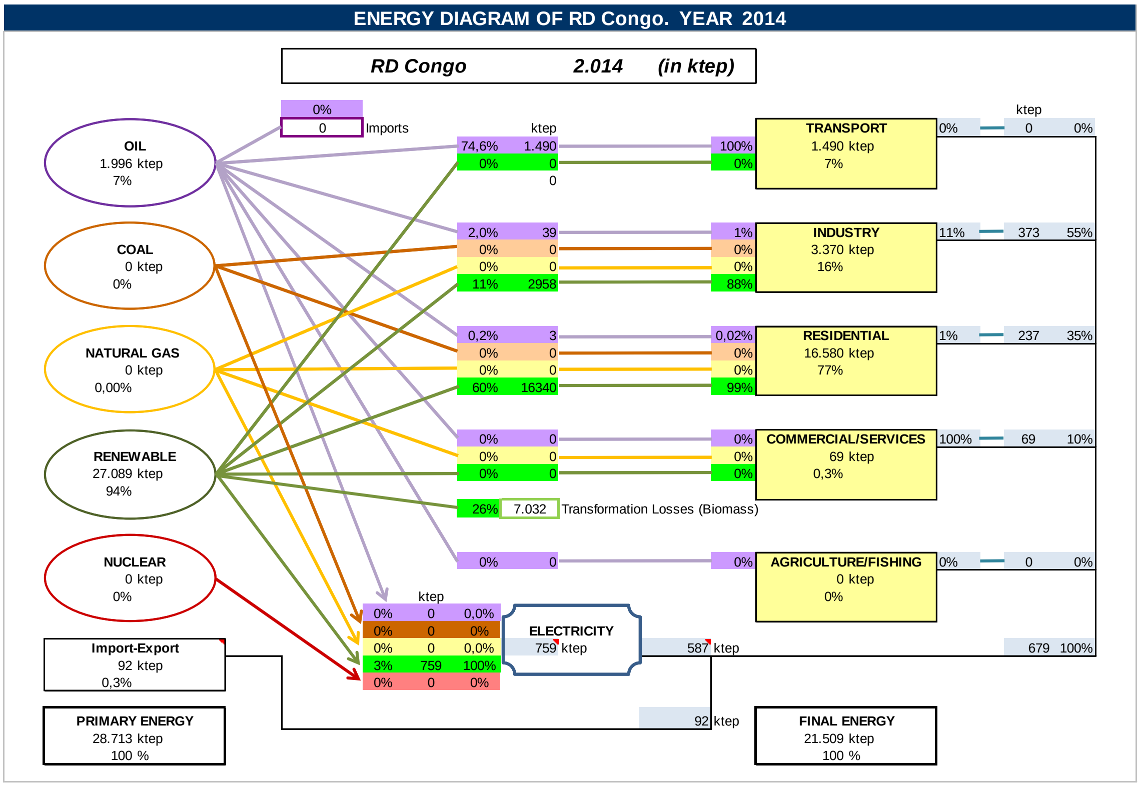


Figure 4.3. Sankey Diagram of RDC (Year 2014)

Total primary energy per capita is 0,38 tep/capita, remaining far below Africa's average (0,67 tep/capita). Similarly, electricity consumption per capita shows a value of 110 kWh/capita, below Africa's average of 570 kWh/capita, while European Union index reaches 5900 kWh/capita. In contrast, CO_2 emissions per capita is 0,06 tCO_2/tep in RDC, while Africa's average is about 0,96 tCO_2/tep. This highlights the renewable energy potential of RDC.

Gross domestic product (GDP) per person employed was 52,2 billion of USD_{2010} in 2014, with a total primary energy per GDP_{ppp} value of 0,55 tep/GDP_{ppp} , 27% higher than Africa's average (0,15 tep/GDP_{ppp}).



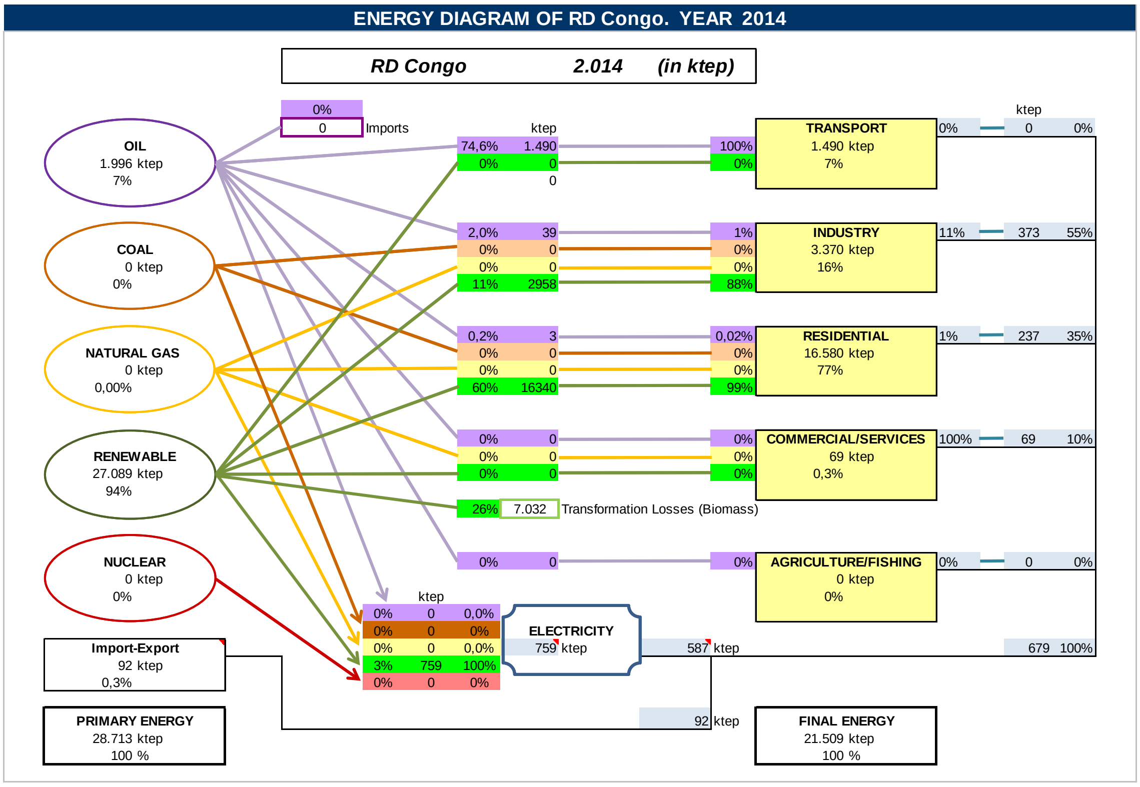


Figure 4.4. SIMESEN Energy Flow of RDC. Year 2014.

Figure 4.4 represents the energy flow diagram of RDC in year 2014, including the origin (energy source) and destination (sector) of energy units. As it may be observed only oil and renewable energies are supplying the country. Country imports are oil products for transport and electricity; while hydro is completely for electricity generation and biomass is mainly used in residential by means of traditional fuels such as wood.

4.1.2 BAU vs HRES Scenario

In this section, two energy scenarios are compared. One is the Business As Usual (BAU) based on a continuous trend where participation of each energy source to the national mix is maintained, together with the electricity import-export balance. To do so, an historical analysis has been carried out in order to forecast the growth rates of population, GDP, primary energy and final consumption for each sector.

Economic Sector	Growth Rate (%)
Industry	1,4
Transport	7,5
Services	0,5
Residential	2,7
Agric. / Fish.	0,1

Other	Growth Rate (%)
Population	3,1
GDP_{ppp}	0,4

Table 4.1. Growth rates for Scenarios.

The second scenario is the proposed HRES, which is based on increasing the access to electricity by means of renewable hybrid systems and palliating the raise of CO_2 emissions introducing biofuels in the transport sector. In order to understand the impact of the proposed measures, next it is shown a series of indicators and graphs representing the comparative analyses of both scenarios.

Next it is provided a series of energy indicators for both scenarios and their forecasted evolution within the time period of study (from 2014 to 2035).

		SCENARIO	BAU	RD Congo			
Indicators	**Units**	**2014**	**2015**	**2020**	**2025**	**2030**	**2035**
Population	Million	74,9	77,2	89,9	104,6	121,8	141,8
GDPppp	M€$_{2010}$	52.200.000	52.412.599	53.488.650	54.586.794	55.707.483	56.851.180
Consumption of Electricity	TWh	7,9	8,0	8,7	9,5	10,4	11,3
CO_2 Emissions	Mt	4,53	4,85	6,82	9,64	13,68	19,45
Primary Energy (EP)	ktep	28.713	29.520	33.978	39.265	45.586	53.214
EP Generated	ktep	20.057	20.558	23.264	26.344	29.852	33.848
Import-Export	ktep	92	94	102	111	121	132
Generated Electricity	ktep	587	597	648	706	771	843
Exterior Dependency	%	30,15	30,36	31,53	32,91	34,51	36,39
GDPppp/capita	M€$_{2010}$/inhab	0,70	0,68	0,60	0,52	0,46	0,40
TEP/capita	tep/hab	0,383	0,382	0,378	0,375	0,374	0,375
TEP/GDPppp	tep/M€$_{2010}$	0,55	0,56	0,64	0,72	0,82	0,94
Electricity/capita	MWh/inhab	0,11	0,10	0,10	0,09	0,09	0,08
CO_2/TEP	t/tep	0,16	0,16	0,20	0,25	0,30	0,37
CO_2/GDPppp	t/M€$_{2010}$	0,09	0,09	0,13	0,18	0,25	0,34
CO_2/capita	t/inhab	0,060	0,063	0,076	0,092	0,112	0,137
Fraction ER in EP*	%	69,9	69,6	68,5	67,1	65,5	63,6
Fraction ER in EE*	%	86,5	86,5	86,5	86,5	86,5	86,5

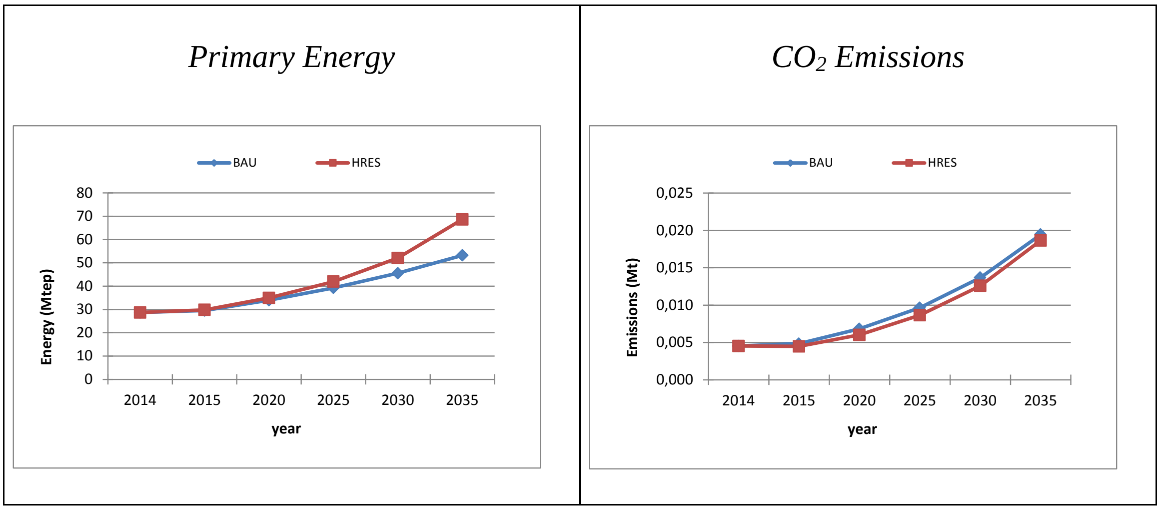
Fraction ER in EP and EE*: % of renewable energies contribution to primary energy and electrical generation.

Table 4.2. Energy Indicators for BAU Scenario.

		SCENARIO	HRES	RD Congo			
Indicators	**Units**	**2014**	**2015**	**2020**	**2025**	**2030**	**2035**
Population	Millions	74,88	77,19	89,87	104,64	121,83	141,84
GDP	Billion€$_{2010}$	52.200.000,00	52.412.598,61	53.488.650,37	54.586.793,92	55.707.482,79	56.851.179,86
Consumption of Electricity	TWh	7,90	8,07	11,64	18,84	33,48	66,74
CO_2 Emissions	Mt	4,53	4,40	5,94	8,53	12,37	18,22
Primary Energy (EP)	ktep	28.713,00	29.524,03	34.675,03	41.107,47	50.314,52	64.915,28
EP Generated	ktep	20.057,00	20.721,46	24.155,96	28.320,24	34.346,50	44.194,58
Import-Export	ktep	92,00	93,98	135,61	219,47	390,01	777,54
Generated Electricity	ktep	587,00	599,62	865,27	1.400,29	2.488,45	4.961,07
Exterior Dependency	%	30,15	29,81	30,34	31,11	31,74	31,92
GDP/capita	M€$_{2010}$/inhab	0,70	0,68	0,60	0,52	0,46	0,40
TEP/capita	tep/inhab	0,383	0,382	0,386	0,393	0,413	0,458
TEP/GDP	tep/M€$_{2010}$	0,55	0,56	0,65	0,75	0,90	1,14
Electricity/capita	MWh/inhab	0,11	0,10	0,13	0,18	0,27	0,47
CO_2/TEP	t/tep	0,16	0,15	0,17	0,21	0,25	0,28
CO_2/GDP	t/M€$_{2010}$	0,09	0,08	0,11	0,16	0,22	0,32
CO_2/capita	t/inhab	0,06	0,06	0,07	0,08	0,10	0,13
Fraction ER in EP*	%	69,9	70,2	69,7	68,9	68,3	68,1
Fraction ER in EE*	%	86,5	86,5	86,5	86,5	86,5	86,5

Table 4.3. Energy Indicators for HRES Scenario.

Analysing the most important indicators, Figure 4.5 represents the analysis of the **primary energy** and **CO_2 emissions** for both scenarios. As it may be observed, scenario HRES shows an increment of total primary energy with respect to BAU. This is due to the increment in distributed electric generation with renewable hybrid systems. CO_2 emissions are similar in both scenarios; HRES is slightly lower since this scenario considers a penetration of 10% of biofuels in transport, thus replacing part of the fossil fuel consumption in this sector.



Primary Energy

CO_2 Emissions

Figure 4.5. Primary energy consumption and associated CO_2 Emissions.

Energy intensity is analysed using three main energy indicators: total primary energy per capita (TEP/capita), average consumption of electricity per capita (electricity/capita), and total primary energy per gross domestic product per employed person (TEP/GDP_{ppp}). In this regard, it is observed how HRES increases the electrification rate to 0,58 kWh/capita by 2035, while continuing with actual energy paradigm will quasi maintain electricity rate to actual value.

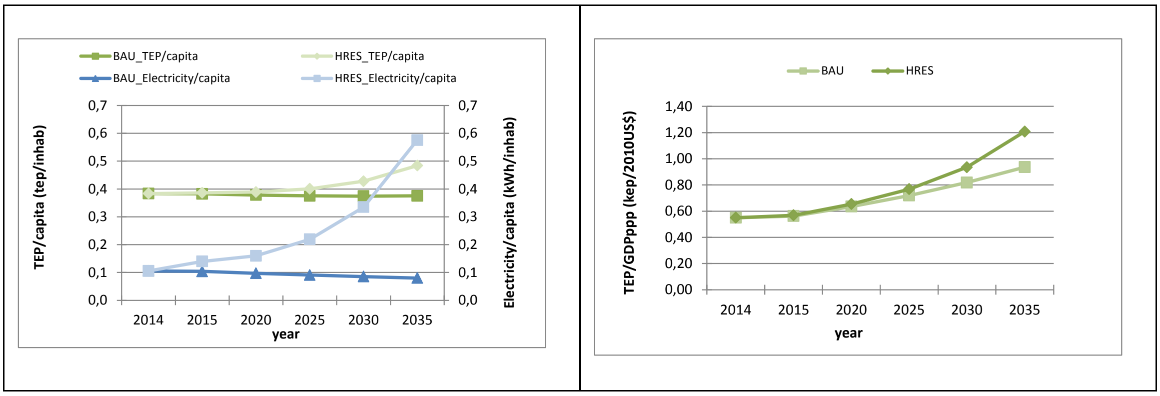


Figure 4.6. Energy Intensity.

Exterior dependency is similarly reduced in HRES scenario. Penetration of renewable hybrid systems in remote areas will increase the percentage of population with electricity access without compromising their energy independence, since HRES are off-grid power plants based on local resources. In the case of continuing with actual scenario (BAU), fossil fuels and electricity dependency will increase along the years.

	BAU	HRES
2014	30,15	30,15
2015	30,36	29,63
2020	31,53	30,17
2025	32,91	30,88
2030	34,51	31,39
2035	36,39	31,37

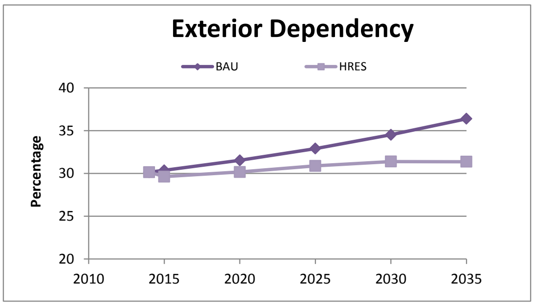


Figure 4.7. Exterior Dependency.

Electricity generation is notorious in the HRES scenario to cover a wider range of electricity access in isolated areas, which will also imply higher electricity consumption and economic development of the area. Increasing electricity rate to Africa's actual values of electricity per capita will require a significant effort and compromise from national and regional government to promote HRES as a local and sustainable alternative for rapid energy development in off-grid areas.

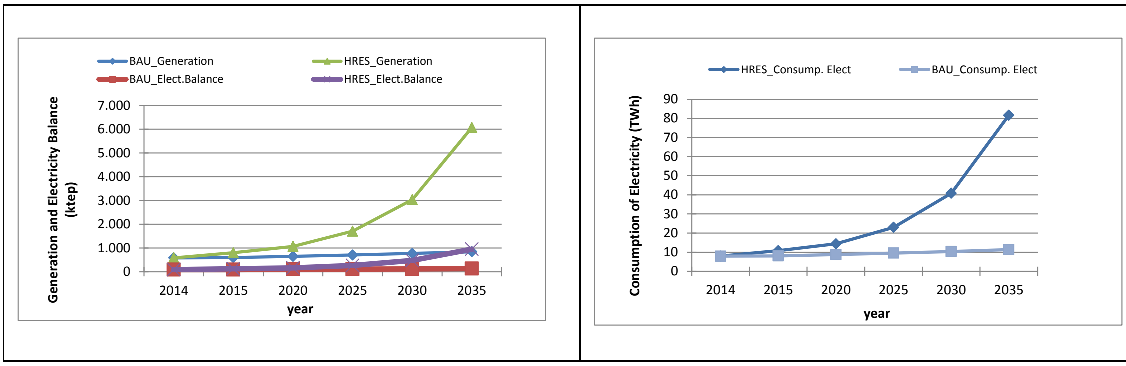
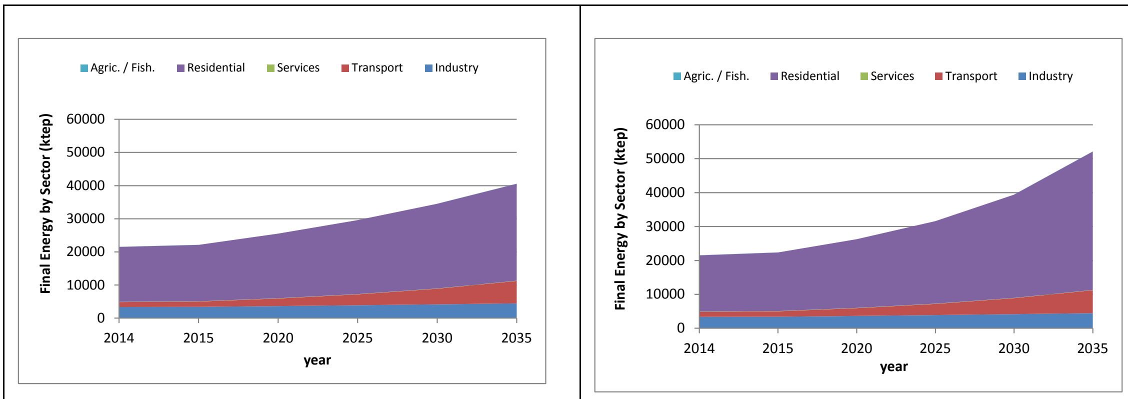


Figure 4.8. Electricity.

Final Energy consumption per economic **sector** indicates a growing energy demand in residential segment in HRES with respect to BAU, while Industry and Transport present similar energy evolution. HRES scenario presents an increment in Residential energy consumption originated by the electrification process in residential segment, reaching 50 Mtep in 2035.

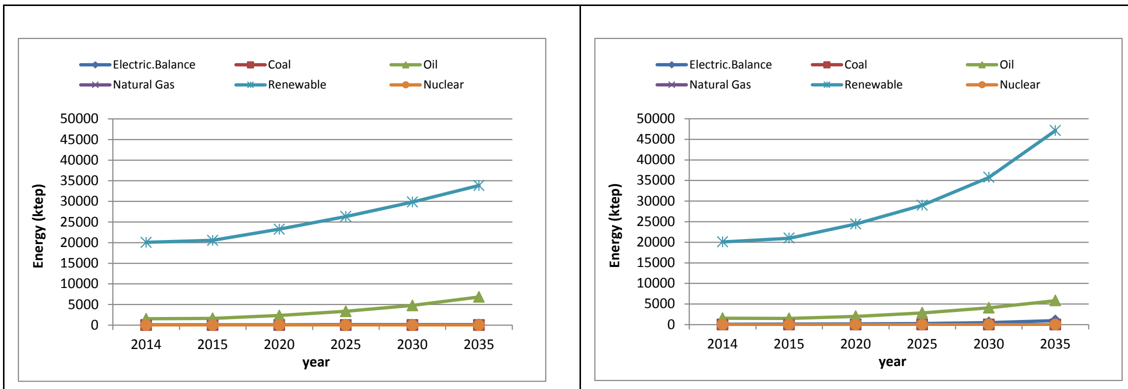


BAU Scenario

HRES Scenario

Figure 4.9. Energy Demand by Sector

Analysis of **Energy sources** highlights the rapid growth of renewable energies to respond to residential electrical needs in 2035. In both scenarios, production with renewable energies increases significantly, but specially in HRES, reaching the value of around 4,7 Mtep in 2035 in contrast with 3,3 Mtep in BAU_{2035}. Oil demand is similar in both scenarios, presenting a value of 6,8 Mtep in BAU_{2035} versus 5,8 Mtep in $HRES_{2035}$, this difference is due to decreasing demand of oil products (gasoline and diesel) in transport and replace them with biofuels, increasing biomass requirements in this economic sector.

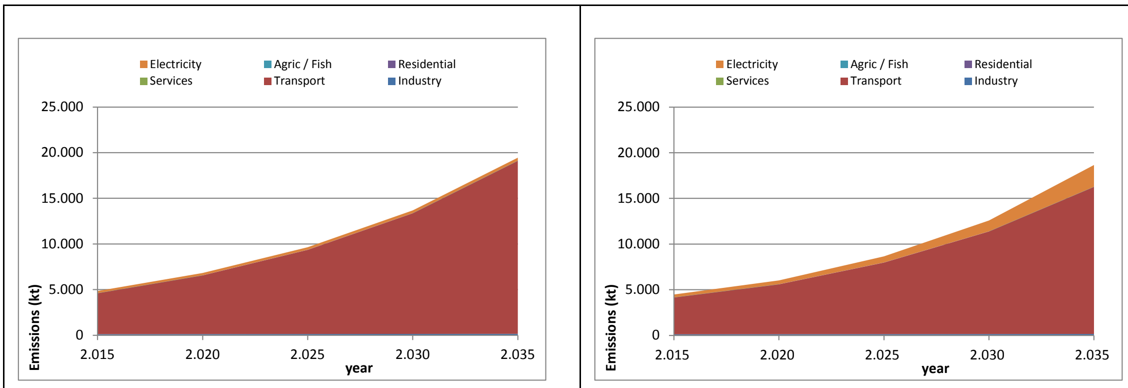


Scenario BAU

Scenario HRES

Figure 4.10. Energy Sources

Emission will evolve similarly in both scenarios. Nevertheless, HRES scenario presents a slight reduction of emissions in transport due to the biofuel penetration in the transport, and an increment in emissions due to the extended used of electricity in the country.



Scenario BAU

Scenario HRES

Figure 4.11. CO_2 Emissions per sector

As it may be observed from the analysis, it is feasible to alleviate energy poverty in the country by means of HRES penetration in remote areas where access to electricity is not available. Once it is analysed the macro impact of the HRES scenario, a micro-energy analysis needs to be conducted in order to verify that HRES configurations will meet the energy requirements of isolated societies in RDC.

4.2 HRES Configuration Set

Once the macro-perspective of the sustainable energy development has been set, it is analysed its applicability to a small community. To do so, different HRES configurations are studied from a techno-economic perspective in order to identify a set of HRES system architectures that will meet the needs of the village and also, facilitate the energy transformation of the country. The aim is to validate whether the HRES Scenario proposed in the previous section can be implemented at a small scale, identifying the energy systems that will comply with it.

In this section, a series of HRES design schemes are modelled and simulated to study its response to the energy requirements of a remote community in the area of Kinshasa (Republic Democratic of Congo). The objective is to analyse whether the community energy needs are met in a reliable and sustainable manner, while analysing the economic and technological aspects of it. The study is conducted in several stages, beginning with the estimation of the village´s demand of electricity, to continue with natural resource assessment, analysis of the technologies, and evaluating a set of different HRES configurations with HOMER software package, developed by NREL for the design of micro-power systems [3.31].

4.2.1 Demand

The village is composed by a school, a bakery industry, a health clinic and households, and street lighting. Demand of the entire community is organized in common loads, including general lighting to commercial and industrial loads.

Residential demand mainly refers to household's loads, including illumination, TV and radio. It has been considered an operation period of electricity for lighting from 18:00 to 23:00 hr which coincides with nocturnal activity of the occupants. Lighting is composed by five lamps of 20 W, two of which are designed to light the bedroom, another two for the living room and kitchen, and the remaining one is used to illuminate the main door. Not all lamps are turned out at all times; at midday it is only used one lamp. The radio of 40 W is supposed to be turned on between 7:00 to 12:00 hr and 18:00 to 20:00 hr; and the TV of 80 W, considering 5 W of the standby, is on from 12:00 to 14:00 hr and during nocturnal activity period. The number of households in the village is 30.

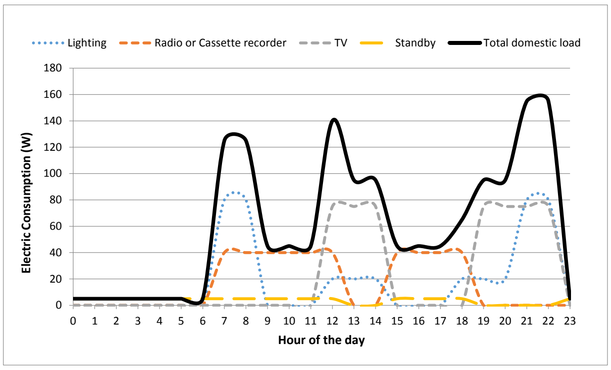


Figure 4.12. Residential Load for the Case Study

Commercial loads include a school and a health clinic. The **school** is composed by classrooms, a toilet for employees and students, and an office for professors. In terms of electrical loads, it consumes in lighting (indoor and outdoor) and office appliances. External illumination includes 4 lamps of 20 W from 18:00 to 22:00 hr, classroom lighting uses 20 lamps of 18 W from 9:00 to 12:00 hr and 14:00 to17:00 hr, office lighting is equipped with 2 lamps of 15 W operating also from 9:00 to 12:00 hr and 14:00 to17:00 hr, and the toilet is illuminated with a lamp of 15 W from 9:00 to 12:00 hr. Moreover, the school is equipped with a 60 W computer used from 9:00 to 12:00 hr and 14:00 to17:00 hr, and a 200 W printer operated only two hours a day.

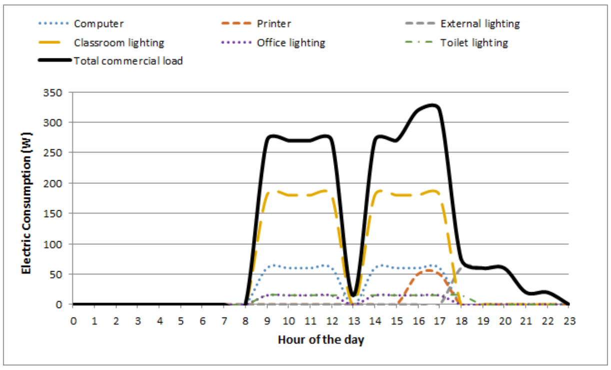


Figure 4.13. School Loads

The **health clinic** is composed of external (6 lamps of 40W) and indoor lighting (10 lamps of 18W), a vaccine freezer, a communication system, a microscope, a printer, a computer and a TV. Due to the fact that is a health clinic, the external lighting is operating all night between 21:00 and 9:00 while the rooms' lighting is on from 8:00 to 22:00 hr. The vaccine freezer is working all day because of the great importance of this service. The communication apparatus' operation is from 8:00 to 11:00 hr and from 13:00 to 16:00 hr. That tool has a power of 50W. A computer of 60W is working from 8:00 to 17:00 hr. The printer of 200W with a standby of 40 W, works from 14:00 to 15:00 hr and the microscope from 8:00 to 11:00 hr. Finally, the TV of 80 W and 5 W of standby, is considered to be turned on between 8:00 and 21:00 hr.

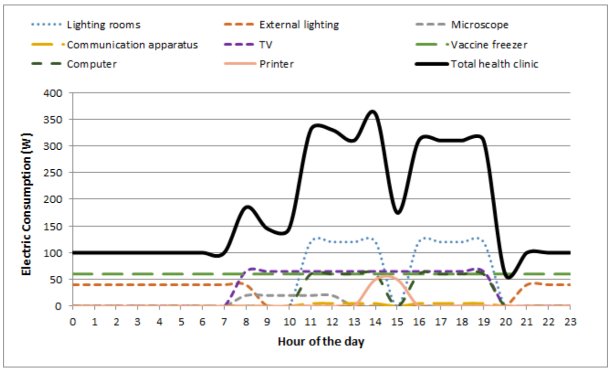


Figure 4.14. Health Centre Loads

Industrial electric demand is composed by a bakery and a milling machine for bread preparation. The baking machine has a capacity power of 2850 W and it is operated in two work shifts. The first one is in the morning from 5:00 to 8:00 hr while the second shift works from 15:00 to 17:00 hr. Subsequent, milling process begins from 8:00 to 11:00 hr and in the afternoon from 15:00 and 17:00 hr.

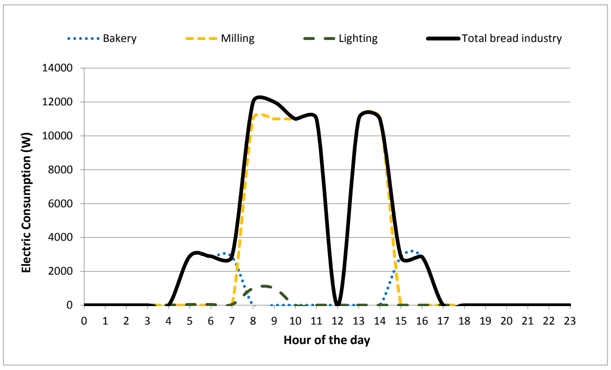


Figure 4.15. Industrial Loads

4.2.2 Resources

Assessing natural resources in the area under study is necessary to determine the capacity for renewable generation. A feasibility analysis of the renewable potential at the specific location highlights solar, wind and biomass as major potential sources, therefore further analysis of these resources is performed.

Solar resource is evaluated using the PVGIS-CMSAF [4.6] [4.7] solar radiation database at the location of Kinshasa (4°19'54" South, 15°18'50" East, and elevation: 283 m a.s.l.), resulting an annual average of solar radiation as high as 6,4 kWh/m^2/day and a clearness index mean in the order of 0,6. Solar radiation is considerable throughout the year (Figure 4.16), thus significant PV power could be expected without high variations.

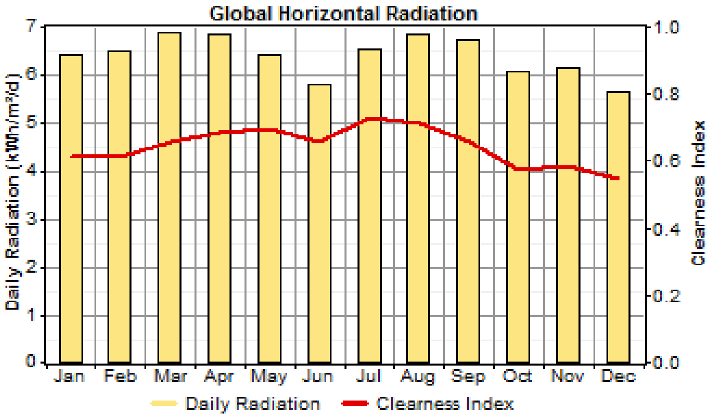


Figure 4.16. Solar Radiation Profile

Wind resource is assessed using meteorological data from METEOBLUE, a local weather source [4.8]. Average wind speed throughout the year is 1,8 m/s, except for September and October where average increases to 2,3 m/s. Despite this low average, the wind profile shows daily peaks close to 3 m/s from November to August, and over 4 m/s in September and October, with highest values around 4,5 m/s and over 8 m/s, respectively.

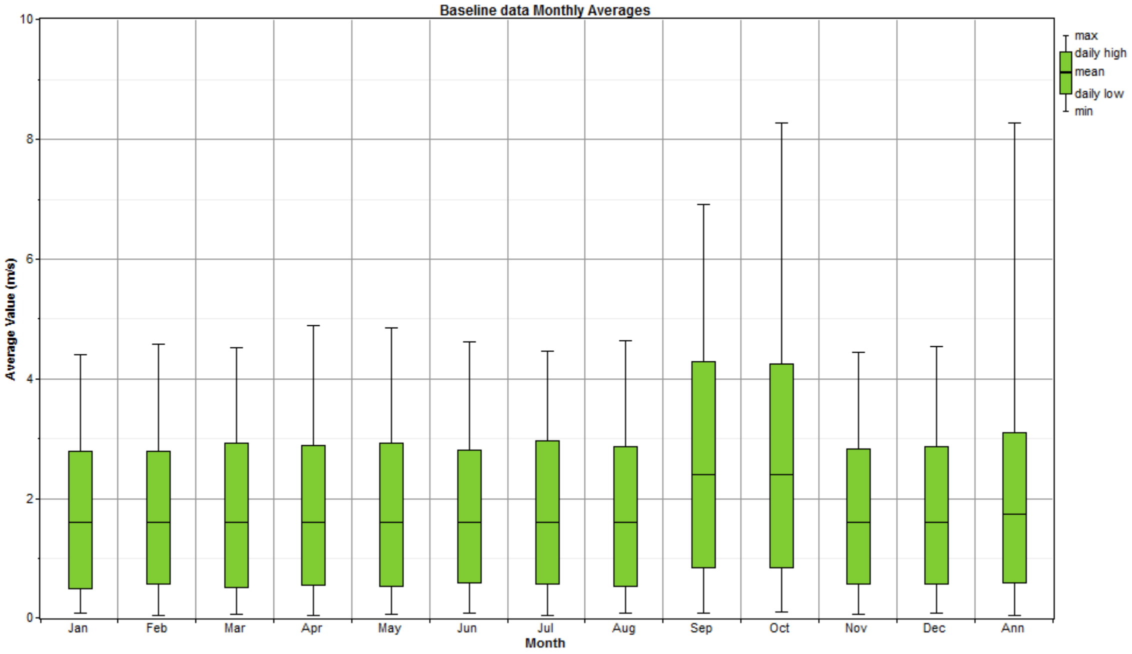


Figure 4.17. Monthly wind speed average

Analysing the daily profile of wind speeds, it is observed similar patterns. The day start with minimum wind speed values, then it intensifies until it reaches its highest record around noon. From this point, wind speed starts decreasing until reaching a minimum value again. Figure 4.18 represents the daily profile of January, with a minimum of 2 m/s and a 3,8 m/s maximum, while in a windy month like October, the figure represents a minimum wind speed value of 3 m/s and maximum values over 5 m/s.

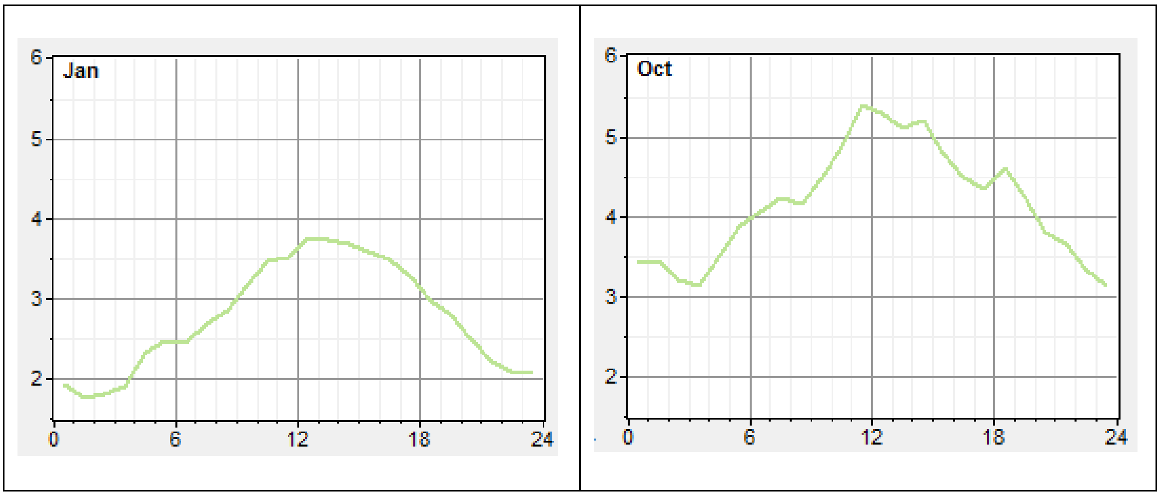


Figure 4.18. Wind speed daily profile

In addition to the wind speed, it is necessary to analyse main wind directions in order to prevent any potential obstacles. Wind rose for this case study shows wind direction mainly from South-West (SW), so special attention should be paid to this direction when installing the wind turbine.

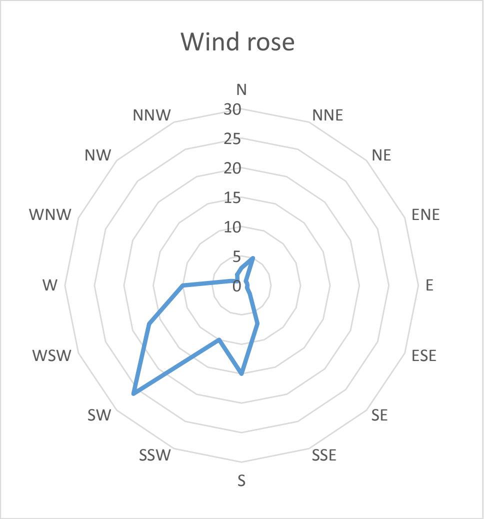


Figure 4.19. Wind rose

Regarding **biomass availability**, RDC has 145 million hectares of forest (47% of the total forest resources in Africa) with an annual growth of 100 million tons (35% moisture) [4.8]. It is estimated that RDC consumed 54,7 million tons (74,5 million m^3) of wood for energy use, mainly for residential energy as firewood and small-scale commercial sectors [4.9][4.10][4.11]. Moreover, reducing the demand for firewood is a key factor for reducing deforestation and exhaustion of DRC's natural resources [4.11][4.12], so more efficient forms of biomass energy generation should be implemented and promoted, being gasification a clean alternative. Biomass potential is large, annual forest growing represent an energy equivalency of 28 million of toe (tons of oil equivalent), while agricultural biomass waste is estimated in 0,48 million of toe and it will probably increase over the time as a consequence of general agricultural progress [4.13]. Characterization of available biomass has been carried out at the Institute for Energy Engineering (IIE), where three samples of the most representative species were analysed, obtaining the results detailed in Table 4.4. Despite biomass species present similar characteristics, NTOLA has higher HHV and lower percentage of ashes, being the more convenient alternative for the gasification process.

Samples	Moisture, (%bh)	Ashes, (%bs)	Density, (g/cm^3)	Higher Heating Value (HHV), Wet (MJ/kg)	HHV, Dry (MJ/kg)
S_1: FUMA	8,31%	0,6%	0,434	16,14	17,60
S_2: NTOLA	13,25%	0,37%	0,513	16,95	19,54
S3: LIFAKI	13,57%	2,36%	0,614	15,74	18,21

(%bh)= % of wet base; (%bs)= % of dry base

Table 4.4. Characterization of biomass forestry species in DRC.

4.2.3 Technologies

This section includes a description of the main renewable energies to be considered in the study. As identified in previous section, main natural resources are solar, wind and biomass, since the area under study did not have access to the Congo River and therefore micro hydro power generation was not available.

Solar PV system is composed by panels in series with no tracking system. Panels are configured as fixed tilted with an optimal slope of -7º at the location 4º19' south (latitude). Estimated losses of the PV system are also considered, such as those related to temperature and low irradiance (12,8%), angular reflectance effects (2,9%), and other losses in wiring, inverter etc. (14.0%). In overall terms, total losses in PV system have been estimated in 27%. Economic modelling includes capital and replacement cost of 1 kW_{PV} are 2,3 k€ and 1,5 k€, respectively, and annual operation and maintenance cost as 0,015 €/$kW_{PV.}$

Considering average wind speeds in the area, a small scale **wind turbine** of 3 kW has been selected. Wind turbine is a DC machine with a hub height of 20 m and 15 years lifetime. Output power is defined by its power curve.

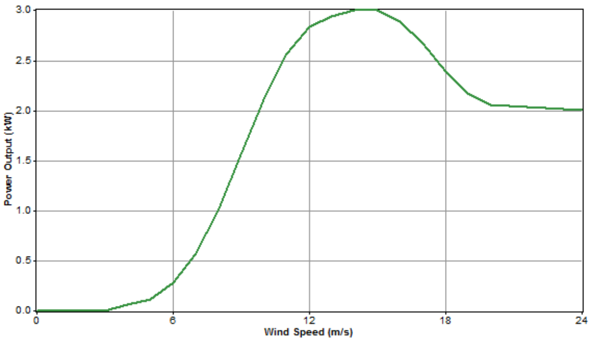


Figure 4.20. Wind turbine Power Curve

Economic modelling for small wind turbines considers a capital cost of 3,6 k€ per installed kW_{WIND}, reduced to 2,3 k€ in replacement purchases. Regarding to annual costs in operation and maintenance, this has been estimated in 200 €/year.

Biomass gasifier is modelled based on experimental data obtained at LabDER [3.38], the IIE laboratory at UPV, where a gasifier was designed and constructed for small scale validation of the system. Gasification plant technology is a downdraft fixed bed, fabricated as a mobile unit to facilitate its operation and educational purposes. Lifetime operating hours of the gasifier unit is 20,000 hours considering a minimum load ratio of 90%. Syngas generated in this system is used as an electric power by generation through an internal combustion engine with a conversion efficiency of 22%.

Parameters	IIE Gasifier	Literature Range Min-Max
Gas generation per kg of biomass, Nm^3/kg	2,1	2-2,5
Electrical generation per kg of biomass, kW/kg	0,9	0,7-1,5
Input air per gas produced, m^3/m^3	0,7	0,5-0,8
Maximum gas LHV, $kCal/m^3$	1595	900-1700
Efficiency of the conversion biomass-gas, %	79%	65%-85%
Efficiency of the conversion gas-electricity using a IC Engine, %	22%	18%-32%

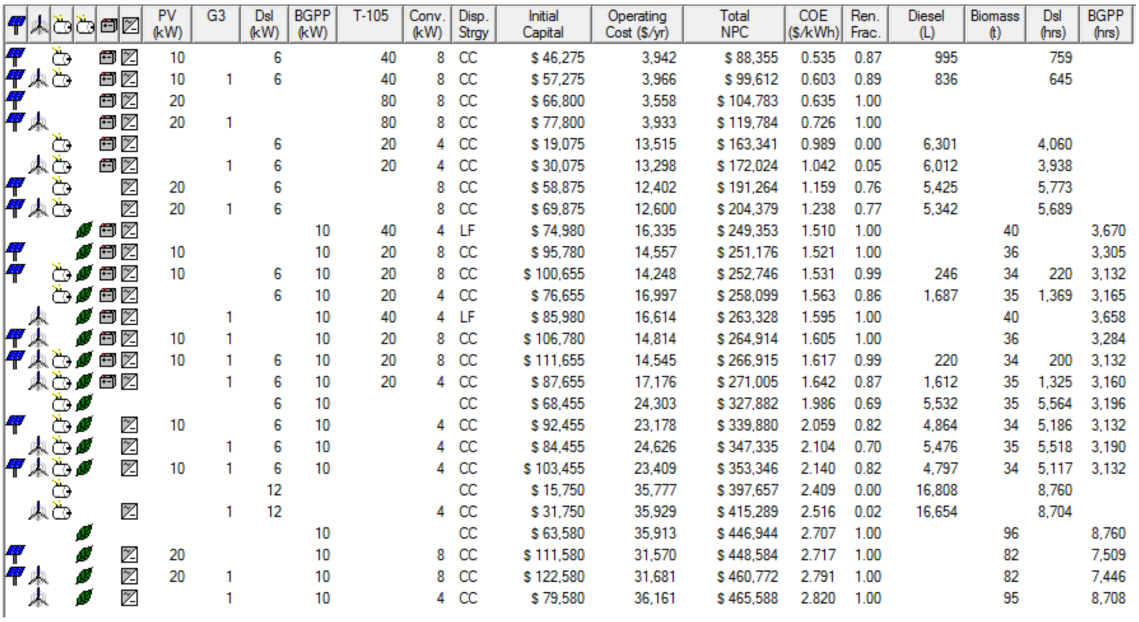
Table 4.5. Gasification Plant Operation Parameters. Source: [3.38].

Based on experimental data, initial investment of the gasification plant is 7,7 k€/kW$_{GASF}$ with a replacement cost of 3,8k€ /kW$_{GASF}$, since many of the parts may be re-used. In terms of operation and maintenance, an annual cost of 0,115 €/kW$_{GASF}$ is registered. Generation fixed costs associated to the gasification plant are 2,05 €/hr while marginal cost are observed as 0,102 €/kWh.

4.2.4 Results

Modelling and simulation of different HRES configurations has been carried out using HOMER as it is widely used in literature [2.30][3.11][3.40]. Detailed data regarding the analysed demand, resources and components are introduced as input data of the model, together with the unitary technology cost (capital, replacement and O&M), the dispatch strategy and model constraints. HOMER uses all this information to simulate all different system configurations, or combinations of components, generating a list of feasible configurations sorted by net present cost, considering the capital, replacement, operation and maintenance, fuel, and interest costs. It simulates the operation of each HRES system, calculating the hourly energy balance. For each of the 8760 hours of the year, HOMER compares the electric demand with the energy supplied by the system and calculates the energy flow to and from each component of the system. Then, it determines whether a configuration meets the electric demand under pre-defined conditions, such as minimum fraction of renewable or demand capacity shortage, and estimates the cost of installing and operating the system over the lifetime of the project.

Results of this simulation are presented in Table 4.7, showing a list of possible HRES configurations capable to satisfy the electric requirements of the community.



PV (kW)	G3	Dsl (kW)	BGPP (kW)	T-105	Conv. (kW)	Disp. Strgy	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	Biomass (t)	Dsl (hrs)	BGPP (hrs)
10		6		40	8	CC	$ 46,275	3,942	$ 88,355	0.535	0.87	995		759	
10	1	6		40	8	CC	$ 57,275	3,966	$ 99,612	0.603	0.89	836		645	
20				80	8	CC	$ 66,800	3,558	$ 104,783	0.635	1.00				
20	1			80	8	CC	$ 77,800	3,933	$ 119,784	0.726	1.00				
		6		20	4	CC	$ 19,075	13,515	$ 163,341	0.989	0.00	6,301		4,060	
	1	6		20	4	CC	$ 30,075	13,298	$ 172,024	1.042	0.05	6,012		3,938	
20		6			8	CC	$ 58,875	12,402	$ 191,264	1.159	0.76	5,425		5,773	
20	1	6			8	CC	$ 69,875	12,600	$ 204,379	1.238	0.77	5,342		5,689	
			10	40	4	LF	$ 74,980	16,335	$ 249,353	1.510	1.00		40		3,670
10			10	20	8	CC	$ 95,780	14,557	$ 251,176	1.521	1.00		36		3,305
10		6	10	20	8	CC	$ 100,655	14,248	$ 252,746	1.531	0.99	246	34	220	3,132
		6	10	20	4	CC	$ 76,655	16,997	$ 258,099	1.563	0.86	1,687	35	1,369	3,165
	1		10	40	4	LF	$ 85,980	16,614	$ 263,328	1.595	1.00		40		3,658
10	1		10	20	8	CC	$ 106,780	14,814	$ 264,914	1.605	1.00		36		3,284
10	1	6	10	20	8	CC	$ 111,655	14,545	$ 266,915	1.617	0.99	220	34	200	3,132
	1	6	10	20	4	CC	$ 87,655	17,176	$ 271,005	1.642	0.87	1,612	35	1,325	3,160
		6	10			CC	$ 68,455	24,303	$ 327,882	1.986	0.69	5,532	35	5,564	3,196
10		6	10		4	CC	$ 92,455	23,178	$ 339,880	2.059	0.82	4,864	34	5,186	3,132
	1	6	10		4	CC	$ 84,455	24,626	$ 347,335	2.104	0.70	5,476	35	5,518	3,190
10	1	6	10		4	CC	$ 103,455	23,409	$ 353,346	2.140	0.82	4,797	34	5,117	3,132
		12				CC	$ 15,750	35,777	$ 397,657	2.409	0.00	16,808		8,760	
	1	12			4	CC	$ 31,750	35,929	$ 415,289	2.516	0.02	16,654		8,704	
			10			CC	$ 63,580	35,913	$ 446,944	2.707	1.00		96		8,760
20			10		8	CC	$ 111,580	31,570	$ 448,584	2.717	1.00		82		7,509
20	1		10		8	CC	$ 122,580	31,681	$ 460,772	2.791	1.00		82		7,446
	1		10		4	CC	$ 79,580	36,161	$ 465,588	2.820	1.00		95		8,708

Table 4.6. List of feasible HRES alternatives

Following a description of the experimental validation of small scaled HRES systems is presented in the next section.

4.2.5 Experimental Validation at Small-Scaled

Any optimization process of a HRES system for a particular application could be improved by an experimental simulation of the selected configuration in order to check its capability to supply the demand profile in a reliable and feasible way. To address this experimental simulation we are using the LABDER laboratory at IIE-UPV that allows for the simulation of different HRES configurations and its response to different load curves. (Full description of LABDER is available in appendix 2). In this chapter we describe the experimental verification at a small, but significant enough, scale of two of the different HRES configurations, which includes all the different renewable sources that have been considered in the previous section. Independent of which configuration will be finally selected from the application of this methodology; its feasibility will be guarantee by this experimental simulation.

4.2.5.1 Simulation of different configurations

Two configuration results are shown here: HRES1, that includes a combination of photovoltaic panels, biomass gasification and batteries bank, dully controlled to supply a typical demand curve in the residential sector with two main peaks, in the order of 4 kW, in the morning and in the evening; and HRES2, a second hybrid system to cover the same demand curve where, in addition to the PV and the biomass gasification plants, a wind generator was included.

To facilitate the experiment, the demand curve was compressed to a 3 hours duration in the pre-programmed load, considering this time was long enough to check the capabilities of the two configurations to fulfil the energy requirements.

Total power generated by HRES1 can be expressed by the addition of the contributions from each of the renewable sources:

$$P_{gen}(t) = \sum_i c_i(t) * P_i(t) \tag{4.1}$$

where $P_i(t)$ represents the nominal power of each renewable source and $c_i(t)$ the contribution at each moment of that source to the total generated power.

Figure 4.21 shows the total power generated to cover the demand profile by adding the contribution of the solar panels, the biomass gasifier and the batteries.

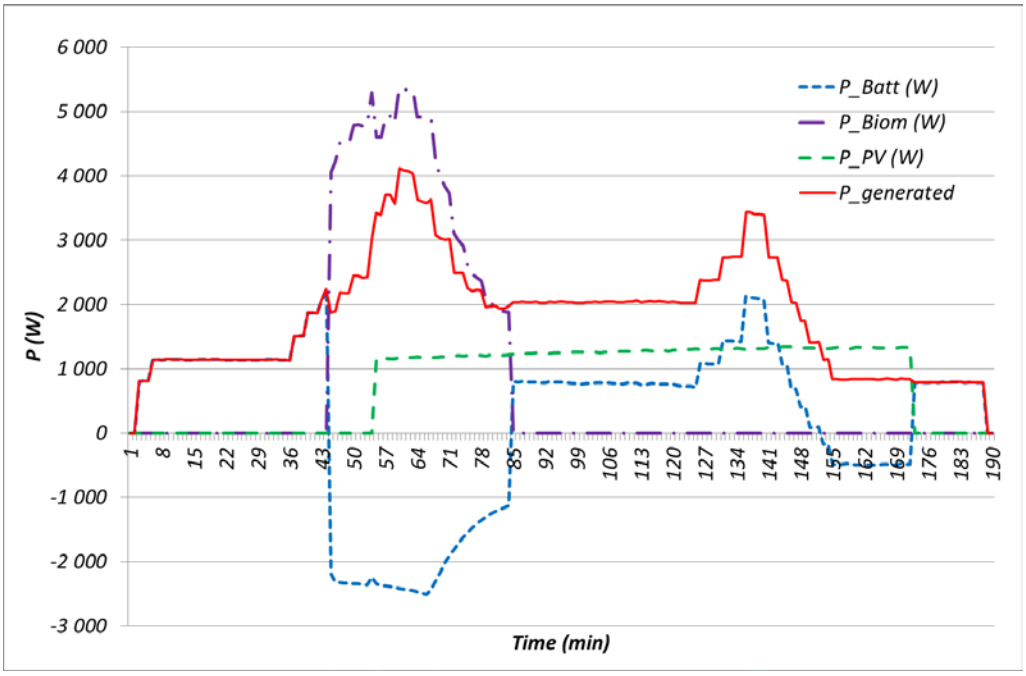


Figure 4.21. Total generated power and contributions from each element in HRES1

As it may be observed in the plot, at the beginning of the experiment, in the absence of solar radiation and with full charged storage bank, the demand is met with the electricity stored in the batteries. When the charging level of the battery bank decreases down to 50%, biomass gasifier starts the generation, covering the demand and recharging the storage bank. Later, PV energy starts, but the gasification plant continues running until battery storage is again full charged, which allows beginning the next cycle of operation under the same conditions of the previous one.

Negative power in the case of batteries indicates that batteries, at that time, are in a charge process taking energy either from the biomass gasifier, in the first part of the discharge, or from the photovoltaic system, during the final part of the discharge. Control system was setup to change to battery charge status when the bank is below 50% of its nominal full charge. The normal solar radiation profile in the experiment was almost constant due to experiment was made around noon. Sunset and sundown were substituted by an on-off control of the PV energy input to the system.

Figure 4.22 plots the contributions of each of the elements of the HRES1 to the total generated power. PV panels contributed with around 60% of their nominal power, while biomass gasifier contribution is slightly smaller, in the order of 50%, and battery bank is just working at 20%. So, the system has enough power to supply any extra power demand that could appear.

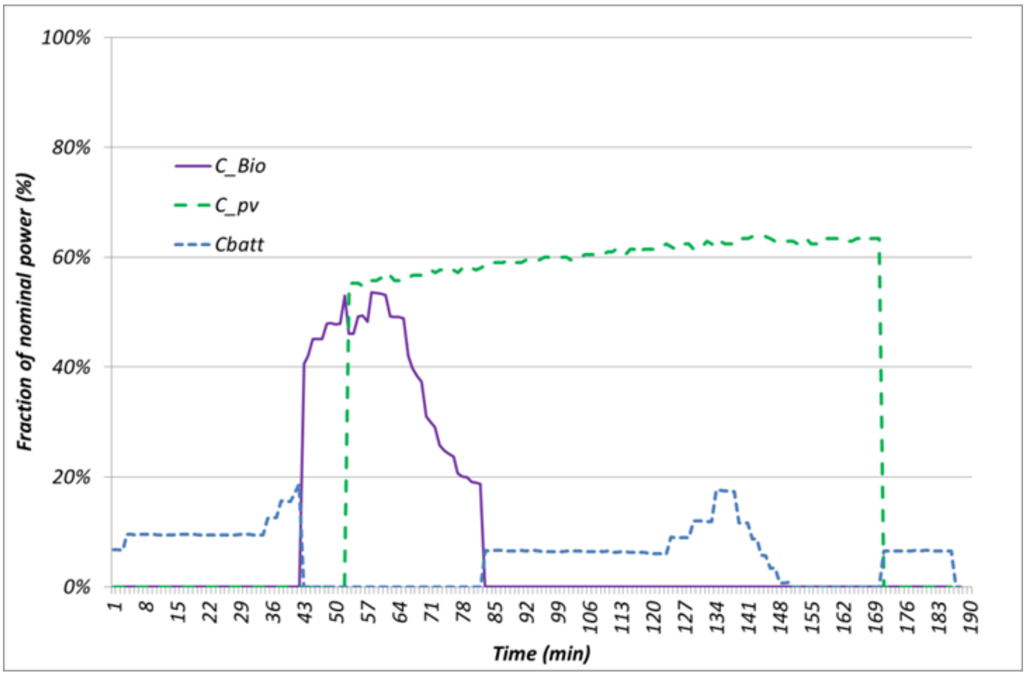


Figure 4.22. Contributions from the different HRES1 elements to the generated power.

By comparison of the generated power and the power transmitted to the load is possible to deduce the losses in the system.

$$P_{loss}(t) = P_{gen}(t) - P_{load}(t) \tag{4.2}$$

and the fraction they represent:

$$f_{loss}(t) = {}^{P_{loss}(t)}\!/_{P_{gen}}(t) \tag{4.3}$$

These losses are shown at Figure 4.23, both in absolute and percentage values.

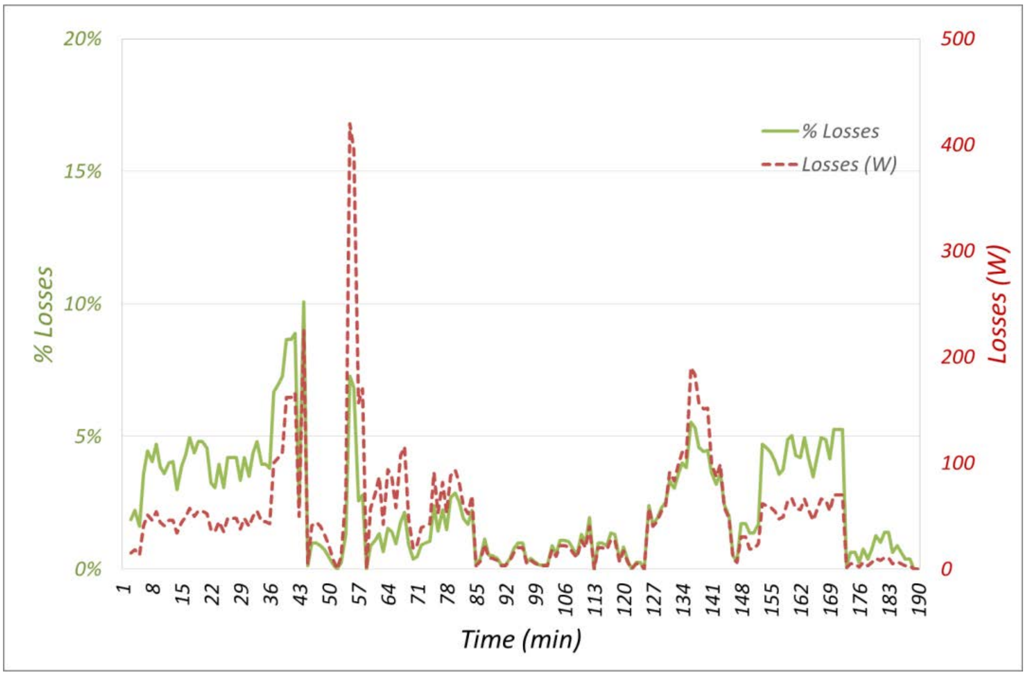


Figure 4.23. Losses in the HRES1

Results indicate that losses are small, 3% on average, and by comparison with Figure 4.23, that shows which source is the dominant one at each time, it can be deduced that main losses appear when battery bank is the dominant source or sink, reaching values at that moment in the range 5-10%.

Finally, the quality of the electric power generated by the HRES1 has been monitored by measuring the voltage and frequency of the transmitted power to the load. Figure 4.24 summarize the results. In the absence of the gasification system, the fluctuation level is almost zero. When the gasifier starts to operate, its associated syngas engine introduces, due to its less stable behaviour, some fluctuation level, in the order of 4%, for both, voltage and frequency, of the output power as detailed at Figure 4.25.

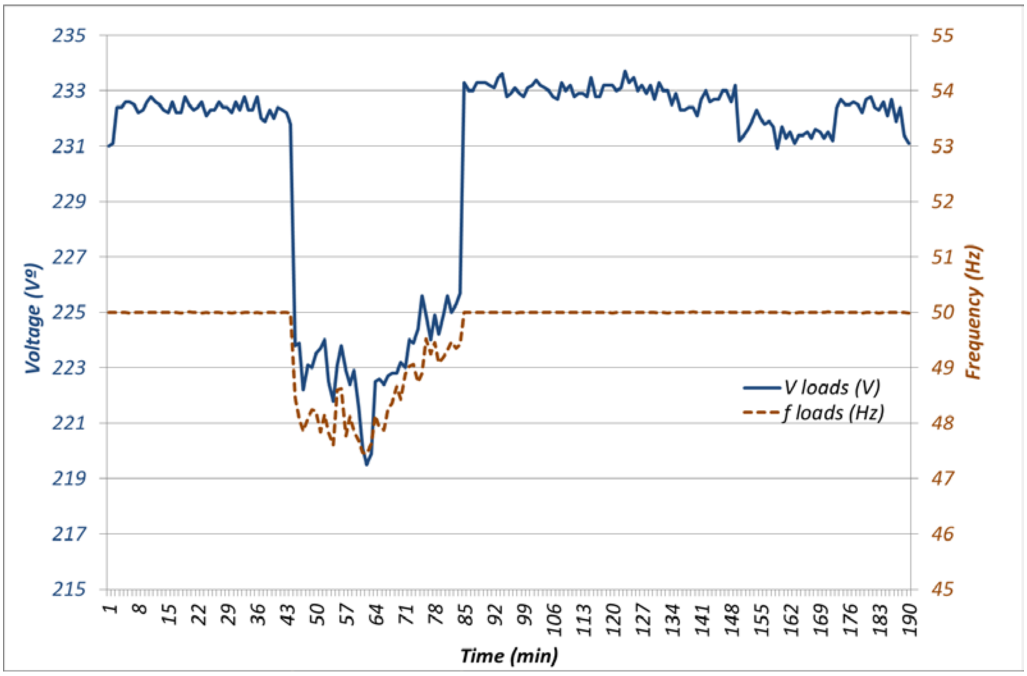


Figure 4.24. Voltage and frequency of the HRES1 delivered power to the load.

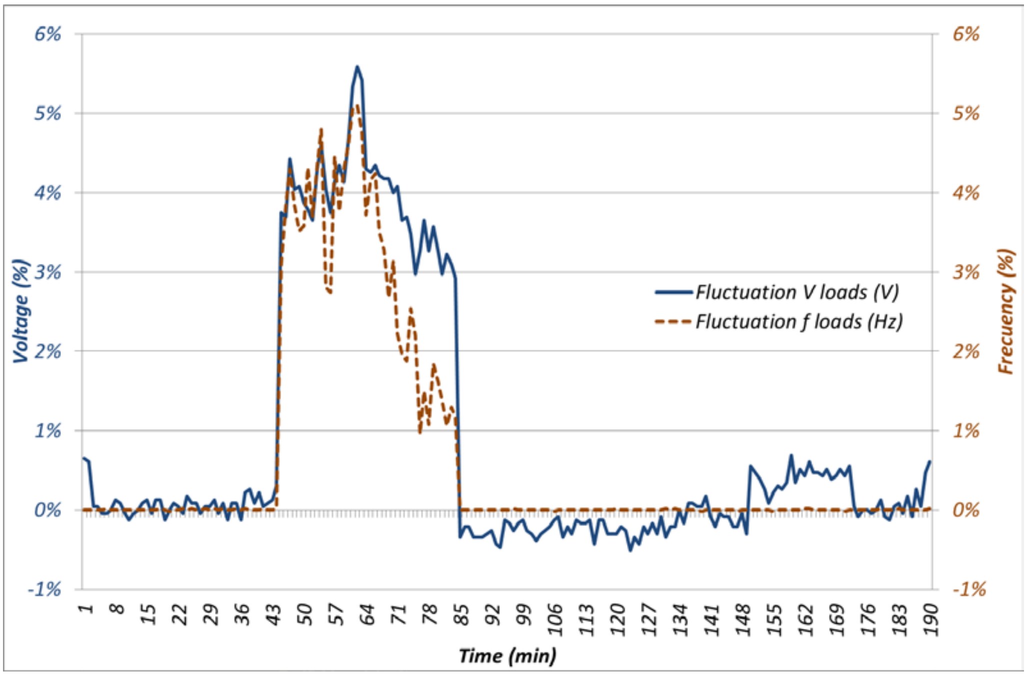


Figure 4.25. Fluctuation levels for voltage and frequency of the HRES1 power output

In summary, it could be concluded that the assembled hybrid system HRES1, whose design was obtained with the optimization methodology, seems to be able to cover the residential electricity demand profile in a flexible and reliable way.

A second hybrid system to cover the same demand curve was checked in LABDER. In this new system (HRES2), in addition to the PV and the biomass gasification plants, a wind generator was included. A similar behaviour to the previous system in its capability to supply the demand curve was observed, as detailed by the data plotted at Figure 4.26.

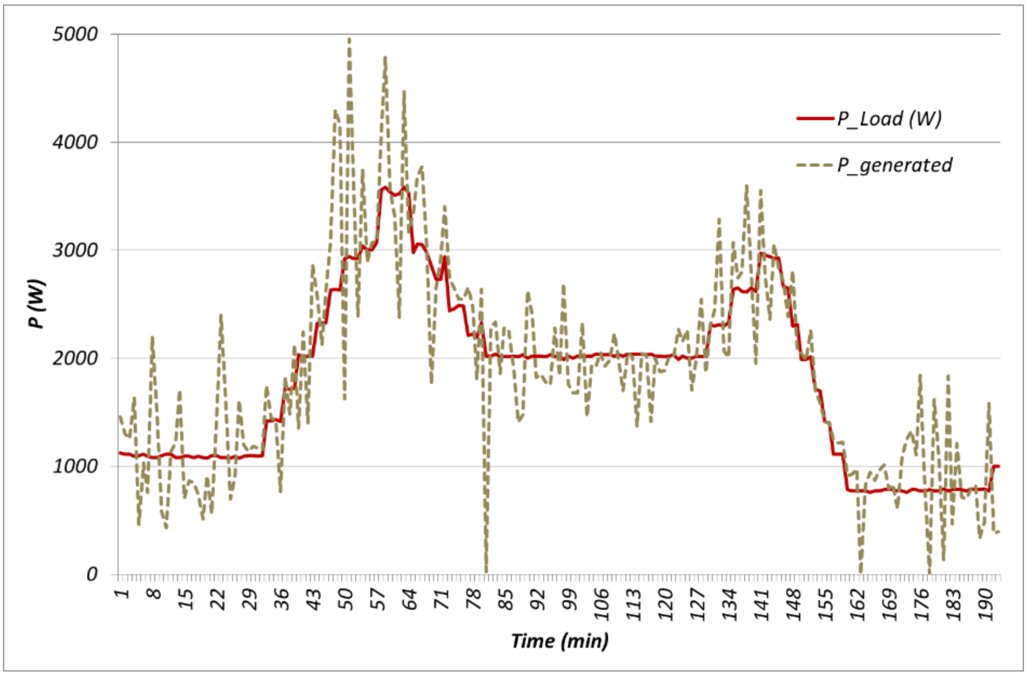
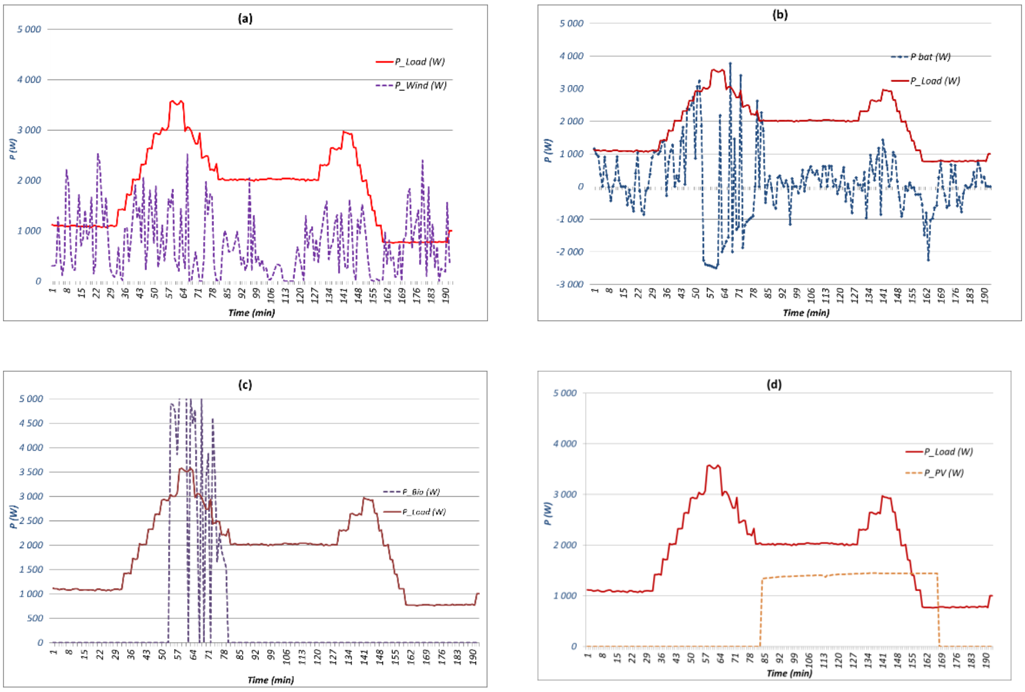


Figure 4.26. Power generated and transferred to the load by the HRES2

The main problem with this configuration is the high level of fluctuations in the power production from the wind generator, which was filtered by the battery bank and the gasifier, as can be deduced from Figure 4.27 where contribution of each component of the HRES2 system is detailed. The power transmitted to the load did not present these fluctuations



(a: wind generator, b: battery bank, c: biomass gasifier, d: PV panels)

Figure 4.27. Contribution of each energy source to the power output in HRES2

Apart from this fact, the system is able to cover the demand curve with the same level of reliability than the previous one, as shown at Figure 4.28.

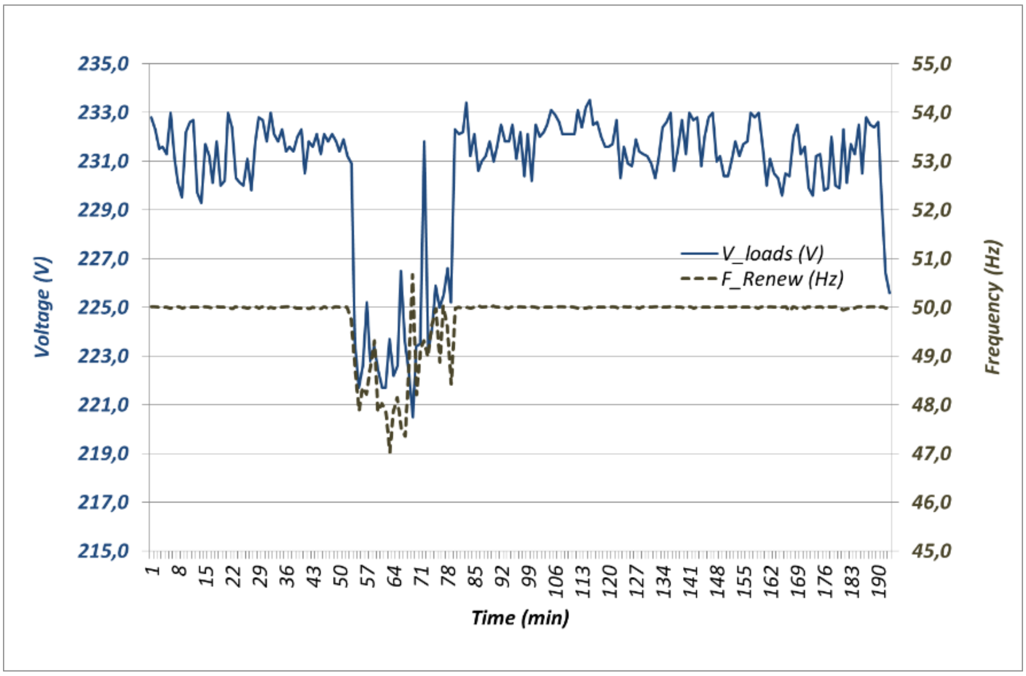


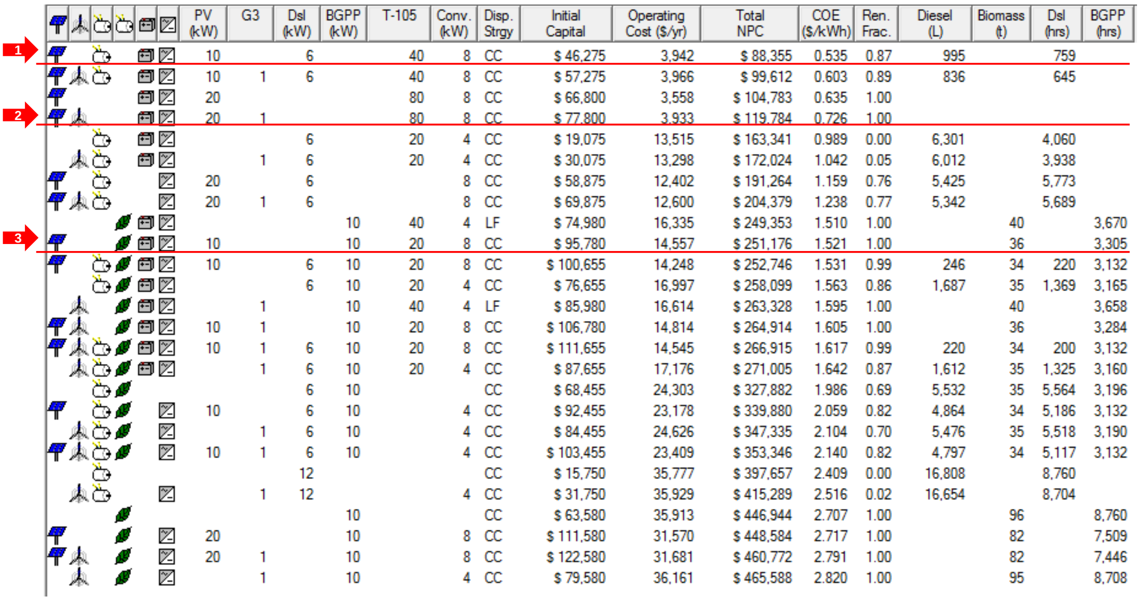
Figure 4.28. Voltage and frequency of the HRES2 delivered power to the load.

In conclusion, it is important to assure the feasibility of HRES configurations deduced from optimization methodologies, before its implementation on site. To check the expected behaviour of the proposed system an experimental simulation of that system at the minimum meaningful level could be advisable. This test would require the use of experimental installations with an adequate micro grid that includes all the possible renewable sources and storage systems assumed in the configuration.

4.3 Multi-criteria Assessment

Finally, a multi-criteria evaluation of the most promising alternatives is carried out in this section. Initially, a series of expert from different disciplines and professions were invited to participate in the assessment. Expert committee was composed by a HRES technician, an economist, a social worker, a politician and a representative of the community. First decision to be taken was to identify and select the three electrification alternatives that resulted more attractive to them, based on their professional experience. This resulted in three HRES systems composed by:

1. Photovoltaics + Genset + Batteries
2. Photovoltaics + Wind turbine + Batteries
3. Photovoltaics + Biomass Gasifiers+Batteries



	PV (kW)	G3	Dsl (kW)	BGPP (kW)	T-105	Conv. (kW)	Disp. Strgy	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	Biomass (t)	Dsl (hrs)	BGPP (hrs)
1	10		6		40	8	CC	$ 46,275	3,942	$ 88,355	0.535	0.87	995		759	
	10	1	6		40	8	CC	$ 57,275	3,966	$ 99,612	0.603	0.89	836		645	
	20				80	8	CC	$ 66,800	3,558	$ 104,783	0.635	1.00				
2	20	1			80	8	CC	$ 77,800	3,933	$ 119,784	0.726	1.00				
			6		20	4	CC	$ 19,075	13,515	$ 163,341	0.989	0.00	6,301		4,060	
		1	6		20	4	CC	$ 30,075	13,298	$ 172,024	1.042	0.05	6,012		3,938	
	20		6			8	CC	$ 58,875	12,402	$ 191,264	1.159	0.76	5,425		5,773	
	20	1	6			8	CC	$ 69,875	12,600	$ 204,379	1.238	0.77	5,342		5,689	
				10	40	4	LF	$ 74,980	16,335	$ 249,353	1.510	1.00		40		3,670
3	10			10	20	8	CC	$ 95,780	14,557	$ 251,176	1.521	1.00		36		3,305
	10		6	10	20	8	CC	$ 100,655	14,248	$ 252,746	1.531	0.99	246	34	220	3,132
			6	10	20	4	CC	$ 76,655	16,997	$ 258,099	1.563	0.86	1,687	35	1,369	3,165
		1		10	40	4	LF	$ 85,980	16,614	$ 263,328	1.595	1.00		40		3,658
	10	1		10	20	8	CC	$ 106,780	14,814	$ 264,914	1.605	1.00		36		3,284
	10	1	6	10	20	8	CC	$ 111,655	14,545	$ 266,915	1.617	0.99	220	34	200	3,132
		1	6	10	20	4	CC	$ 87,655	17,176	$ 271,005	1.642	0.87	1,612	35	1,325	3,160
			6	10			CC	$ 68,455	24,303	$ 327,882	1.986	0.69	5,532	35	5,564	3,196
	10		6	10		4	CC	$ 92,455	23,178	$ 339,880	2.059	0.82	4,864	34	5,186	3,132
		1	6	10		4	CC	$ 84,455	24,626	$ 347,335	2.104	0.70	5,476	35	5,518	3,190
	10	1	6	10		4	CC	$ 103,455	23,409	$ 353,346	2.140	0.82	4,797	34	5,117	3,132
			12				CC	$ 15,750	35,777	$ 397,657	2.409	0.00	16,808		8,760	
		1	12			4	CC	$ 31,750	35,929	$ 415,289	2.516	0.02	16,654		8,704	
				10			CC	$ 63,580	35,913	$ 446,944	2.707	1.00		96		8,760
	20			10		8	CC	$ 111,580	31,570	$ 448,584	2.717	1.00		82		7,509
	20	1		10		8	CC	$ 122,580	31,681	$ 460,772	2.791	1.00		82		7,446
		1		10		4	CC	$ 79,580	36,161	$ 465,588	2.820	1.00		95		8,708

Table 4.7. Set of HRES configurations

4.3.1 Expert's validation

Once the goal and criteria of the analysis are well defined and the alternatives are selected, it is carried out the multi-criteria assessment based on the AHP method. Initial step consist on setting the hierarchical structure of the problem (Figure 4.29) and collecting the results of the pair-wise comparisons from the expert's committee, which was performed by means of a questionnaire. In this regard, special attention is provided to the consistency ratio based on the matrix size, since a high inconsistency value will indicate that assessment have been inconsistent and, therefore, the expert committee should reconsider their evaluation.

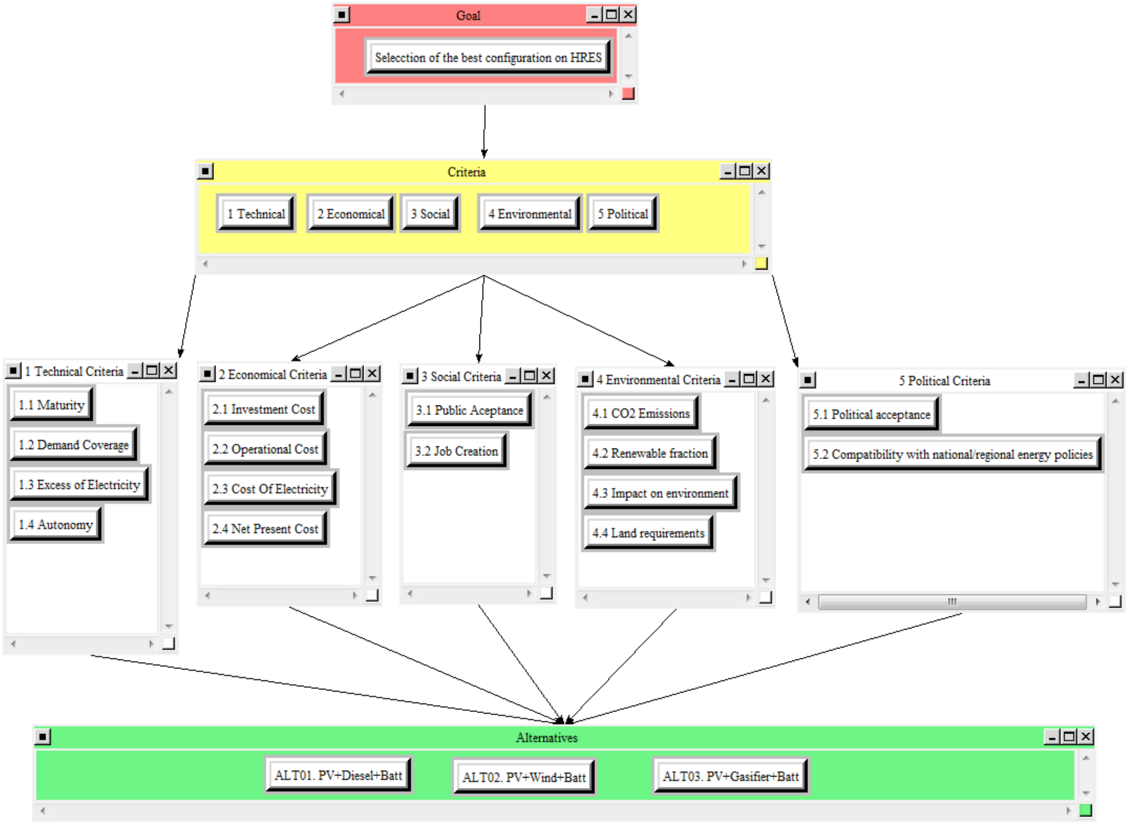


Figure 4.29. AHP multi-criteria scheme

Initial assessment involves comparing **first level alternative**s, which results in the following weights:

- C1. Technical: 21,3 %
- C2. Economic: 21,3 %
- C3. Environmental: 12,3 %
- C4. Social: 12,3 %
- C5. Political: 32,9 %

Inconsistency in this level is **1,7 %,** far below from the 10% limit for matrix size of 5. Thus, it is possible to proceed to the next level of pari-wise comparison.

Second level variables to be analysed involve:

C1. Technical characteristics:

- C1.1 Maturity: 27,6 %
- C1.2 Demand coverage: 19,5 %
- C1.3 Excess of electricity: 13,8 %
- C1.4 Autonomy: 39,1 %

Inconsistency is equal to **4,5 %**, below the consistency ratio of 9% for a 4x4 matrix.

C2. Economic Criteria.

- C2.1. Initial investment: 27.8 %
- C2.2. O&M: 16,3 %
- C2.3. Cost of Electricity: 16,3 %
- C2.4. Net Present Cost: 39,6

Inconsistency is equal to **2,3 %**, below the consistency ratio of 9% for a 4x4 matrix.

C3. Social Criteria

- C3.1. Public acceptance: 50 %
- C3.2. Job creation: 50 %

Inconsistency is equal to **0%**, so the consistency ratio condition is fulfilled.

C4. Environmental Criteria

- C4.1. CO_2 emission: 28,6 %
- C4.2. Renewable fraction: 28,6 %
- C4.3. Impact on environment: 28,6 %
- C4.4. Land requirements: 14,2 %

- **Inconsistency** is equal to **0%**, so the consistency ratio condition is fulfilled.

C5. Political Criteria

- C5.1. Political acceptance: 50 %
- C5.2. Compatibility with national/regional energy policies: 50 %

Inconsistency is equal to **0%**, so the consistency ratio condition is fulfilled.

Finally, **alternatives** are pondered based on qualitative and quantitative considerations. Qualitative aspects are evaluated by means of a questionnaire, while quantitative variables are assessed using specific values obtained from the above detailed simulations. Normalized weights will be obtained from these values and introduce in the comparison matrix.

	x	**1/x**	**Normalized Weight (1/x)**
ALT1	70,000 €	0.00001429	0.38884354
ALT2	119,400 €	0.00000838	0.22802721
ALT3	71,000 €	0.00001408	0.38312925
	Sum	0.00003675	1

Table 4.8. Evaluation of quantitative variables

Continuing with the evaluation, next it is assessed each alternative per criteria (technical, economic, social, environmental, political), obtaining the following weights.

C1. Technical characteristics	ALT1. PV + Diesel + Batt	ALT2. PV+ Wind + Batt	ALT3. PV + Gasifier + Batt
C1.1 Maturity	49,3 %	31,1 %	19,6 %
C1.2 Demand coverage	40,0 %	20,0 %	40,0 %
C1.3 Excess of electricity	87,0 %	7,8 %	5,2 %
C1.4 Autonomy	40,0 %	20,0 %	40,0 %

Table 4.9. Assessment of Technical characteristics in each alternative

C2. Economic characteristics	ALT1. PV + Diesel + Batt	ALT2. PV+ Wind + Batt	ALT3. PV + Gasifier + Batt
C2.1. Initial investment	48,1 %	28,6 %	23,3 %
C2.2. O&M	43,9 %	44,1 %	12,0 %
C2.3. Cost of Electricity	47,8 %	35,2 %	17,0 %
C2.4. Net Present Cost	54,9 %	36,2 %	8,9 %

Table 4.10. Assessment of Economic characteristics in each alternative

C3. Social characteristics	ALT1. PV + Diesel + Batt	ALT2. PV+ Wind + Batt	ALT3. PV + Gasifier + Batt
C3.1. Public acceptance	31,1 %	20,6 %	49,3 %
C3.2. Job creation	13,1 %	20,8 %	66,1 %

Table 4.11. Assessment of Social characteristics in each alternative

C4. Environmental characteristics	ALT1. PV + Diesel + Batt	ALT2. PV+ Wind + Batt	ALT3. PV + Gasifier + Batt
C4.1. CO_2 emission	0,0 %	98,4 %	1,6%
C4.2. Renewable fraction	11,2 %	44,4 %	44,4 %
C4.3. Impact on environment	10,9 %	34,4 %	54,7 %
C4.4. Land requirements	49,4 %	19,6 %	31,0 %

Table 4.12. Assessment of Environmental characteristics in each alternative

C5. Political characteristics	ALT1. PV + Diesel + Batt	ALT2. PV+ Wind + Batt	ALT3. PV + Gasifier + Batt
C5.1. Political acceptance	41,3 %	25,9 %	32,8%
C5.2. Compatibility with national/regional energy policies	9,8 %	22,9 %	67,3 %

Table 4.13. Assessment of Political characteristics in each alternative

Finally, **global weights** for each **alternative** are calculated according to the following mathematical expression:

$$W_{Global} = \sum (W_{C1} * W_{C2} * W_A) \tag{4.4}$$

Where:

W_{C1}: are the weighs of the first level analysis

W_{C2}: are the weighs of the second level analysis

W_A: are the weighs of the alternatives

Thus, **final global weights** of the alternatives are ALT1 (41,4 %), ALT2 (38,0 %) and ALT3 (20,6 %), which indicates that the **best alternative** for this study case is the HRES configuration that includes **PV+Diesel Gen+Batteries**.

ALTERNATIVES	Finals Weights
ALT1. PV + Diesel + Batt	**41,44 %**
ALT2. PV+ Wind + Batt	37,99 %
ALT3. PV + Gasifier + Batt	20,57 %

4.4 Conclusions

This chapter presented an implementation of the integral methodology introduced in previous unit. The methodology has been applied to an isolated area near Kinshasa in Republic Democratic of Congo. First it has been analysed the energy context of the country, and then BAU scenario has been compared with a scenario based of HRES, aiming to increase the electrification rate in the country without compromising their energy independency or the environment. Results from this first analysis showed that a sustainable scenario based on HRES is possible.

Next, it has been modelled and simulated a series of HRES configurations to obtain a set of feasible HRES alternatives for the area of Kinshasa. Once, the promising HRES configurations have been identified, an experimental validation of small scaled systems has been carried out in LabDER, Distributed Energy Resources Laboratory at UPV, concluding that these systems can provide reliable supply of energy to isolated communities.

Finally, a multi-criteria evaluation of the promising HRES alternatives was carried out by an expert's committee, who has analysed the importance of each variable in comparison with the rest. Final result from this last stage of the methodology is the selection of the most adequate HRES alternative for Kinshasa area, considering not just the economic, environmental and technical aspects, but also the socio-political context of the isolated community.

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CHAPTER 5. CONCLUSIONS

This last chapter includes the conclusions and recommendations of the research, whose objective was developing an integral methodology for assessing and optimising the integration of Hybrid Renewable Energy Systems (HRES) in isolated areas electrification. Firstly, it has been reviewed the state of the art related to energy planning, distributed energy generation in remote areas, characteristic electrical loads in off-grid communities, and the application of multi-criteria evaluation applied to energy projects. Secondly, it has been described the methodology step by step, from the definition of a planning analysis to the identification of feasible HRES solutions applied to off-grid sites, to final multi-criteria assessment using the AHP approach. Finally, the methodology has been applied in a case study for its validation.

Main **conclusions** extracted from the development of this work are:

- The sustainable development of countries with low electrification rates based on HRES is possible and should be accompanied by national and regional energy directives. Enhancing HRES in remote communities will provide energy access to isolated areas, promoting the economic development of these communities without increasing CO_2 emissions.
- HRES modelling and simulation of off-grid HRES configurations may be optimized in a first stage based on the electricity load, climatic data sources, and economics of the power components in which the NPC has to be minimized to select an economic feasible power system. However, in a second stage is crucial to gather the opinion of local experts and local residents.
- The process of decision taken in selecting feasible energy projects is a complex problem that needs to be tackled from different perspectives (technical, economic, social, environmental and political). In this regard, the use of multi-criteria methods is essential for the success and continuity of the project in the future.
- State of the art revealed an important effort carried out by the scientific community to study isolated areas electrification, mainly based on decentralized

energy generation, but an integral methodology for the optimization of this electrification based on HRES had not been yet published.

- This integral methodology should optimize the quality of energy services to non-connected areas from three main approaches: technical, economical, and sustainability, assessing the potential for energy generation with renewable energies, evaluating possible hybrid configurations, together with demand side management strategies.
- In addition, the methodology should analyse the available resources with potential for demand response actions for distributed generation and energy storage needs, and integrate qualitative assessment of social and political aspects of the implementation of HRES in the isolated community using the Analytic Hierarchy Process. The methodology has been developed in this thesis and used, as a test case of its applicability and example of the procedure to follow in its application, to a local community located in the Democratic Republic of Congo. Two possible HRES configurations were experimentally simulated in a significant scale in LABDER laboratory to demonstrate its feasibility and reliability behaviour.
- Electrification of rural areas will remain a challenge for governments in developing countries like Republic Democratic of Congo. Comparing renewable energy systems with conventional generation units powered by fuel may not be cost effective yet, but the necessity of environmental protection and global tendency toward more environmental friendly habits will derive in a decrement of fossil fuels and its substitution by renewable energy technologies.

Continuing with this research, **future works** may focus on tacking the following aspects:

- Compare the technological and economic implications of the proposed HRES solutions with an extension of the grid to cover the currently isolated areas.

- Applied this methodology to different pilots in Republic Democratic of Congo and compared the deduced optimal configurations, identifying which HRES best alternatives repeat the most.
- Analyse possible financing schemes that will facilitate the penetration of HRES systems in rural areas.
- Evaluate the applicability of the methodology in its application to grid connected communities, but with the possibility to work in a peninsula mode.

APPENDICES

Throughout this section, it is provided a series of appendices, including additional information related to the development of this research work.

Appendix 1. Energy Reports on RDC Scenarios

In this Appendix is included the Energy Report on RDC Scenarios.

BAU SCENARIO (BUSINESS AS USUAL)

PREVIOUS CONSIDERATIONS

* BAU Scenario maintains the % of contribution from each energy source to each consuming sector.

* Efficiency in Electricity generation is deduced from input data.

* Nuclear contribution is maintained constant to the initial value. No additional power plants are projected.

* Nuclear growth is supplied by the import-export balance.

INITIAL ENERGY CONSUMPTION DATA AND SUSTIANBLE INDICATORS

	RD Congo, 2014		AFRICA, 2014	
Primary Energy (EP)	**ktoe**	**%**	**ktoe**	**%**
Coal	0	0%	90.184	14%
Oil	1.532	7%	150.238	23%
Natural Gas	0	0%	78.952	12%
Renewable	20.057	93%	320.322	50%
Nuclear	0	0%	3.595	1%
Import-Export	92	0%	633	0%
Total Primary Energy (TEP)	**21.681**	**100%**	**643.924**	**100%**
Final Energy (EF)	**ktoe**	**%**	**ktoe**	**%**
Industry	3.370	16%	86.009	16%
Transport	1.490	7%	95.822	18%
Services	69	0%	20.030	4%
Residential	16.580	77%	317.566	60%
Agric. / Fish.	0	0%	10.483	2%
Total Final Energy (TEF)	**21.509**	**100%**	**529.910**	**100%**
Indicators				
Population	74,88	Millions	1.155,72	Millions
GDP$_{ppp}$	52.200.000	M€$_{2010}$	5.131.220.000	M€$_{2010}$
Consumption of Electricity	8	TWh	257.118	TWh
CO$_2$ Emissions	4,53	Mt	1.105,29	Mt
Generated Electricity	587	ktep	49.487	ktep
Exterior Dependency	30,15	%	35,69	%
GDP$_{ppp}$/capita	0,6971	M€$_{2010}$/inhab	4,4398	M€$_{2010}$/inhab
TEP/capita	0,38	tep/hab	3,08	tep/hab
TEP/GDP$_{ppp}$	0,6	tep/M€$_{2010}$	176,2	tep/M€$_{2010}$
Electricity/capita	0,1	kWh/inhab	0,5	kWh/inhab
CO$_2$/TEP	0,16	t/tep	1,72	t/tep
CO$_2$/GDP$_{ppp}$	0,09	t/M€$_{2010}$	0,22	t/M€$_{2010}$
CO$_2$/capita	0,06	t/inhab	0,96	t/inhab

EVOLUTION OF ENERGY INDICATORS

SCENARIO **BAU** **RD Congo**

Indicators	**Units**	**2014**	**2015**	**2020**	**2025**	**2030**	**2035**
Population	Million	74,9	77,2	89,9	104,6	121,8	141,8
GDPppp	M€$_{2010}$	52.200.000	52.412.599	53.488.650	54.586.794	55.707.483	56.851.180
Consumption of Electricity	TWh	7,9	8,0	8,7	9,5	10,4	11,3
CO$_2$ Emissions	Mt	4,53	4,85	6,82	9,64	13,68	19,45
Primary Energy (EP)	ktep	28.713	29.520	33.978	39.265	45.586	53.214
EP Generated	ktep	20.057	20.558	23.264	26.344	29.852	33.848
Import-Export	ktep	92	94	102	111	121	132
Generated Electricity	ktep	587	597	648	706	771	843
Exterior Dependency	%	30,15	30,36	31,53	32,91	34,51	36,39
GDPppp/capita	M€$_{2010}$/inhab	0,70	0,68	0,60	0,52	0,46	0,40
TEP/capita	tep/hab	0,383	0,382	0,378	0,375	0,374	0,375
TEP/GDPppp	tep/M€$_{2010}$	0,55	0,56	0,64	0,72	0,82	0,94
Electricity/capita	MWh/inhab	0,11	0,10	0,10	0,09	0,09	0,08
CO$_2$/TEP	t/tep	0,16	0,16	0,20	0,25	0,30	0,37
CO$_2$/GDPppp	t/M€$_{2010}$	0,09	0,09	0,13	0,18	0,25	0,34
CO$_2$/capita	t/inhab	0,060	0,063	0,076	0,092	0,112	0,137
Fraction ER in EP*	%	69,9	69,6	68,5	67,1	65,5	63,6
Fraction ER in EE*	%	86,5	86,5	86,5	86,5	86,5	86,5

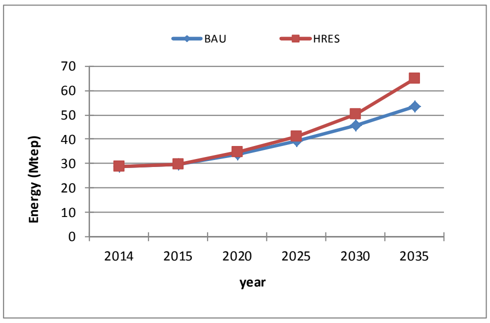
Fraction ER in EP and EE*: % of renewable energies contribution to primary energy and electrical generation.

SCENARIO HRES RD Congo

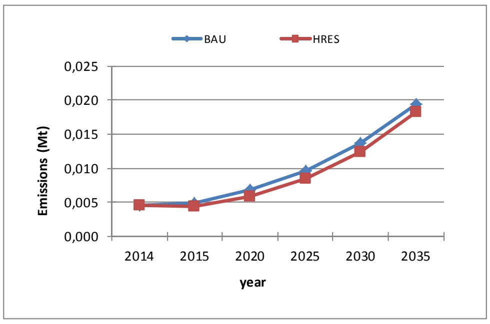
Indicators	**Units**	**2014**	**2015**	**2020**	**2025**	**2030**	**2035**
Population	Millions	74,88	77,19	89,87	104,64	121,83	141,84
GDP	Billion€$_{2010}$	52.200.000,00	52.412.598,61	53.488.650,37	54.586.793,92	55.707.482,79	56.851.179,86
Consumption of Electricity	TWh	7,90	8,07	11,64	18,84	33,48	66,74
CO_2 Emissions	Mt	4,53	4,40	5,94	8,53	12,37	18,22
Primary Energy (EP)	ktep	28.713,00	29.524,03	34.675,03	41.107,47	50.314,52	64.915,28
EP Generated	ktep	20.057,00	20.721,46	24.155,96	28.320,24	34.346,50	44.194,58
Import-Export	ktep	92,00	93,98	135,61	219,47	390,01	777,54
Generated Electricity	ktep	587,00	599,62	865,27	1.400,29	2.488,45	4.961,07
Exterior Dependency	%	30,15	29,81	30,34	31,11	31,74	31,92
GDP/capita	M€$_{2010}$/inhab	0,70	0,68	0,60	0,52	0,46	0,40
TEP/capita	tep/inhab	0,383	0,382	0,386	0,393	0,413	0,458
TEP/GDP	tep/M€$_{2010}$	0,55	0,56	0,65	0,75	0,90	1,14
Electricity/capita	MWh/inhab	0,11	0,10	0,13	0,18	0,27	0,47
CO_2/TEP	t/tep	0,16	0,15	0,17	0,21	0,25	0,28
CO_2/GDP	t/M€$_{2010}$	0,09	0,08	0,11	0,16	0,22	0,32
CO_2/capita	t/inhab	0,06	0,06	0,07	0,08	0,10	0,13
Fraction ER in EP*	%	69,9	70,2	69,7	68,9	68,3	68,1
Fraction ER in EE*	%	86,5	86,5	86,5	86,5	86,5	86,5

PRIMARY ENERGY CONSUMPTION AND CO_2 EMISSIONS

Primary Energy

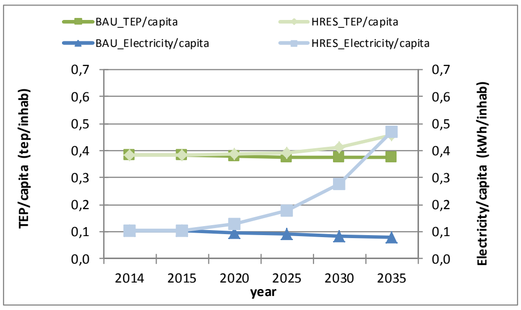


CO_2 Emissions

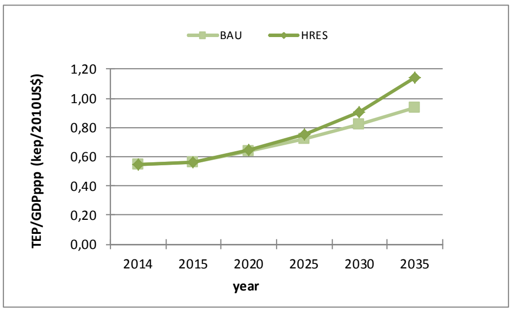


ENERGY INTENSITY

TEP/capita and Electricity/capita

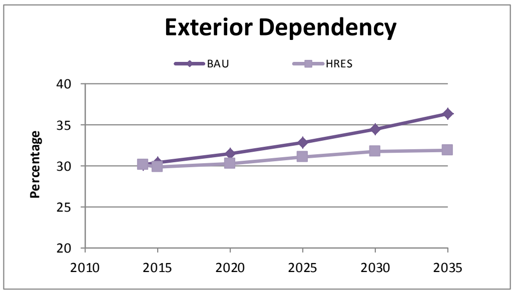


TEP/GDP$_{ppp}$



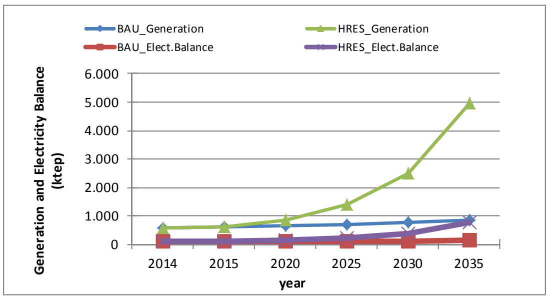
EXTERIOR DEPENDENCY

	BAU	HRES
2014	30,15	30,15
2015	30,36	29,81
2020	31,53	30,34
2025	32,91	31,11
2030	34,51	31,74
2035	36,39	31,92

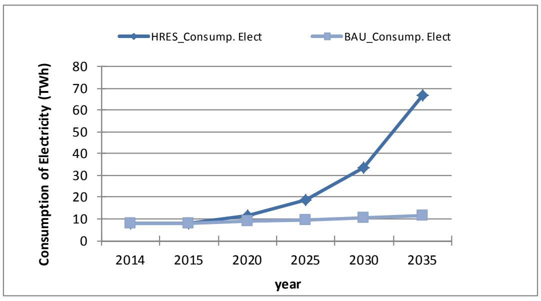


ELECTRICITY

Electricity Generation and Electric Balance (Import-Export)



Consumption of Electricity



ENERGY DEMAND PER SECTOR

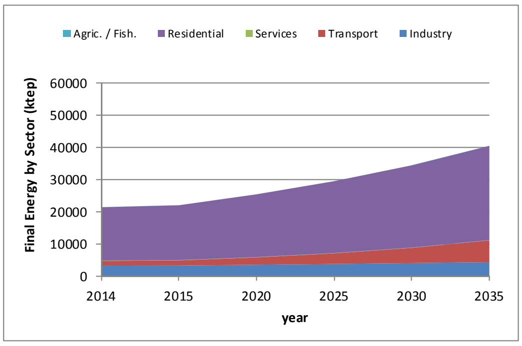
BAU

	2014	2015	2020	2025	2030	2035
Industry	3.370	3.416	3.653	3.908	4.179	4.470
Transport	1.490	1.601	2.296	3.292	4.721	6.769
Services	69	69	67	65	64	62
Residential	16.580	17.035	19.501	22.324	25.557	29.257
Agric. / Fish.	0	0	0	0	0	0

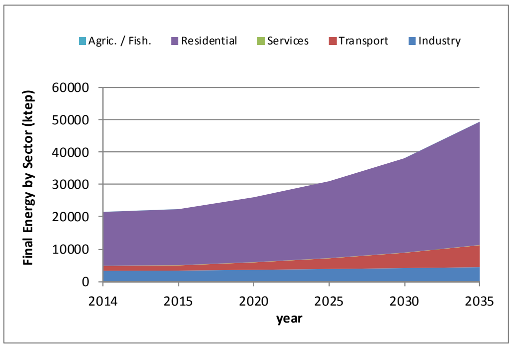
HRES

	2014	2015	2020	2025	2030	2035
Industry	3.370	3.416	3.653	3.908	4.179	4.470
Transport	1.490	1.601	2.296	3.292	4.721	6.769
Services	69	69	67	65	64	62
Residential	16.580	17.272	20.019	23.712	29.109	38.027
Agric. / Fish.	0	0	0	0	0	0

BAU_Demand by Sector



HRES_Demand by Sector



DEMAND BY ENERGY SOURCE

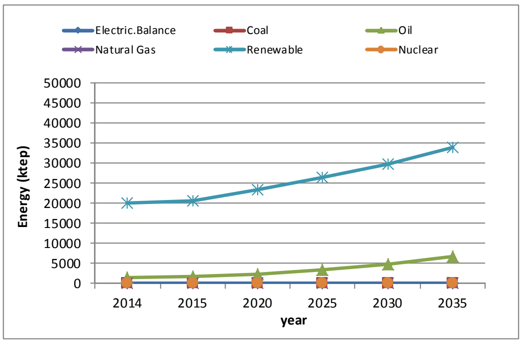
BAU

Year	Electric.Balance	Coal	Oil	Natural Gas	Renewable	Nuclear
2014	92	0	1.532	0	20.057	0
2015	94	0	1.644	0	20.558	0
2020	102	0	2.342	0	23.264	0
2025	111	0	3.342	0	26.344	0
2030	121	0	4.774	0	29.852	0
2035	132	0	6.826	0	33.848	0

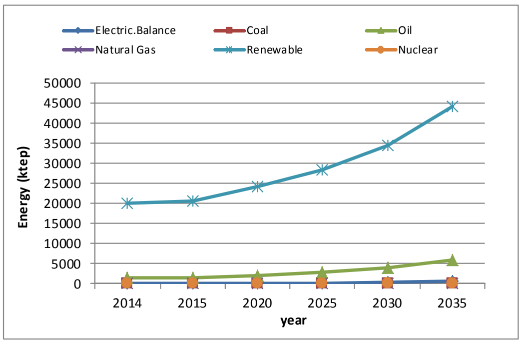
HRES

Year	Electric.Balance	Coal	Oil	Natural Gas	Renewable	Nuclear
2014	92	0	1.532	0	20.057	0
2015	94	0	1.484	0	20.721	0
2020	136	0	1.998	0	24.156	0
2025	219	0	2.848	0	28.320	0
2030	390	0	4.065	0	34.347	0
2035	778	0	5.810	0	44.195	0

BAU_Primary Energy by Source



HRES_Primary Energy by Source



CO$_2$ EMISSIONS PER SECTOR

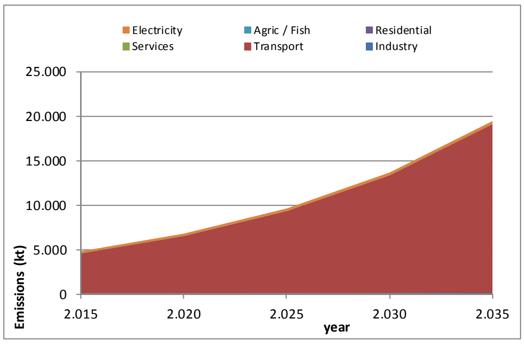
BAU

	2.015	2.020	2.025	2.030	2.035
Industry	119	127	136	145	155
Transport	4.484	6.429	9.218	13.218	18.952
Services	0	0	0	0	0
Residential	10	11	13	14	16
Agric / Fish	0	0	0	0	0
Electricity	234	254	277	302	330

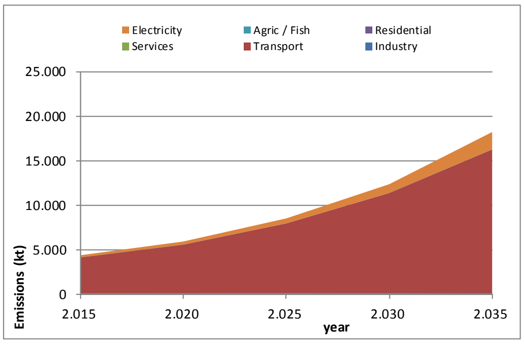
HRES

	2.015	2.020	2.025	2.030	2.035
Industry	119	127	136	145	155
Transport	4.035	5.465	7.836	11.235	16.109
Services	0	0	0	0	0
Residential	10	11	13	13	15
Agric / Fish	0	0	0	0	0
Electricity	235	339	549	975	1.944

BAU_CO_2 Emissions



HRES_CO_2 Emissions



CO_2 EMISSIONS PER ENERGY SOURCE

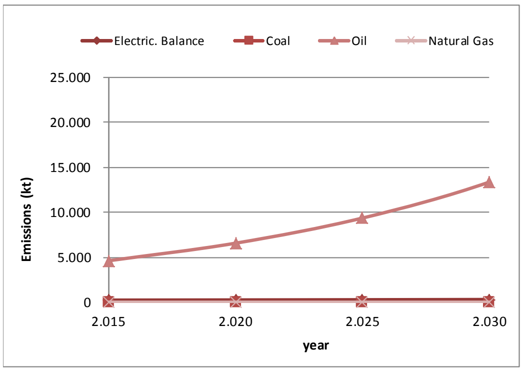
BAU

Year	Electric. Balance	Coal	Oil	Natural Gas
2.015	234	0	4.612	0
2.020	254	0	6.567	0
2.025	277	0	9.366	0
2.030	302	0	13.377	0
2.035	330	0	19.124	0

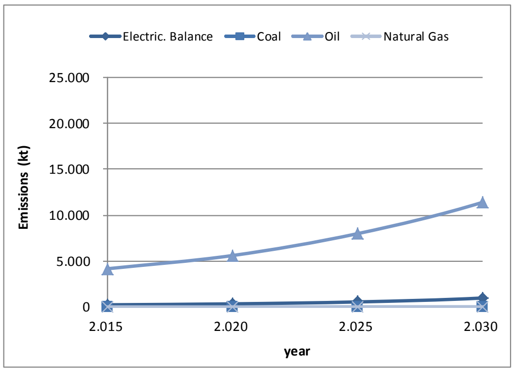
HRES

Year	Electric. Balance	Coal	Oil	Natural Gas
2.015	235	0	4.164	0
2.020	339	0	5.603	0
2.025	549	0	7.984	0
2.030	975	0	11.393	0
2.035	1.944	0	16.280	0

BAU_CO2 Emissions by Source



HRES_CO2 Emissions By Source



Appendix 2. Description of the Laboratory LabDER

LabDER: Laboratory for experimental verification of hybrid renewable systems.

Given the potential of Hybrid Renewable Energy Systems (HRES), many studies have been completed to simulate and optimize their design [1, 2, 3, 4, 5], but before the construction of such kind of systems an experimental verification of their capabilities at the minimum significant power is advisable. With this goal, a laboratory has been designed and built at the Institute for Energy Engineering of the Universitat Politècnica de València [6] that allows for the assembly of HRES combining different renewable sources: photovoltaic, wind, biomass and hydrogen fuel cells, all of them interconnected by a controlled micro grid that supplies to a demand curves simulator to verify the capability of the selected HRES to satisfy different demand curves with high reliability. Additionally, the laboratory includes the capability to storage energy, both in batteries and hydrogen, to cover most of the possible HRES configurations. This laboratory enables to prove experimentally the feasibility in the short and long term of different hybrid configurations, by combining adequately the renewable sources available at the plant, to satisfy any particular electricity demand, which can be defined by a programmable load. All the systems and the programmable loads are working in the 10 kW range.

1. LABDER DESCRIPTION

Block diagram of the laboratory is displayed at figure 1 and brief descriptions of each of its components are included in the next paragraphs.

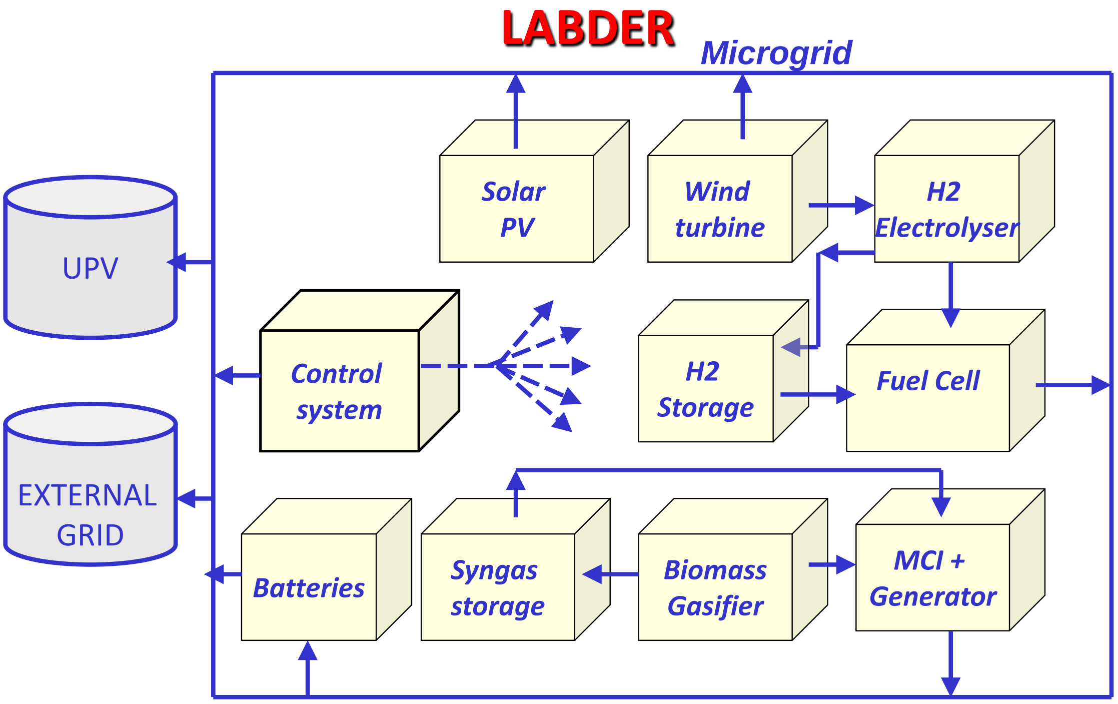


Figure 1: Block diagram of LabDER system

a) Photovoltaic system

The LabDER photovoltaic generator is made up of monocrystalline and polycrystalline silicon modules mounted on the roof of the laboratory, facing south with tilt angle of 30º to produce maximum annual energy. The total power of the photovoltaic generator now installed is 2.1 kWp, and the panels are connected to a single phase grid inverter. The system is being expanded up to 9 kW three phases system by adding additional modules and 2 new single phase inverters.

The solar radiation in the photovoltaic generator and the modules temperature are measured using a Datasol Met computer system. The operating point of the panels and the inverter, currents, voltages, power and energy injected to the grid are also monitored. This information allows to the management system to check the correct operation of the system and to know the energy produced at any time.

b) Wind energy system

Electricity generation from wind energy is obtained in LabDER by a wind turbine with 5 kW peak power and 3 kW for winds with a 12 m.s-1 speed (figure 2). Located at the top of a 16 m. tower, this system is composed by a three pales 3,5 meters diameter wind turbine with an electrical machine connected to the turbine axis. This electrical machine, optimized for the available power of the turbine, is a synchronous one with the excitation provided by permanents magnets.

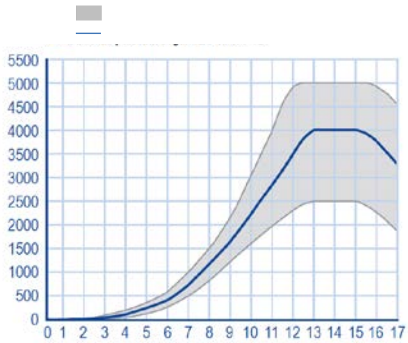


Figure 2: Power dependence on wind speed.

The system includes a rectifier and inverter devices, with a 3,2 kW power and input voltages in the range 350 to 500 V, that matches the output of the wind system to the micro grid frequency, and a dumping load to receive that fraction of the generated electricity that the micro grid cannot absorb in situations where high generation and low demand are present.

This system has been design and built with flexibility enough to allow for the change of blades and turbine in order to determine the dynamical response and power of different blades geometries and turbine characteristics.

c) Biomass system

Biomass energy in LABDER is provided by a biomass gasification power plant. This plant includes a gas internal combustion engine for power generation, in addition to the control and monitoring systems. The gasifier with a consumption of 13 kg/h of biomass (with 10% of moisture) produces about 30 Nm3/h of syngas that, when burnt in the gas internal combustion engine that drives a electricity generator, provides a maximum electricity power of 10 kWe. Table 1 shows the main features of biomass gasification power plant.

Biomass gasification reactor type	Bubbling fluidized bed
Biomass reactor dimensions	Diameter: 106 mm, Height: 155 mm
Material	Stainless Steel
Fuel type	Wood chips < 10 – 15 mm length Pellets (diameter 6 mm, 15-25 mm length)
Biomass hopper capacity	237 liter (up to 166 kg of biomass depending on bion density)
Biomass screw feeder diameter	two screw conveyor: diameter 25 mm and 55 mm
Biomass input (@ 10% moisture)	6-13 kg/h
	30 – 60 kWt (referred to Higher Heating value)
Syngas production	13-33 Nm^3/h
Syngas Higher Heating Value	5-5,8 MJ/Nm^3
Total Efficiency (generated electricity to biomass input ratio (HHV)).	15 – 20%
Power generation engine	cylinder capacity 1.8 liter engine velocity 1500 rpm compression ratio 8.5:1 Maximum Power 10 kW [220/240 V & 50 Hz

Table 1: Main features of biomass gasification power plant

d) Hydrogen system

Hydrogen system is composed by an electrolyser and a PEM fuel cell, both of them connected to the micro grid. (Figure 3).

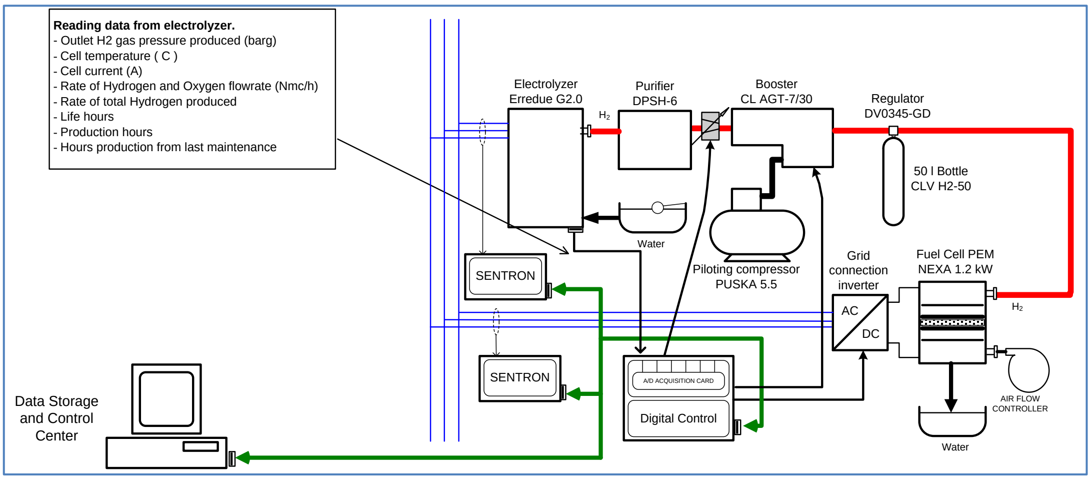


Figure 3: LabDER Hydrogen system

Fuel cell is the well-known Nexa 1200 model from Ballard. Maximum output DC power is 1300 W. Output voltage range is 22 V to 50 V and corresponding current range is 49 A to 1 A. Both output voltage and current are DC values. In order to inject the necessary current into the grid, a grid connected power inverter is used. This converter is managed by the digital control, which fixes the corresponding current with the power that should be compensated

Hydrogen production is done by means of an alkaline electrolyser, with a nominal power of 7,2 kW, using distilled and deionized water. Products of electrolysis are hydrogen and oxygen. Currently, oxygen is not used, but in the future it will be used to increase the efficiency of syngas production in the biomass power plant. Hydrogen is pipelined to a purifying system which can increase its purity up to the value requires by the PEM fuel cell (99.995%). Purification is made by extracting residual oxygen, humidity and electrolytic solution from the hydrogen flow. Purifying system is based on a Pressure Swing Adsorption process. It consists of three filters (activated carbon, aluminium oxide and hygroscopic salts), and requires a minimum of 6 bar of compressed air flow supplied by an additional compressor. The generated hydrogen is stored in a 50 litre gas bottle up to 200 bar pressure. Nominal hydrogen production is 1.33 Nm3/h at 2.5 bar of outlet pressure. The entire electrolysis process is controlled by a Programmable Logic Controller (PLC), with a serial port that makes it possible to consult all these parameters from an external device by means of a RS232 serial communication with Modbus RTU protocol.

e) Storage systems

Looking for feasibility of HRES in isolated applications, storage systems could play an essential role. To prove this potential in specific configurations, LabDER includes two different storage systems: batteries and hydrogen. Hydrogen system has been explained in the previous paragraph. The battery bank of LabDER is composed for 4 batteries ENERSOL 250 connected in series working at 12 V and 250 each. The whole battery bank work at 48V and the maximum storage capacity of the batteries is close to 12 kWh. However, because the depth of discharge of battery is 50%, the stored energy available in the bank is 6 kWh.

A storage system for the syngas generated by the biomass gasification plant is now under consideration to prove its potential and technical and economic viability in this type of applications.

f) Micro grid control system and data acquisition system

Two main systems have been developed for LABDER management: a micro grid control system (MCS) and a data acquisition system (DAS). The MCS is devoted to control the operation of all micro grid systems and it is developed as a distributed control, where the application packages for communicating with the distributed intelligent processors reside in a control server and update the relational databases in real time. The control server also acts as a file server host, where the graphical information (screens design, images, etc.) are stored. End user work station represents the graphical link between the server and the operator of the micro grid. DAS system is based on the storage of all distributed intelligent processors data, via communication cards, in a common database and processed thereafter. This database is operated by a graphical SCADA to provide the requested information to the energy operators in an easy-to-use format. The SCADA has been developed using LabVIEW. The main components to perform the control of the micro grid are a PLC (to control various contactors to connect and disconnect the renewable sources (solar panels, wind turbine, generator, etc.), and a hybrid inverter (HI). The HI sets up the operating modes of the micro grid: grid-tied, insulated, generator support, battery support, batteries charging, load supply and energy sales. The HI can work in grid-tied mode, to inject energy into the grid from batteries or renewable resources or in insulated mode where creates an electrical network from a DC power source and use the renewable resources to charge the batteries. To manage the energy flows, the control system gets information from the HI, PLC and existing power meters. All data is stored in the database located in the server.

Control system for LabDER is displayed at figure 4. Hardware for the communication net uses Modbus TCP/IP protocol; to achieve it, all data sources are transduced from original protocol to MB TCP/IP; figure 5 shows the basic scheme of installation: communication path starts in data source device (inverter, sensor, or power analyser) and follows to specific transducer (RS-232, RS-485 and others to TCP/IP), to the network switch and finally to a PC. To determine LabDER energy consumption, a power analyser has been installed in the laboratory power input.

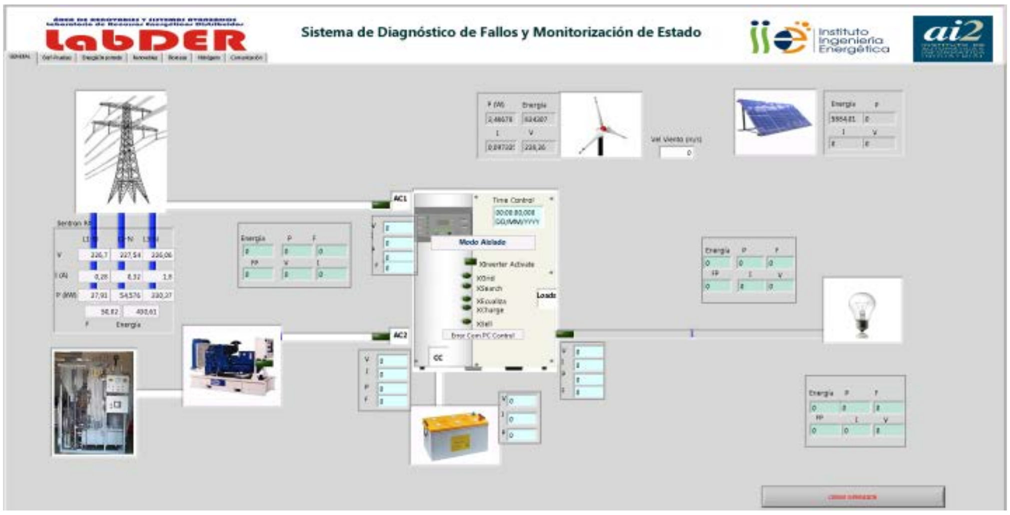


Figure 4: LabDER main supervisor system, user interface

All supervisory software has been developed using a LabVIEW environment. Program code is split in modules which performing tasks such as: Supervisor, Communications, Save data and Virtual Server. All device registers and its times are posts in a virtual server which acts as slave for another PC in the same net. This makes possible to share information on line with the main control system.

Related to condition monitoring and fault diagnosis, each renewable energy source has different treatment; also, using LabVIEW environment have been created interconnected program blocks representing the components of each group generating; after that, was carried out the following activities: simulation and calculation of standard deviations, model fitting, definition and development trend analysis and refinement of fault trees.

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[2] S. Pedrazzi, G. Zini, P. Tartarini (2010). "*Complete modeling and software implementation of a virtual solar hydrogen hybrid system*". Energy Conversion and Management, Vol. 51(1):122–9.

[3] T. Zhou, B. Francois (2009). "*Modeling and control design of hydrogen production process for an active hydrogen/wind hybrid power system*". International Journal of Hydrogen Energy, Vol. 34(1):21–30.

[4] M. Uzunoglu, O.C. Onar, M.S. Alam (2009). "*Modelling, control and simulation of a PV/FC/UC based hybrid power generation system for stand-alone applications*". Renewable Energy, Vol. 34:509–20.

[5] R. Dufo-Lopez, J.L. Bernal-Agustin (2008). "*Multi-objective design of PV- wind-diesel-hydrogen- battery systems*". Renewable Energy, Vol. 33:2559–72.

[6] A. Pérez-Navarro et al. (2016). "*Experimental verification of hybrid renewable systems as feasible energy sources*". Renewable Energy, Vol. 86, pp. 384–391.

Appendix 3. Author's articles associated to this thesis

1. A. Pérez-Navarro, D. Alfonso, H.E. Ariza, J. Cárcel, A. Correcher, G. Escrivá-Escrivá, E. Hurtado, F. Ibáñez, **E. Peñalvo**, R. Roig, C. Roldán, C. Sánchez, I. Segura, C. Vargas. (2016). "*Experimental verification of hybrid renewable systems as feasible energy sources*". Renewable Energy, 86, pp. 384–391.
2. E. Hurtado, **E. Peñalvo**, A. Pérez-Navarro, C. Vargas, D. Alfonso. (2015). "*Optimization of a hybrid renewable system for high feasibility application in non-connected zones*". Applied Energy, 155, pp. 308–314.
3. H. Fernández-Puratich, J.V. Oliver-Villanueva, D. Alfonso-Solar; **E. Peñalvo-López** (2013). **"***Quantification of potential lignocellulosic biomass in fruit trees grown in Mediterranean regions*". BioResources, 1, pp.88 - 103.
4. D. Alfonso; C. Perpiñá; A. Pérez-Navarro; **E. Peñalvo**; C. Vargas; R. Cárdenas. (2009) "*Methodology for optimization of distributed biomass resources evaluation, management and final energy use*". Biomass & Bioenergy, 33, pp.1070-1079.
5. C. Perpiñá; D. Alfonso; A. Pérez-Navarro; **E. Peñalvo**; C. Vargas; R. Cárdenas. (2009) "*Methodology based on Geographic Information Systems for biomass logistics and transport optimization*". Renewable Energy 34, pp.555–565.